Designing Smart Electrical Panels for Existing Wastewater Treatment Plants to Achieve Optimised Biogas Production and Cogeneration with HV/LV and Communication Redundancy for Smart Grid

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Thesis submitted for the fulfilment of the requirements of the degree of

Doctor of Philosophy's Electrical Engineering

March, 2018

Abstract

Recognising the deep potential in wastewater treatment plant (WWTP) automation strategies, this research focuses on expanding the plant operations in order to optimally utilise the produced biogas during the wastewater treatment process to achieve electricity cogeneration and High Voltage/Low Voltage (HV/LV) redundancy. The research has resulted in a proposed design for a smart Remote Terminal Unit (RTU). The proposed design also enables a failsafe mechanism at different levels of the water treatment process and biogas production thus facilitating an automated WWTP electricity cogeneration. The proposed design also increases the life span of substations, reduces power demand load on the grids and enhances safety of WWTP equipment during various scenarios of electricity cogeneration, shut downs and maintenance operations**.** Monitoring, operating and controlling of WWTPs is a complex and challenging task. The power equipment in most of the existing or old WWTPs that generates electricity from the biogas produced in the water treatment process requires intensive supervision and control to enable failsafe and redundant electricity cogeneration process. This research focuses on setting up an effective communication system between power equipment at existing or older WWTP distribution substations and power company`s zone substations, without the need to upgrade expensive switchgear and power equipment in the network. The proposed philosophy achieves automated and failsafe communication network for SCADA link to enable WWTP electricity cogeneration, utilising exiting or old infrastructure. This critical multidirectional power and data flow requires proper compliant and semantic data models to guarantee smooth and safe operations. It also requires to be flexible and have the ability to develop and implement the telemetric mapping philosophy between the substations during various scenarios of electricity cogeneration and faults. This research has resulted in a proposal of smart Remote Terminal Units (RTUs) on existing or old infrastructure of WWTP to achieve electricity cogeneration with integrated renewable energy resource

Student Declaration

Doctor of Philosophy by Classical Thesis Declaration "I, Muhammad Anser Kazim, declare that the Ph.D thesis entitled

Designing Smart Electrical Panels for Existing Wastewater Treatment Plants to Achieve Optimised Biogas Production and Cogeneration with HV/LV and Communication Redundancy for Smart Grid

is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature	Date
M Anser Kazim	17/03/2018

This research is dedicated to the hard-working staff of Melbourne Water Western Treatment Plant (MW-WTP), who works tirelessly to ensure clean and continuous water supplies. I would also like to dedicate this research to the supervisory staff at Victoria University of Technology, Australia, for guiding and advising me through this challenging work by imparting their valuable knowledge. I thank them for their encouragement and support.

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1. Designing of a Smart Remote Terminal Unit at Wastewater Treatment Plants to Achieve Optimised Biogas Production and Electricity Cogeneration. (IJTRS), Vol 2, Issue XI 2017 IJTRS-V2-I10-006
2. Modelling Smart Remote Terminal Units to Achieve Telemetric Communication Redundancy for Electricity Cogeneration at Wastewater Treatment Plants. (IJTRS), Vol 2, Issue XI, 2017 IJTRS-V2-I10-007
3. Optimisation of Existing Waste Water Treatment Plants by Sub-station Automation. Under review (AJEEE), EATJ-S-17-00735
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Index Terms

Wastewater Treatment Plant, Biogas, Optimised Electricity Cogeneration, Smart Remote Terminal Unit, Energy Management, Health and Safety, Wastewater Management, Smart RTU, Communication Redundancy, HMI and SCADA, Electricity Cogeneration, Relay Coordination, Smart Grids, Electricity Trigeneration, Sub-station Automation Systems, Carbon Emissions

List of Nomenclature

CHP	Combined Heat and Power
TSS	Total Suspended Solids
BOD	Biological Oxygen Demand
WAS	Waste Activated Sludge
CT	Current Transformer
HRT	Hydraulic Retention Time
HV	High Voltage
I/O	Input and Output
LV	Low Voltage
MVAR	Mega Volt Ampere Reactive
MW	Mega Watt
O&M	Operations and Maintenance
PLC	Programmable Logic Controller
CB	Circuit Breaker
POC	Point of Contact
PT	Power Transformer
RMU	Ring Main Unit
RTP	Remote Terminal Plant
RTU	Remote Terminal Unit
MTU	Master Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SCL	Sub-station Configuration Language
TS	Total Solids
VS	Volatile Solids
WAS	Waste Activated Sludge

WTP	Water Treatment Plant
HMI	Human Machine Interface
SAS	Sub-station Automation
IED	Intelligent Electronic Device
CB	Circuit Breaker
EMI/EMC	Electromagnetic Interface/Electromagnetic Control
PLC	Programmable Logic Controller
TCP/IP	Transmission Control Protocol/Internet Protocol
MCC	Master Console Centre
DNP	Distributed Network Protocol
FOC	Fibre Optic Connectivity
HV/LV	High Voltage/Low Voltage
VT	Voltage Transformer
PTP	Precision Time Protocol
LCTA	Least Cost Technically Acceptable
QOS	Quality of Service
GSE	Generic Sub-station Event
SCL	Sub-station Configuration Language
LACP	Link Aggregation Control Protocol
GOOSE	Generic Object-Oriented System-wide Events
ICMP	Internet Control Message Protocol
ICCP	Inter-control Centre Communication Protocol
DA	Distribution Automation
ADA	Advanced smart Distribution Automation
ADO	Advanced Distribution Operation
ADM	Advanced Distribution Management

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Acknowledgment

I would like to take this opportunity to thank my family and friends, who provided me with their valuable support and encouragement through the course of this research and contributed to the completion of this research project.

I would also like to thank my honourable supervisor, Professor Dr. Akhtar Kalam, who was very cooperative and provided me with insightful feedback, constructive criticism and invaluable support during my studies, without which my research work could not have been completed successfully. I am also very thankful to my co-supervisor, Professor Aladdin Zayegh, for his support in my research work.

Moreover, I would like to convey my special thanks to the hard-working staff of Melbourne Water Western Treatment Plant, who work tirelessly to ensure clean and continuous water supply, for supporting this challenging research work.

CHAPTER 1: THESIS OVERVIEW

1.1 INTRODUCTION

The modern world has been facing a lot of challenges in providing adequate power generation, transmission and distribution to meet its growing energy demands. Demand for electrical energy is increasing globally at a steady rate of approximately 3% annually, hence requiring intelligent and a smart energy solution with flexible infrastructure for efficient and cost-effective strategies is the way forward.

Waste Water Treatment Plants (WWTP) offer a renewable energy resource to resolve the intensive energy requirements for the water treatment process. Any excess supply generated is feedback to the power company`s grid. WWTPs play a vital role for a sustainable environment by providing clean water for agriculture along with other by-products like biogas that can be utilised for power cogeneration [1].

The evolution of Wastewater Treatment Plants (WWTPs) towards smart grids with integrated renewable energy resources will result in optimised biogas production and electricity trigeneration, which will provide energy management and environmental solutions, together with economic growth on old or existing infrastructure.

The research utilises telemetric signal monitoring for biogas production and multidirectional power flow through remote data to achieve automated and efficient protective relay coordination for a failsafe and redundant system using smart Remote Terminal Unit (RTU) at WWTP substations. The proposed philosophy uses Least Cost Technically Acceptable (LCTA) principles by utilising existing infrastructure along with IEC61850 and IEEE1588 standards for Supervisory Control and Data Acquisition (SCADA) and Human Machine Interfaces (HMI) of remote stations. The research was carried out using LCTA principles at Melbourne Water Western Treatment Plant (MW-WTP), which is the largest treatment facility in the Southern Hemisphere.

WWTPs have a potential to produce electrical energy as wastewater contains about five times the energy required for its treatment [2]. Ideally, using the sustainable power sources from the WWTPs can give numerous ecological advent systems by adequately decreasing the carbon emissions entering the climate and keeping the seas clean, thereby assisting the marine life and the coral reefs. Water demand has been anticipated to increase rapidly. Water crisis can be a worldwide issue for the general population and the economy in the near future, if no tangible actions are taken to resolve it sooner.

Figure 1.1 demonstrates the significance of WWTP, which produces energy from inexhaustible assets to meet its energy demands while giving numerous useful by products [3].

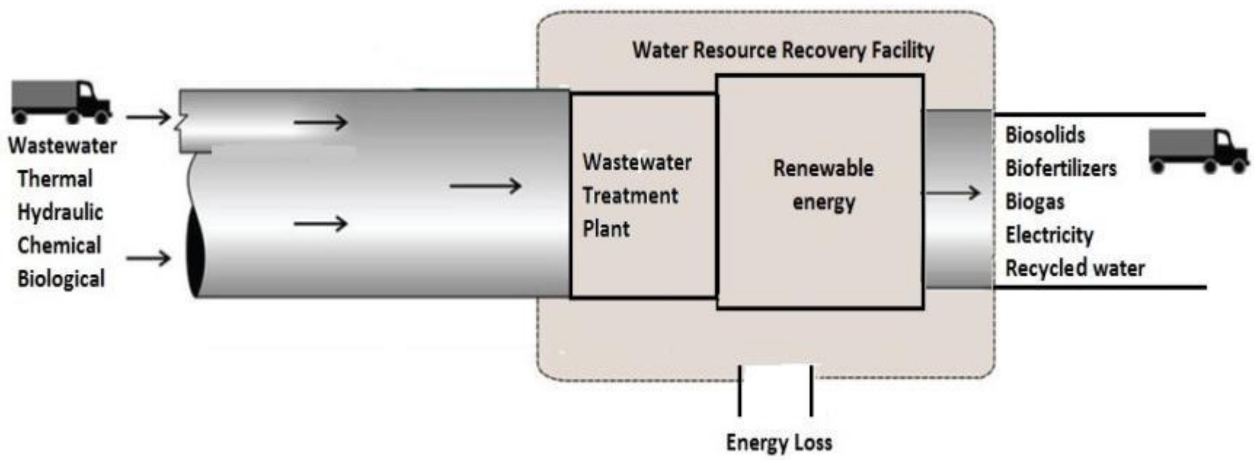


Figure 1.1 Importance of WWTP

This chapter covers a brief introduction of the research topic along with the key objectives and milestones along with the original contribution and the methodologies applied to the work. It also provides an insight into the research significance in the discipline of engineering.

There is a universal realisation towards exploring and innovating new sources of energy and conservation of available resources. In this context, power engineers are working towards achieving sustainable solutions for enhanced energy efficiency, reconsidering energy production methods and integrating renewable energy for industrial and commercial use [4]. Increased urbanisation has triggered problems associated with water supply, waste collection and its treatment. Though wastewater treatment has gained momentum with substantial increase in the number of WWTPs during the recent years, the major concern of the sector has been to achieve higher efficiency in the treatment process with cost effectiveness and minimum consumption of energy along with other resources [5]. Other WWTPs have an issue of integrating recently explored renewable energy resources in their Power Management Systems (PMS) as they were designed in an era where automation haven’t really kicked off [6].

Wastewater is composed of roughly 99% of water and 1% suspended colloidal and dissolved solids. It is well understood that the water systems and WWTPs are high energy consumers. The energy consumption in the USA for the movement and treatment of water and wastewater has been estimated to be 3 to 4% of the total electricity consumption [7]. The existing water treatment infrastructure lacks certain important features that could enhance energy efficiency and utilise the biofuels formed in an effective way. With certain modifications in the existing systems, the extensive energy utilisation of WWTPs can be addressed. This research, therefore, aims to address these features by proposing a technology-driven approach to optimise on-site electricity production and enable efficient control levels for power generation and transmission between the power company`s zone substations and WWTP distribution substations [8,9]. It also proposes a solution using least cost, technically acceptable principles to achieve power and communication redundancy for such systems. Figure 1.2 demonstrates the basic process of wastewater treatment and the production of resources like biogas, biosolids and recycled water.

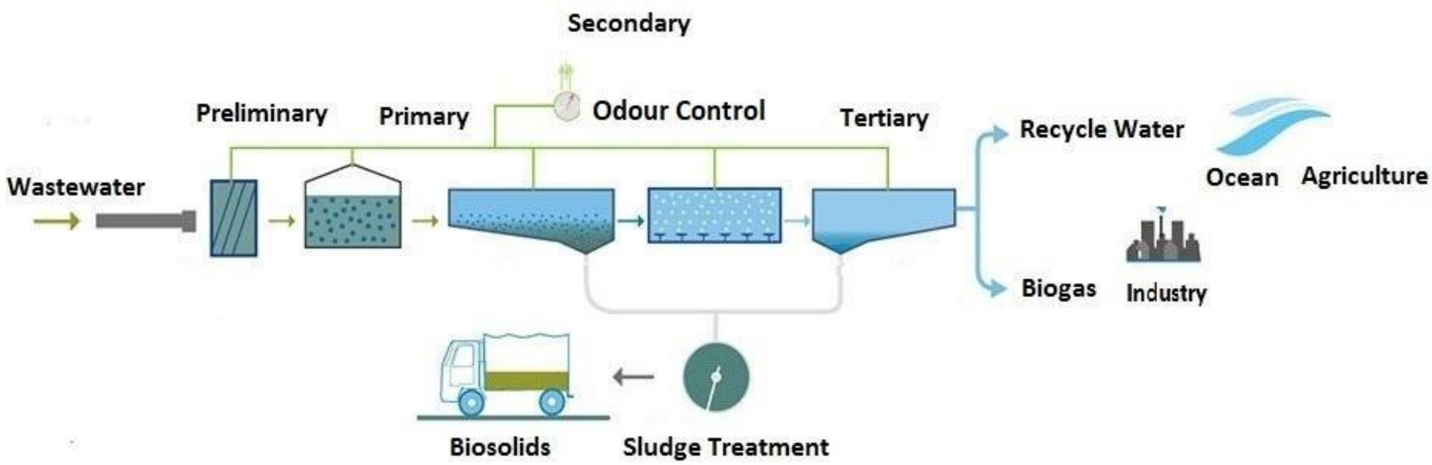


Figure 1.2 Wastewater Treatment Process

Water is the greatest ordinarily available resource yet only 3% of it is fresh water of which just 1/3 is open for use in cultivation and urban zones. The rest is set in frosty masses or significantly underground. Today, the standard water source for more than 2 billion people of the world is the underground freshwater, mostly extracted through bores and tube wells [10, 11]. As water levels and the population of the world has risen globally, so has the need for the water-intensive systems and consumers stock for instance, manufacturing, meat, dairy and many more. Such augmentation in overall freshwater use has incited the utilization of water treatment and recycling plants to its maximum output [12].

As the global warming phenomenon picks up pace, climate change can threaten ecosystems and environments that protect vital water resources, limiting access to them. This can create unwanted security threats as well. Hence the need for efficient and sustainable WWTP has increased all the more that can cater the wastewater from urban areas and process them before pumping it in the oceans [13].

1.1.1 Water Sustainability in the Future

2015 marks the end of a decade of action by the UN on promoting water and sanitation issue, a campaign, which has seen an improvement in awareness of the threat that water sustainability poses both to sustainable development and political security. Water sustainability is, therefore, at the core strategy for all the countries. Failure to address unsustainable use of water and its treatment will create bottlenecks to achieve goals in a myriad of other areas [14, 15].

Protecting the environment for the coming generations begins with more effective water management systems today.

The Australian Government is working with all states, territories and communities to improve the Australia's water resource and preparing for a future with less water to restore the health of the rivers. The governments across the globe have now passed legislations to establish initiatives and programs that include development and upgradation of water treatment and pumping stations. Considering all situations, it is most important to focus more deeply on wastewater treatment and its methodology to preserve this valuable resource in the driest continent of the world [16].

1.1.2 Water Consumerism in Agriculture

The agricultural sector guzzles 70 % of the world's annual water consumption and it will be one of the first to feel the strain as demand supersedes the water capacity. An efficient and a sustainable WWTP and desalination plants can easily resolve this issue by reusing water supplies and the fertilizers that are produced during the process. Hence the need for automated and efficient WWTPs across the globe is being realized all the more [17].

1.1.3 Water availability and Use

Australia utilizes around 5 % of its aggregate sustainable freshwater assets, compared to 20% for the United States and 43 % for Italy: the provincial conveyance of utilization is exceedingly uneven across Australia [18]. Water assets assume a predominant role in the presence of life and are likewise a standout amongst the most vital wellsprings of vitality.

1.1.4 Power Demand for WWTP and MW-WTP

Amid late years, the number of WWTPs has generously expanded, making the investigation of energy resources and sustainability utilization critical, which has been identified with the research and development of the systems and methodologies that manage the water treatment processes [19,20]. The optimum utilization in WWTPs diminished with the expansion of scale and task stack rate. MW-WTP Melbourne Water Western Treatment Plant (MW-WTP) in Melbourne, Australia, is the largest water treatment facility in the southern hemisphere and is chosen as the contextual analysis to dissect the task of various water treatment processes and the related units. Electrical energy utilization at the MW-WTP is in the vicinity of 35 kW and 45 kW. Power demand varies depending on the plant's size, as well as the methodologies of the water treatment implied. Anaerobic digestion is the preferred method implied in this research [21].

As per the research work already done in this area, the highest utilization of electricity is to pump and treat wastewater. The dynamic slop treatment, with the natural oxidation of contaminations, assimilates around half to 65 % of the WWTP maximum demand load, 11 % is required for the essential treatment, coarseness, sand and oil elimination in addition to sedimentation. Nonetheless, plant supervisors have an opportunity to altogether reduce the energy costs through automation and energy efficient strategies that has been researched and studied in this thesis, after making minor changes to the WWTP assets management [22]. Intensive examinations of a large portion of the MW-WTP in this research demonstrated that their energy utilization could be decreased by 60 % to 80 %.

Investment in the water industry should be directed towards modernization existing infrastructure and integrating the available renewable energy resources in the existing or old assets. This includes implementation of Smart Devices (SD) and Supervisory Control and Data Acquisition (SCADA) and achieving cogeneration of electricity at the WWTPs by adopting Sub-station Automation Systems (SAS). This research discusses a technology driven approach to achieve this without too much investment in commissioning new facilities.

In nearly all the WWTPs across Australia, the achievable power cost funds surpassed the required costs by about 15 %. On-site energy production and upgrades are quite often required and a practical approach of tackling this.

In the last decade, the number of WWTPs across the globe has increased and their abilities have expanded. With the research and development and the realization to secure the water assets, the MW-WTP has been expanding gradually, which can currently treat around an aggregate limit of 1.056×10^8 m^3/d of grey water or sewerage. Number of investigations on the tasks and administration of WWTPs has been carried out as part of this research that is focused on the WWTP operations effectiveness and procedures that can reduce the carbon footprint of the processes and the WWTPs, along with the evaluation of ecological systems [23]. Optimum utilization of the existing infrastructure and the resources is considered.

In order to optimally utilize the existing renewable energy resources at the WWTP, a smart electrical panel is proposed on the WWTP distribution sub-stations and the power company`s zone sub-station with SDs. This research then discussed the control philosophy that will monitor and control the processes and the upgrades involved at site to achieve WWTP cogeneration.

1.2 ENERGY RESOURCES

Currently, society relies mostly on non-renewable fossil fuels for energy and constitutes around 39 % oil, 24 % natural gas, 23 % coal, 8 % nuclear and 6 % other. Australia is a prime example where a developed nation where 93.8% of the energy needs are met using fossil fuels. Non-renewable resources have a limited supply. The supply comes from the Earth itself and it typically takes millions of years for them to form and develop [24, 25].

1.2.1 Types of Non-Renewable Resources

Non-renewable resources can generally be separated into two main categories; fossil fuels and nuclear fuels.

Fossil Fuels

Fossil fuels are derived from organic matter, which has been trapped between layers of sediments within the Earth for millions of years. The organic matter, typically plants, have decomposed and compressed over time, leaving what are known as fossil fuel deposits. The deposits and the materials produced tend to be highly combustible, making them an ideal energy source. They are difficult to obtain as they are typically retrieved through drilling or mining.

Crude Oil/Petroleum

Crude oil is a non-renewable resource that builds up in liquid form between the layers of the Earth's crust. It is retrieved by drilling deep into the ground and pumping the liquid out. The liquid is then refined and used for many different products. Crude oil is versatile fuel and is used to produce plastics, artificial food flavourings, heating oil, petrol, diesel, jet fuel and propane.

Gas

Natural gasses gather below the Earth's crust and, like crude oil, must be drilled for and pumped out. Methane and ethane are the most common types of gasses obtained through this process. These gasses are most commonly used in home heating as well as gas ovens and grills.

Coal

Coal is the most commonly used fossil fuels. Created by compressed organic matter, it is solid like rock and is obtained via mining. China produces the most coal by far. According to the Statistical Review of World Energy, published in 2011 by BP, China produced an astounding 48.3% (3,240 million tons) of the world's coal in 2010, followed by the United States, which produced a mere 14.8%. Coal is most typically used in home heating and the running of power plants.

Nuclear Fuels

The other form of non-renewable resource used to produce energy, nuclear fuel, is primarily obtained through the mining and refining of uranium ore. Uranium is a naturally occurring element found within the Earth's core. Mostly, uranium deposits occur in small quantities, which miners gather together, refine and purify. Once gathered, the uranium is brought together and compounded into rods. The rods are then submersed into tanks of water. When it reaches critical mass, uranium begins to break down and release energy that heats the water it is immersed in. This is known as "fission." The steam then creates pressure and it is this pressure which drives the turbines that generate the electricity. Nuclear fuels are key to maintaining the Earth's environment since they are the cleanest as compared to all other sources of energies [26].

It is widely understood that the burning of fossil fuels has harmful consequences to the environment and contributes to global warming and climate change. For this reason, many organizations have developed alternative energy sources. There are also risks associated with nuclear material, since its radioactive nature makes it toxic, and it must be handled properly. Climate change has been brought to the forefront of international talks in recent years, and the countries involved have made pledges to significantly reduce carbon emissions and pollution. Most of the countries at present rely intensely on coal, oil, and gaseous petrol to meet their energy needs. Petroleum derivatives are non-sustainable, that is, they draw on limited assets with excessive cost, making it impossible to recover.

1.2.2 Renewable Energy Sources

Sustainable power resource assets for example the wind and the sun-oriented energy resources that can be supplant and will never run out are known as the renewable resources. For example, the sun's warmth drives the breezes whose energy is captured by the wind turbines. This mechanical energy from the breeze and the heat energy from the sun is converted into the electrical energy using various systems. The water vapor in the atmosphere transforms into the rain or snow that streams downhill into waterways or streams. Its energy can be captured utilizing the hydroelectric power.

Hydropower

Streaming water is used to rotate the turbines. This mechanical energy is converted into electrical energy using generators. The power generated is increased for efficient voltage transmission using step-up transformers across the power network, for decreased voltage losses. Currently, 5 % of the power systems and world`s demand utilizes hydropower [27].

Wind Power

Power systems using wind energy has expanded fundamentally in numerous nations commonly close to costal zones since 1970. Wind turbines and mills generate close to 2 % of power of the world [28].

Biomass

Biomass is obtained from plants and animals. It incorporates timber, paper, scraps, grass, leaves, paper, wood and other civil waste with junk. These materials can be scorched straight in steam-electric power plants, or they can be changed over to a gaseous that can be synched in steam generators, gas turbines, or inside ignition motor generators.

Solar Power

Most sustainable power source comes either specifically or by implication from the sun. Daylight or solar power can be utilized specifically for commercial use and households, for producing power and water warming. Photovoltaic (PV) cells generate power straight from the daylight. Solar power is widely embraced now and recently, Adelaide Desalination Plant recently commissioned 1.5 MW solar powered sub-stations to energize their pumping stations.

Geothermal Power

Not all sustainable power source assets originate from the sun. Geothermal energy can be captured by tapping the Earth's core, which can be converted to electrical energy. This can be achieved using steam turbines.

Tidal Energy

The energy of the sea's tides originates from the gravitational draw of the moon and the sun upon the Earth. Tidal energy is being harvested across the globe now as there is no input costs apart from the infrastructure required.

1.3 POWER GENERATION METHODS

Coal

Coal is predominantly carbon. Consuming one ton of carbon creates around 3.7 tons of carbon dioxide. Smoke can be an issue, particularly in urban communities. Some coal contains sulphur and mercury, which create harmful gasses when consumed. The slag contains dangerous substances that can drain into streams and groundwater. An open, old-style, chimney is most likely close to 15 % proficient [27,28].

It has been trusted that the world's coal stores would last a century or all the more, yet some current research has shown this was idealistic. Coal generates most carbon dioxide CO_2 per Watt-hour of energy produced than some other system strategy. The strategies for mining coal can be extremely damaging.

Slag must be disposed of and a significant measure of smoke is dispersed into the atmosphere. The air pollution from the expending of coal causes a number of human deaths worldwide consistently. At present, first world countries are introducing measures to get rid of the coal-powered stations.

Coal contains harmful substances, for example, sulphur, arsenic, selenium, mercury and the radioactive components uranium, thorium, radium and radon. When this coal is mined and consumed, these substances can be discharged into the earth atmosphere. Consumed sulphur is one of the primary driver of corrosive rain, however most present day Western coal-terminated power stations evacuate the greater part of the sulphur oxides from the discharged gasses. In short, coal does not have any space in the modern world and is not considered as a feasible technique.

The deceptive term 'clean coal' is now and then used to allude to coal-terminated power stations that effectively separate substances like sulphur from the coal, either previously or in the wake of consuming. It is difficult to consume coal without creating carbon dioxide, so all coal powered stations are filthy. Nonetheless, it is conceivable to discard sequestrate the carbon dioxide with the goal that it isn't discharged into the environment for quite a while.

It appears that some coal-terminated power stations that are not monetarily suitable are being kept in task on the grounds that decommissioning and tidying up would be costlier than propping or upgrading them.

Natural Gas

Gaseous petrol control power plants utilize flammable gas as fuel, keeping in mind the end goal to generate power. This procedure involves utilizing a huge gas turbine, where the flammable gas is mixed alongside a surge of air, which is combusted and pumped through a turbine making a generator turn. Gaseous petrol control power plants have numerous benefits contrasts to the other essential energy sources utilized for generating power. Consuming of flammable gas is inconceivably spotless contrasted with coal and oil.

The utilization of flammable gas represents around 23% of the world's power system. This is second just to coal, which is the overwhelming energy source in various countries [29].

Flammable gas is a petroleum derivative, however an unnatural weather change outflows from its burning are much lower than those from coal or oil. Flammable gas transmits 50 to 60 percent less carbon dioxide CO_2 when combusted in another, productive petroleum gas control plant contrasted and emanations from a run of the mill new coal plant. Thinking about just tailpipe discharges, gaseous petrol likewise produces 15 to 20 percent less warmth catching gases than fuel when copied in the present run of the mill vehicle.

The penetrating and extraction of petroleum gas from wells and its transportation in pipelines brings about the spill system of methane, essential segment of flammable gas that is 34 times more grounded than CO_2 at catching warmth over a 100-year term and 86 times more grounded more than 20 years. Preparatory examinations and field estimations demonstrate that these alleged "criminal" methane emanations go from 1 % to 9 % of aggregate life cycle outflows [30].

One late investigation found that methane misfortunes must be kept beneath 3.2 percent for gaseous petrol influence plants to have bring down life cycle discharges than new coal plants over brief time periods of 20 years or less. Advances are accessible to decrease a significant part of the spilling methane yet sending such innovation would require new arrangements and ventures. Produces carbon dioxide CO_2, which is a critical ozone depleting substance.

The world's petroleum gas holds are constrained, however not all that restricted as oil saves. Spill system of methane to the climate, exceptionally hard to evaluate, expands the greenhouse impact.

Oil

Though most oil is used for transportation or home heating purposes, a small percent’s system is still used as a fuel for electricity generating plants. Oil sits in deep underground reservoirs. Like other fossil fuels, this liquid is the end-product of millions of years of decomposition of organic materials. Since the ultimate amount of oil is finite and cannot be replenished once it is extracted and burned - it cannot be considered a renewable resource. Once extracted, oil can be refined into a number of fuel products such as gasoline, kerosene, liquefied petroleum gas such as propane, distillates diesel and jet fuels and "residuals" that include industrial and electricity fuels. Three technologies are used to convert oil into electricity. Conventional steam, Oil is burned to heat water to create steam to generate electricity. Combustion turbine, oil is burned under pressure to produce hot exhaust gases which spin a turbine to generate electricity. In combined-cycle technology, oil is first combusted in a combustion turbine, using the heated exhaust gases to generate electricity. After these exhaust gases are recovered, they heat water in a boiler, creating steam to drive a second turbine [31].

1.3.1 Environmental Impacts

Oil sits in profound underground repositories. Like other non-renewable energy sources, this fluid is the final result of a large number of years of decay of natural materials. Since a definitive measure of oil is limited and can't be recharged once it is extricated and consumed - it can't be viewed as an inexhaustible asset. Once removed, oil can be refined into various fuel items gas, lamp oil, melted oil gas, for example, propane, distillates diesel and fly energize and "residuals" that incorporate mechanical and power fills. CO_2 is continuously penetrating the atmosphere from these production methods, which is an major greenhouse gas and the biggest contributor to the carbon emissions, has detrimental impacts on the environment and human life. They also require a substantial amount of cooling water. The world's oil reserves are limited. Oil spills, especially at sea, cause severe pollution. Some oils contain high levels of sulphur. The world's supply of oil is limited and hence fossil fuels are not the choice of the future [30, 31]. With world moving towards renewable energy resources, WWTPs have to evolve as well and this research provides that case study and effective philosophy to implement and integrate renewable energy resource in the existing WWTP and incorporate advance cogeneration techniques in the future ones.

This research will assist the designers of the WWTPs to sketch out an energy efficient and sustainable facility with minimized risks.

1.4 POWER GENERATION FROM WASTEWATER

Researchers have discovered very efficient ways for water treatment that guarantee to expel smelling salts from wastewater, to make it clean and to generate power all in the meantime. The methodology implies using internal and renewable energy resources at the WWTP and is hence green electricity [32].

Anaerobic digestion approach to treat wastewater is now widely regarded as the most efficient way. The process involves biogas production that can be utilized for power generation and other energy demands on-site. It acts like a petrol gas. Wastewater treatment using anaerobic digestion can be separated into high rate frameworks including biomass maintenance and low rate frameworks without biomass maintenance [33]. A moderately short pressure driven maintenance time defines the low rates however long-term maintenance strategies, which can be implied in time, describe high rate frameworks. Low rate frameworks are used for processing sludge and grey water, followed by long-term driven maintenance time. The biogas yield differs with the sort and centralization of the feedstock and the process conditions. For natural processing, waste creates compost biogas yields of 80-200 m^3 for every ton and 2-45 m^3 for each m^3, separately. An oxygen consuming processing facility is an imperative factor for enhancing productivity and financial stability of a WWTP [34].

The biogas produced during the anaerobic digestion can be utilized to excite the turbine of on-site generators for electricity cogeneration at WWTP. Furthermore, it provides financial benefit, as wastewater is a sustainable power resource, which delivers biogas. Europe has an aggregate of 1,500 MW being, while the potential sending in 2010 is evaluated at 5,300-6,300 MW. Worldwide a limit up to 20,000 MW was acknowledged by 2010. Ecological weights to enhance squander administration and creation of practical vitality and in addition enhancing the innovation's financial matters will add to more extensive application [35]

1.4.1 Power Supply Redundancy

Future frameworks for such systems at WWTPs rely on comparing real time information that incorporates an efficient and redundant communication technology, accommodating all fault conditions on site and is monitored and controlled at one stop centralized station. Situations like blackouts, operation and maintenance (O&M) procedures and other upgrades to a WWTP including any minor or major capital works shall not allow shutdowns for continuous processing and water supplies. Keeping this in view, Smart Grids are implemented these days at the newly commissioned WWTPs and pumping stations. This research proposes and assesses strategies for enhanced adaptation to non-critical failure with fail-safe mechanisms and redundancy utilizing the ring topology framework. Using the ideas of cutting-edge IEEE and IEC standards and utilizing fiber optic cabling system (FOCS) link for swift and dependable flag transmission with centralized SCADA System, all existing WWTPs can be upgraded to cater for these redundant and efficient systems [36].

Under fault scenarios, ring topology or mesh topology for the links can be established on existing WWTP assets, so that if there is a fault on one end, the communication is enabled via the other loop. These interconnections are achieved by interlinking these loops or links via the smart electrical panels or Remote Terminal Units (RTU). The control and monitoring data from various sections of the plant is communicated in the form of telemetric signals via this arrangement of smart RTUs and FOCs [37]. A control philosophy is then developed to design these smart RTUs. Some of the key features include time synchronization, layers of protection and redundancy to accommodate the rolling stock and water flow on continuous basis at the WWTPs [38].

Ethernet based technology is proficiently utilized as a part of SAS. A redundant communication system correspondence framework requires converging of Intelligent Electronic Devices (IEDs) with information transmission to make it secure and dependable. It also enables failsafe mechanisms with a redundant power supply source that is provided via the smart RTUs. The arrangement complies with the IEC61850 model that empowers all IEDs to speak to their relevant information utilizing indistinguishable data structures that compares to their relative power framework capacities [39]. Installed IEDs collect synchronized examined information from at least one coordinating unit for successive arrangement and handling as per the defined control philosophy. Failover downtimes are reduced by 4.5 ms, complying with the IEC 61850 Smart Grid necessities, while giving ideal characterized Quality-of-Service (QoS) levels [40].

In order to maximize WWTP efficiency and reduce Green House Gases (GHG) and carbon emissions, a continuous monitoring system is required to handle the abrupt variations in the biogas during the water treatment process. This increased communication between various sub-stations and electrical equipment in the power network provides an automated structure to the existing network to accommodate cogeneration at the WWTPs [41].

Data collected through these remote sites is transmitted via the proposed smart RTUs in this research. A 4G network is perfect for such harsh environment and frameworks, as it considers the bi-directional correspondence, remote observing and control of the WWTP, easy and simple establishment and in addition to the higher broadband rates. With the wireless 4G, utilities can remotely find, confine and re-establish control outages, expanding the reliability and efficiency of the networks [42].

1.5 KEY OBJECTIVES

The key objectives of this research are synopsised as follows:

1.5.1 Wastewater Management System

WWTPs are designed to produce effluent of higher quality. Advanced wastewater treatment consists of multiple processes in which different by-products like biogas and biofertilisers are formed. There are four main processes through which suspended solids and Chemical O_2

Demand (COD) are removed in the form of Waste Activated Sludge (WAS), which is further processed through anaerobic digestion thus producing biogas [43]. This biogas is utilised to excite on-site biogenerators for green electricity. Any treatment of sewerage or grey water that goes past the optional or natural water treatment organises and incorporates the expulsion of supplements; for example, phosphorus, nitrogen and high levels of suspended solids. Figure 1.3 shows the flowchart of wastewater treatment and the energy resources produced at different levels. Treated wastewater produced sludge, which was further processed through anaerobic digestion resulting in the production of biogas, which was then utilised in power generation. Through advanced technology, the heat produced in power generation was utilised in the cooling process. This phenomenon is known as the Combined Heat and Power Process (CHP). The flowchart demonstrates the multiple outcomes of the wastewater treatment green lines indicated outputs of the digester gas while red lines indicated utilisation of treated wastewater. Indigo line indicates corelationship of heat energy and electric power [44]. This forms the basis of WWTP electricity cogeneration.

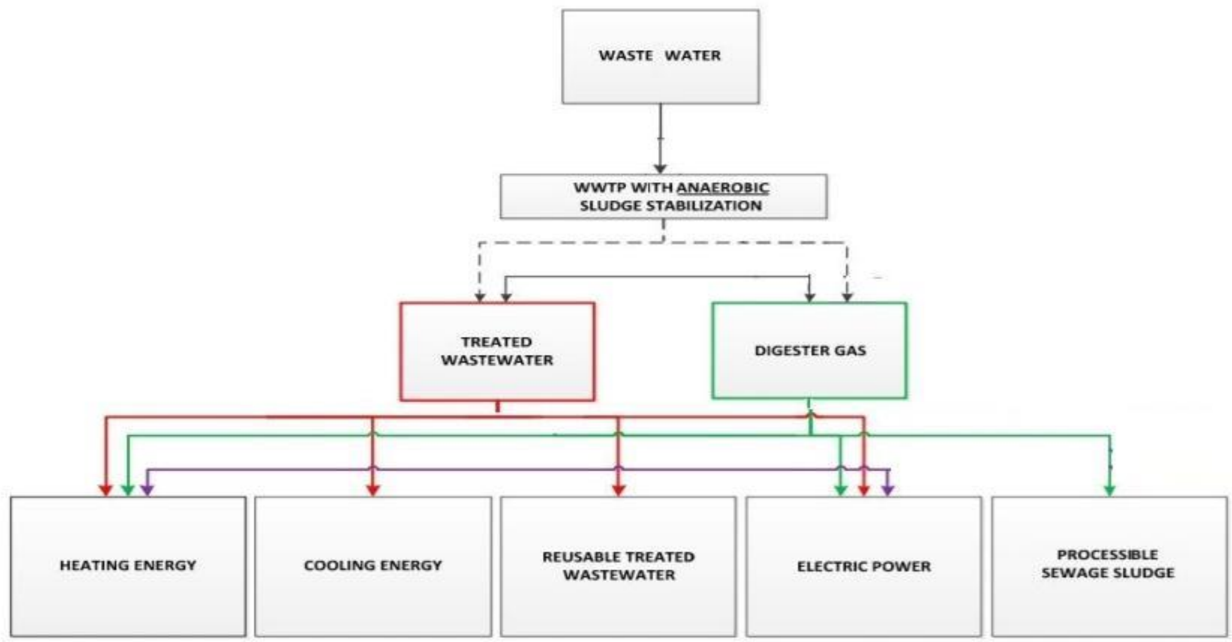


Figure 1.3 By Products from the Wastewater Treatment Plant

An efficient water management system is important since it helps determine the future irrigation expectations. Water, once an abundant natural resource, is becoming a more valuable commodity due to droughts and overuse. Water resource management is the activity of planning, developing, distributing and managing the optimum use of water resources. Ideally, water resource management and planning have regard to all the competing demands for water and seek to allocate water on an equitable basis to satisfy all uses and demands. Water is an essential resource for all life on the planet. Of all the water resources on Earth, only 3% of it is fresh and two-thirds of the freshwater is locked up in ice caps and glaciers. The remaining 1 % is in remote, inaccessible areas. At present only about 0.08 % of all the world fresh water is exploited by mankind in ever increasing demand for sanitation, drinking, manufacturing, leisure and agriculture [45]. This research provides solution for an efficient water management system during various seasons and environmental conditions and the best philosophy to achieve a fail-safe and redundant system at the existing WWTP.

1.5.2 Waste Water Treatment

One of the most well-known types of contamination control in the United States is wastewater treatment. US has an extensive arrangement of gathering sewers, pumping stations, and treatment plants. Sewers gather the wastewater from homes, organizations, and numerous enterprises, and transfer to the WWTPs for treatment. Most WWTPs operate to clean grey water for release into streams or other getting waters, or for reuse in the agriculture industry. A few decades ago, when sewerage was dumped into conduits and unreliable pipes, a characteristic procedure of decontamination started [46]. To start with, the sheer volume of clean water in the stream weakened the pipe walls. Microbes and other little life forms in the water expended the sewerage system and other naturally occurring bacteria, transforming it into new bacterial cells, carbon dioxide and Waste Activated Sludge (WAS). The fundamental function for wastewater treatment is to accelerate the regular procedures by means of which the water is decontaminated. There are two fundamental systems in the treatment of sewerage, essential and optional. In the essential system, solids are permitted to settle and expelled from wastewater. The optional system utilizes organic procedures to additionally refine wastewater. These systems are joined into one task at the WWTP [47].

Essential Treatment is done immediately as the sewage enters a plant in its initial phase. It moves through a screen, which evacuates vast coasting articles, for example, clothes and sticks that may stop up funnels or harm the plant equipment and gear. After grey water has been screened, it goes into a coarseness chamber, where soot, sand, and little stones settle to the base. Sedimentation can be implied at this phase. A course chamber and clarifiers are also utilised in groups with consolidated sewer frameworks where sand or rock may wash into sewers alongside storm water. When screening is finished and WAS has been expelled, sewerage and grey water still contains natural and inorganic contaminations alongside other suspended solids. These solids are in the form of minute particles that can be expelled from sewerage in the sedimentation tank. At the point when the speed of the course through one of these tanks is decreased, the suspended solids will continuously sink to the base, where they frame a mass of solids called crude essential biosolids and was also known as the “muck” some time ago. Biosolids are typically expelled from tanks by pumping, after which it might be additionally regarded for use as a compost or discarded in a land fill or burned [48].

Throughout the years, essential treatment alone has not been able to meet numerous requests for higher water quality. To meet this, urban communities and ventures typically carry out water treatment to an optional treatment level, and now and again, additionally utilize propelled treatment to evacuate supplements and different contaminants. Auxiliary Treatment, the optional phase of the water treatment, evacuates around 85 percent of the natural occurring bacteria from the sewerage by utilization of the microscopic organisms in it. These primary and optional treatment methods are utilized as a part of auxiliary treatment from the streaming grey water channels and the initial treatment process. After emanating leaves, the water in the sedimentation tank of the essential system is streamed or is pumped to a farm utilizing either of these products. A streaming channel is just a bed of stones from three to six feet through which sewer passes. Microorganisms assemble and duplicate on these stones until the point where they can expend the greater part of the natural occurring bacteria [49]. Clean water streams and channels promote water treatment. From a streaming channel, the half-treated sewer streams to another sedimentation tank to flush the abundant microbes. The pattern today is towards the utilization of the initial muck process as opposed to the streaming channels. After the sewerage leaves the settling tank from the essential system, it is directed into an air circulation tank, also known as the aerators, where it is blended with air and stacked with microscopic organisms, which is permitted to stay for a few hours. Amid this time, the microscopic organisms is separated. The grey water, now enacted with extra billions of microorganisms and other minor life forms, can be utilized again by returning it to the air circulation tank for blending with air [50].

To finish the auxiliary treatment, effluents from the sedimentation tank is normally sterilized with chlorine on the chlorination centre, by sampling various levels as per the requirement, before being released into water for usage. Chlorine is sustained into the water to execute pathogenic microorganisms, and to lessen scent. If done properly, chlorination kills in excess of 99 percent of the destructive microscopic organisms in effluents. It is also essential to now require the filtration of abundant chlorine before the release to surface waters by a procedure called dechlorination.

1.5.3 Water Recycling

Australia needs to guarantee water security, as it is the driest continent of the world. Reused water can give a dependable, versatile and monetarily stable solution to the water crises, which can be an essential part of a strong and flexible water supply framework. This will also support the environment.

Numerous ventures utilize a lot of water amid their operational needs and site exercises, which can be inefficient, insufficient and earth harming. Water reusing frameworks offer organizations a chance to decrease water related costs and additionally showcase their customers and administrations to be ecologically responsible.

Recycled water can be utilized for various purposes, including agriculture, car wash and toilets. Water reusing frameworks will differ as per the nature of wastewater to be dealt with and the expected application for the water. The procedure may include the utilization of oil and water separator, a filtration network, a cleanser evacuation unit and a sanitation unit. Recycled water can fulfil most water requests, as long as it is satisfactorily treated to guarantee water quality for the utilization. In places where there is a more prominent possibility of human presentation to the water, high level of treatment is required. With respect to any water source that isn't legitimately treated, medical issues could emerge from drinking or interaction [51].

Water recycling can lessen the anticipated contamination. At the point when treated water releases to seas, waterways, and other water bodies, the contamination loadings are diminished.

1.5.4 Renewable Energy Resource

Wastewater contains about five times the measure of vitality required for the wastewater treatment process. Wastewater is an inexhaustible asset and its treatment provides renewable energy in the form of biogas, biosolid and biofertilisers. Utilising these renewable resources reduces load on the power company`s grid and additionally, provides electricity in case of excess WWTP power generation. This creates new opportunities for electricity generation.

1.5.5 Biogas Production

Figure 1.4 shows wastewater treatment in which the digester used for biogas production is stored in large tanks. The produced biogas is further utilised for the production of electricity cogeneration and distributed to the external grid.

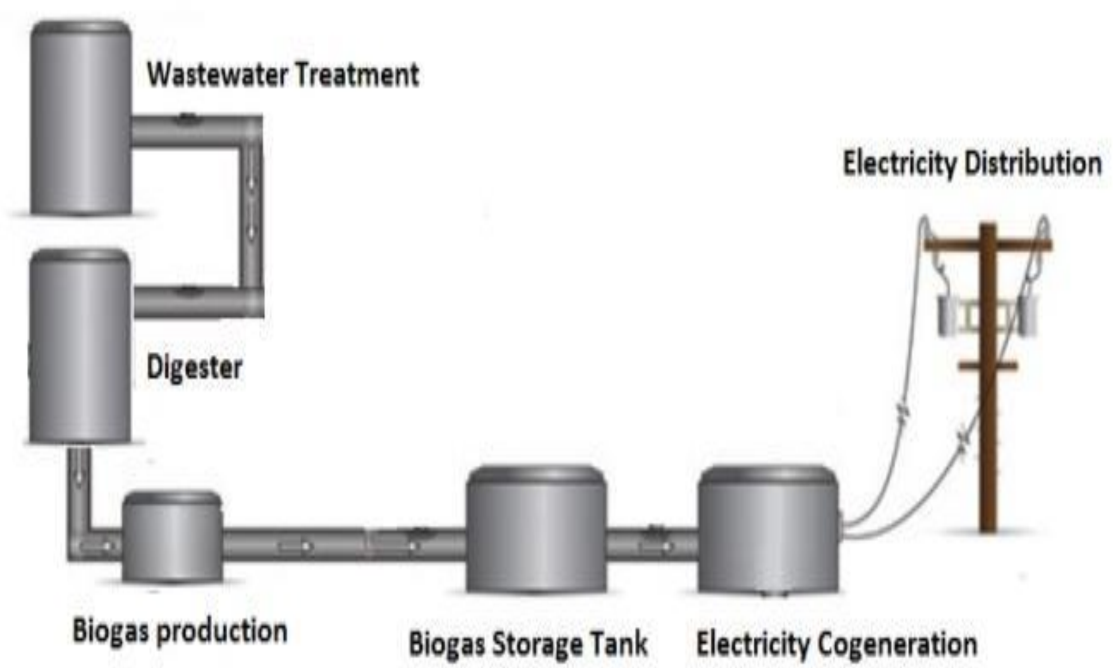


Figure 1.4 Biogas Production and Electricity Cogeneration

1.5.6 Electricity Cogeneration

The Electricity Cogeneration process utilises Combined Heat and Power (CHP) systems simultaneously for electricity generation. WWTP cogeneration is highly efficient for electricity generation and distribution. Approximately 40% of the energy used can be conserved through this process as compared to the separate on-site gas boiler system of heat for electricity generation. CHP system improves power generation with high efficiency for electricity transmission and distribution with minimum losses. Cogeneration systems are ideally suited as captive power plants located at the site for use of self-generated electricity [52].

Figure 1.5 shows statistical power generation comparative analysis between separate power generation and cogeneration.

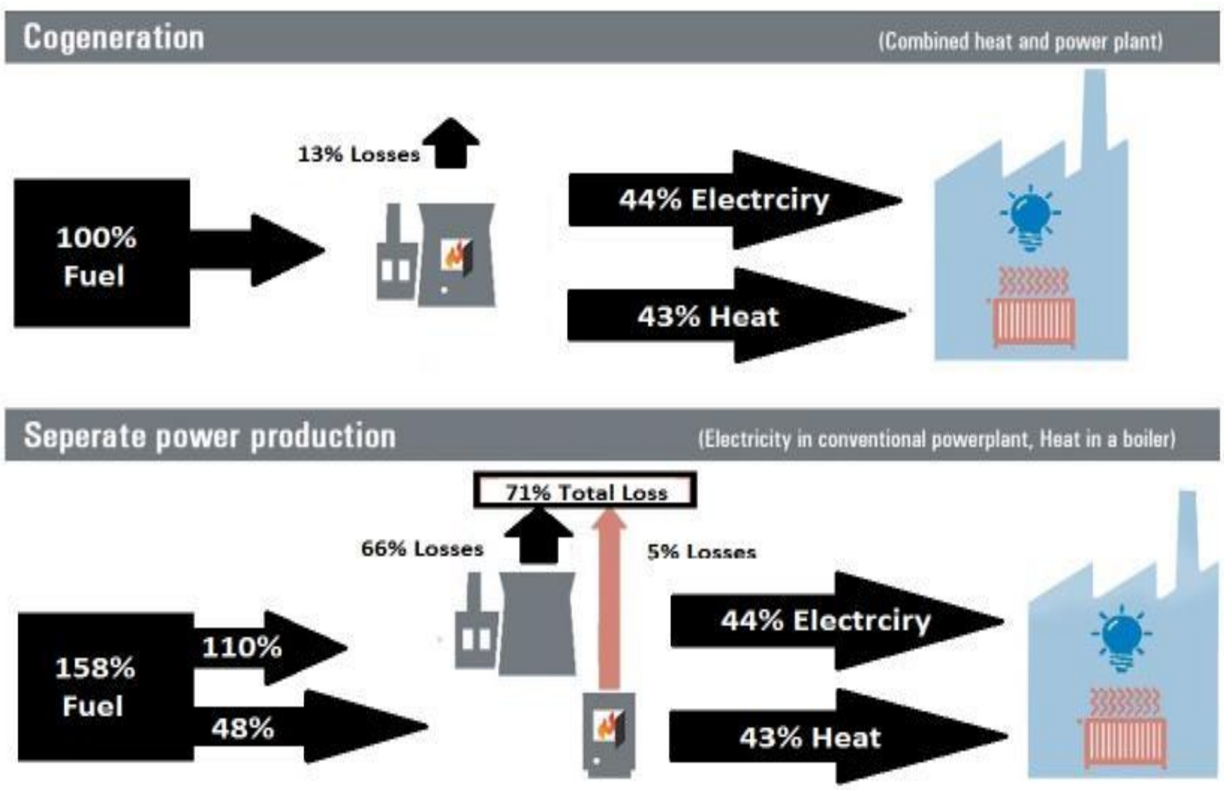


Figure 1.5 Cogeneration and Separate Power Generation

1.5.7 Advanced Network System

The IEC 61850 enables Sub-station Automation Systems (SAS) that opens up new opportunities to outline the framework of the control philosophy that governs such systems, like WWTPs. The associated communication frame network linking the Intelligent Electronic Devices (IEDs), sensors and other field devices are connected with the RTU which provides these features on a human Machine Interface (HMI) [53].

1.5.8 Telemetric, Redundant and Fail Safe WWTP Communication System

The smart sensing devices and the IEDs corresponding processors contain a lot of significant Sub-station information that have been accessible for quite a long time, however, generally ignored. The introductions of HMI and SCADA have made this possible now.
Remote areas have harsh environmental conditions normally hence observing and conveying of the state of numerous water assets and the subsequent information and action items isn't generally basic or clear or too slow on occasions. Telemetric signal monitoring is an automated procedure for performing action items against the gathered information back to the switchgear and other field devices including a centralized control room. Remote or out of reach areas require the utilization of various radio correspondence innovations coordinated into the telemetry framework to transmit the data. In this context, the proposed smart RTU philosophy discussed in this research provides a framework for water assets management [53].

1.5.9 Network Protocols

Distributed Network Protocol (DNP3) utilizes SCADA to control and monitor the IEDs through their respective smart RTUs. The IEC61850 gives full similarity and compatibility that exists between the IEDs and the field devices. It permits coordination with existing regular and conventional protocols, including the Modbus. IEC61850 standards solve all existing problems of Sub-station equipment coordination. Moreover, IEC61850 with IEEE1588 provides time synchronisation and is also compatible with old equipment of Sub-station automation [38,59]. This research is based on IEC and IEEE standards, which are compatible with existing or old WWTPs. Effective correspondence amongst substations and smart devices is one of the primary goals to achieve WWTP power cogeneration. This also provides advanced control system. Ring topologies are perfect with SCADA and FOCs while IEEE 802.11, which measures the proficiency of the information transmission, governs remote correspondence. Remote sensors can be utilized for transmitting information to IEDs and SCADA via the RTUs [54].

1.5.10 Relay Coordination and Protection Relaying

Efficient protective relaying and coordination between the primary and secondary power equipment is eminent for power transmission and distribution during WWTP cogeneration, especially in multidirectional distributed power flow systems. Protection relays are able to discriminate between various fault conditions, normal and abnormal operating conditions and functions of specifically designed operations [55]. Some basic functions integrated in the smart RTU philosophy proposed in this research are listed below.

1. Multidirectional power control relays.
2. Reverse power control relays.
3. Over-current phase fault relays.
4. Over-current earth fault relays.
5. High set relay settings to ensure protection against primary zone faults.
6. Coordination with maximum load current.
7. Coordination with maximum motor starting current and time.
8. Coordination with transformer in-rush current.
9. Provision for user defined back up relays for specific primary relays.
10. Built in libraries of commercial relays, IEEE and IEC characteristics.
11. HV supply redundancy.
12. LV supply redundancy.
13. Communication redundancy.

1.5.11 Electricity Trigeneration

Advanced electricity generation methods provide higher efficiency with the same resources. Trigeneration can be achieved at WWTPs using combined cooling, heating and power (CCHP) system. CCHP utilises the heat produced by the WWTP electricity cogeneration for air conditioning or refrigeration. A special chiller is installed for the absorption of heat, which is produced by a combined heat and power (CHP) system. Combined cooling and power (CCP) system is the one in which electricity and cooling are utilised on their own [56].
Figure 1.6 demonstrates the basic method for electricity trigeneration. Heat produced during generation of power is used in the absorption chiller for cooling.

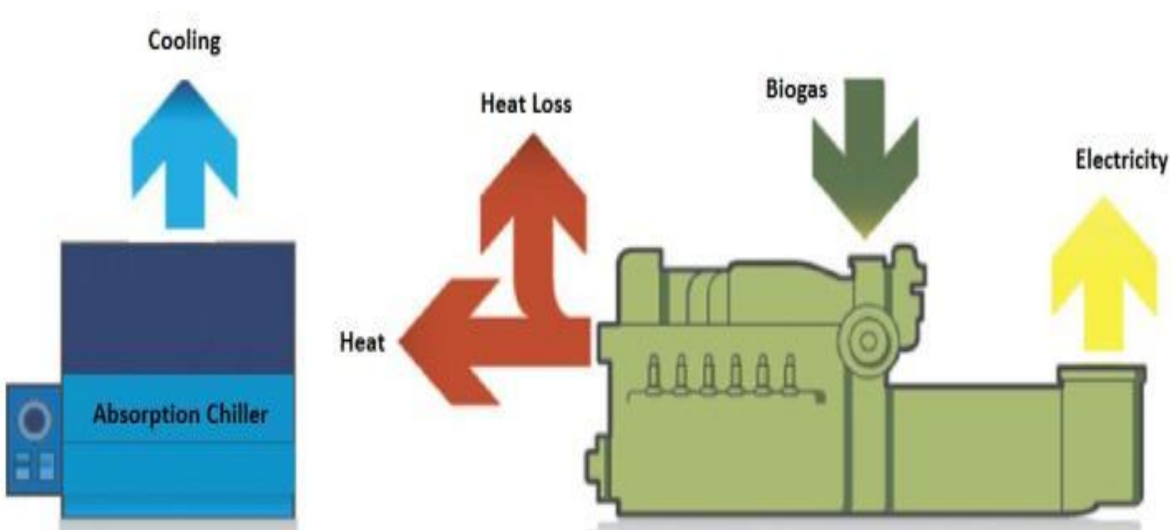


Figure 1.6 Electricity Trigeneration

Some of the advantages for WWTP electricity trigeneration are:

1. On-site, high efficiency production of electricity and heat.
2. Reduced fuel and energy costs.
3. Lower electrical usage of the system during peak demand in the summer.
4. Engine heat can be used to produce steam of hot water for on-site use.
5. Significant reductions in GHG and carbon emissions.
6. No harmful chemical pollutants since water is used as the refrigerant.
7. Beneficial for improving building's energy efficiency ratings.

Figure 1.7 shows efficiency of electricity trigeneration with respect to output of electricity, heat and its utilisation in the absorption chillers, given in percentage.

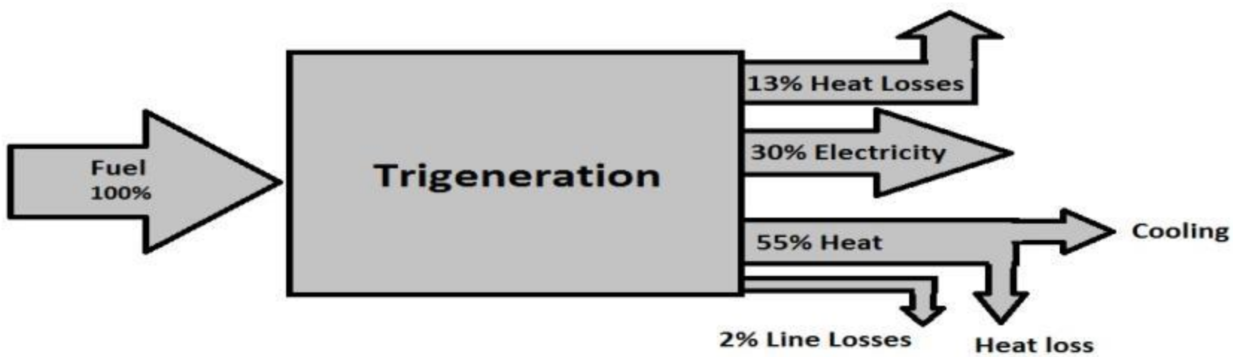


Figure 1.7 WWTP Electricity Trigeneration Efficiency

1.5.12 Advanced SCADA Monitoring System

Intelligent Electronic Devices (IEDs) instrumentation, Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs) provide a control and communications solution in cogeneration and trigeneration models. Power companies are setting up Power Management Systems (PMS) with these devices through advanced configurations. SCADA system with IEDs can provide the perfect platform to achieve a failsafe cogeneration model that can be replicated on existing or older infrastructure.

Figure 1.8 shows a block diagram of communication between IED, smart RTU and relays with the SCADA system. The communication network system incorporates the smart RTUs proposed in this research to achieve WWTP cogeneration using existing assets [57].

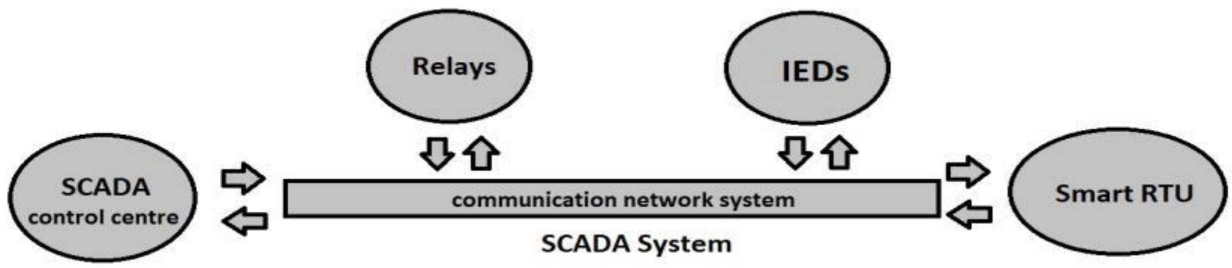


Figure 1.8 SCADA System Communication

1.5.13 Smart Grid

The smart grid technology enables integration of renewable energy resources from wastewater with advanced IEDs and smart RTUs to achieve failsafe and redundant telemetric communication. This advanced technology can also integrate advanced sensors with wired and wireless communication for enhanced monitoring, which allow operators to access grid stability and give continuous information while automatically reporting outages in the systems to relay that sense and recover from the faults in the Sub-stations per the WWTP developed control philosophy. Consequently, there is a reduction in manual operations and safety hazards as the interaction of the WWTP operators is minimized with the HV equipment. The inter tripping and inter locking of the power supplies can be managed automatically and remotely from a centralized control room. Figure 1.9 shows a block diagram indicating how a smart grid plays a crucial role in advanced power generation while providing multiple integrated energy solutions [58].

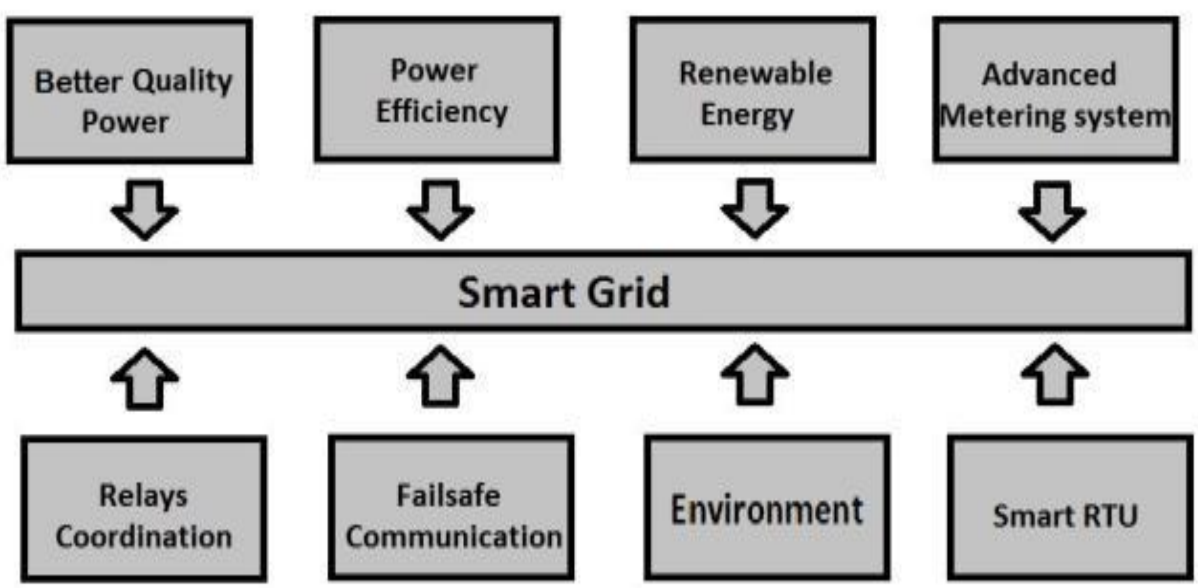


Figure 1.9 Integrated Smart Grid Solution

1.5.14 Improvement of Occupational, Health and Safety (OH&S) Standards

This research shows that health and safety parameters can be improved through sub-station automation and smart RTU with the SCADA system. The manual windings of the spring charge motors is replaced by an automated DC control system. Switching and inter tripping of various energy sources can be done remotely without even entering a substation. The optimum utilization of gases produced at the WWTP reduces the environmental footprint of the facility. This results in increased safety, thereby increasing the QoS.

1.5.15 Financial

Financial savings are achieved in this research in three ways:

1. Reduction in power bills.
2. Man-hours required to operate and maintain WWTPs.
3. Increase in the life of substations without replacing the existing switch-gears in the POCs or commissioning new substations to manage the WWTP demand load.
4. Carbon dating reductions.

1.5.16 Improvement of Soil Fertilisation through Biofertilisers

Biofertilisers are produced as a by-product during the wastewater treatment process, which is used for soil improvement and fertility. Figure 1.5 shows the biofertiliser produced during the wastewater treatment process. This is used to increase the fertility of different kinds of soils.

Figure 1.10 Fertiliser as a By-Product of Wastewater Treatment

1.5.17 Utilisation of Biosolids for Landfills

Special type of biosolids are produced as a by-product in WWTPs, which are utilised for landfills to reduce corrosion at the seashores. Figure 1.6 shows biosolids being used for landfills for better surface utilisation.

Figure 1.11 Biosolid Utilisation for Landfills

1.5.18 Environmental Impacts

In Europe, the execution of the European Union's (EU's) Directive 91/271/EEC gave new guidelines to the release of sewage and for its treatment, so as to maintain a strategic distance from natural contamination and harm to the environments. The latest investigations have intended to discover new procedures for wastewater treatment that enhance the contamination expulsion rate at the same time. The cost of energy at WWTPs can fluctuate, extending from 25% to 60% of total operational costs. The electricity utilization to treat per m^3 of wastewater can fluctuate, running from around 0.26– 0.84 kWh/m^3 depending on a few operational and natural attributes, for example, toxin loads, plant size and system, and the type of WWTP. The normal energy utilization for Germany, the United Kingdom, and United States is 0.67, 0.64, and 0.45 kWh/m^3, individually, and for Italy, utilization in the vicinity of 0.40 and 0.70 kWh/m^3 was estimated, contingent upon the sort of plant. For Australia, energy consumption of wastewater is around 0.46 kWh/m^3 [59]. WWTP can have multiple environmental benefits, if properly designed and planned with integrated renewable energy resource. Some of these major impacts are:

- Reduction in greenhouse gases and carbon emissions
- Production of multiple by-products during Sewerage treatment processes
- Production and Utilisation of own renewable energy
- Improved fertility
- Green electricity
- Water management system
- Forest industry

Figure 1.12 shows wastewater treatment for the industries of agriculture & forestry, which produces biosolids, biofertilisers and biosolid fertilisers when provided with this environmental solution.

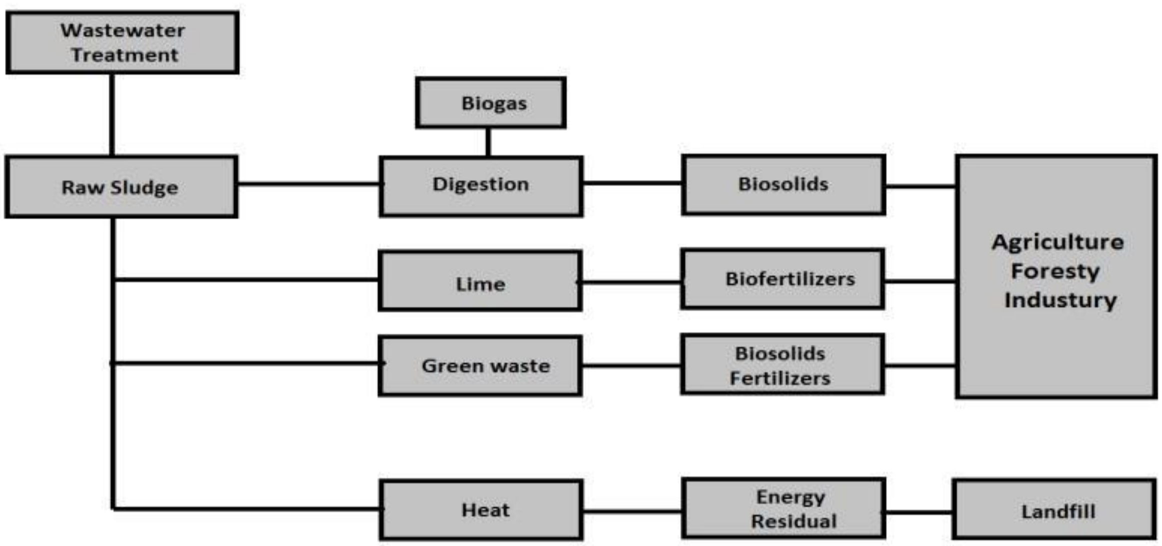


Figure 1.12 Wastewater Treatment Solution to Forest Industry

1.5.19 Birds Habitats

Wastewater is stored in huge ponds, which provide a great habitat for birds to which they migrate from far off places. There are leftover nutrients that the insects feed on and then these insects are fed on by birds of many different species. Hence, it acts as a food chain becoming a natural biological cycle [60].

Melbourne Water Western Treatment Plant has very huge ponds at the perfect locations, right next to the ocean, which have resulted in a variety of natural habitats, supporting a diverse variety of plants, animals and reptiles, including some of the endangered species. More than 280 bird species have been recorded at the plant, including migratory shorebirds that travel from Siberia each year.

1.6 DESIGN AND METHODOLOGY

MW-WTP has been going through extensive upgrades. One of the key objectives has been to integrate the renewable energy sources on site with the power company`s main supply. The Asset Managers have been focussing on upgrading the substations to cater for the proposed cogeneration system on-site. This research has been carried out as part of cost saving measure to use existing infrastructure efficiently to form an embedded system that can allow this MW-WTP cogeneration.

1.6.1 Standards

The IEC61850 and IEEE1588 standards are compatible with all the WWTP electrical equipment. Thus, the research was carried out in synchronisation with these standards, to ensure an effective system that provides enhanced power generation with efficient power management system. The research also focuses on establishment of a multi directional communication system [61].

1. Smart RTU design aims to set up suitable configurations and connectivity based on cost effectiveness, enhanced performance and maintenance.
2. Ring topology is used for communication with IEEE1588 and IEC61850 standards and protocol.
3. Fibre optic cables are used for communication between different devices, which will result in reduced intertripping downtime and provide reliable communication.

1.6.2 Smart RTU

As the name implies, a remote terminal device, RTU, is a smart electrical enclosure that houses IEDs and smart relays, which can be installed in a remote location and acts as a termination point for field contacts. A dedicated pair of copper conductors is used to sense every contact (Normally Open and Normally Close) and transducer value. These conductors originate at the power system device, are installed in trenches or overhead cable trays, and are then terminated on panels within the smart RTU. These electrical panels can transfer collected data to other devices and receive data and control commands from other devices through a serial port. User programmable RTUs are referred to as “smart RTUs”. They can replicate all the modern features of switchgear in a sub-station.

1.6.3 Bidirectional Communication Network System

Sub-station Automation Systems (SAS) provide reliable bedrock for future smart grid development in electrical and power utilities. Implementation of high quality SAS system enables high efficient control system and transfer rate using the state-of-the-art computerized functions of monitoring, control, and protection. As a result, it can immensely reinforce the reliability index of smart grid systems. However, the inextricable interdependency of cyber and power components in an automated sub-station creates other risks in the WWTP operation process. Since the introduction of multi-vendor SAS based IEC-61850 protocol, the interoperability of various SAS components with variety of manufacturers brands is now possible. The modular nature of implemented Programmable Logic Controllers means that any upgrades and future modifications can be done easily, once the Geographical Interface System (GIS) is implemented [61,62].

This thesis also surveys the most efficient and reliable methodology for the use of SAS and their configuration in an HV substation, which leads to high reliable performance and fail-safe mechanisms. Findings can pave the future smart grid development and implementation in a cost effective and user-friendly manner.

1.6.4 Communication Topology

This research aims to address these features by proposing a technology driven approach to optimise WWTP electricity cogeneration on existing or old infrastructure. This can be achieved by enhancing protection, monitoring and controlling levels for smart metering, with two-way power flow between the grids and WWTP or any site where biogas or any other renewable energy resource is available. Typical arrangement for cogeneration at WWTP in ring topology is shown in the power flowchart where biogas is produced and then utilised to excite on-site generators with controlled two-way power flow between distribution and zone substations. Figure 1.13 shows typical arrangements for electricity cogeneration with high efficiency at WWTP.

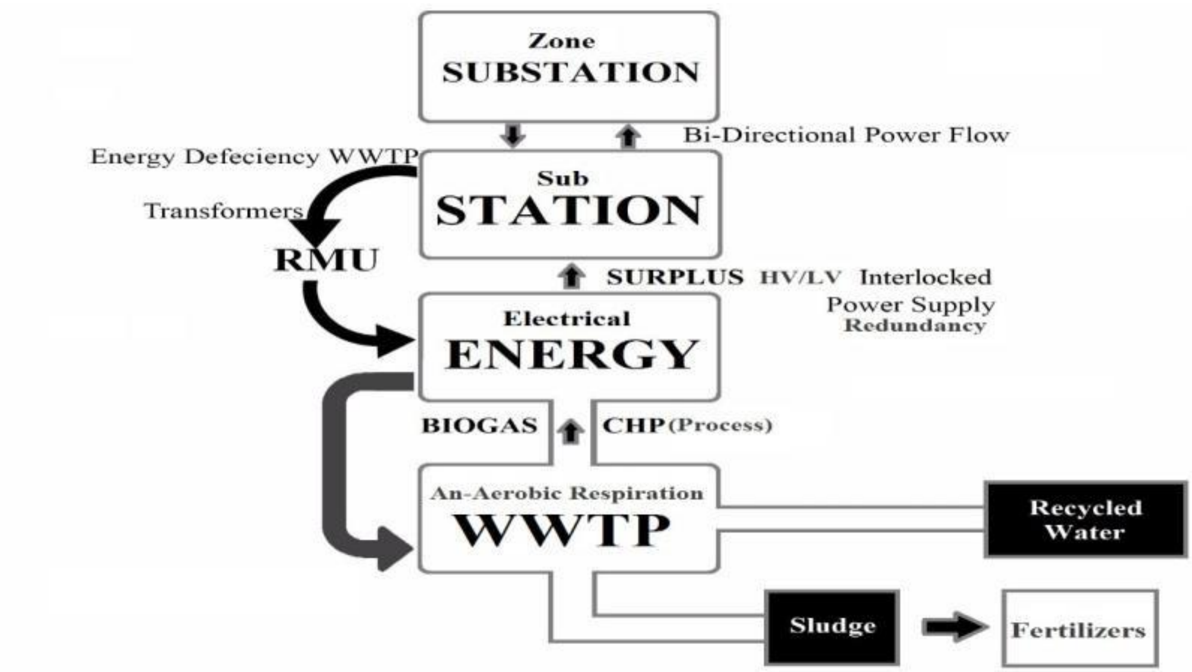


Figure 1.13 Typical Arrangement for Electricity Cogeneration at WWTP

1.7 ANALYSIS OF TEST RESULT

There are various types of testing and results analysis undertaken to ensure that the outcome of the project is compliant with the industry standards and compliance requirements as well as satisfies the scope of the project.

- ETAP
- MATLAB
- Real time simulation
- On site visual inspections

Results are simulated and tested at MW-WTP. Most of the research results are simulated by ETAP®, which is a full spectrum analytical engineering software specialising in analysis, simulation, monitoring, control, optimisation, and automation of electrical power systems. ETAP software provides most comprehensive power system enterprise solution that ranges from modelling to operation. Millions of engineers and scientists all over the world use MATLAB® to analyse and design the systems. This is a powerful tool to integrate data and simulation for real time results.

1.8 RESEARCH SIGNIFICANCE

The power demand of WWTPs is very high, hence making it a very expensive process. Estimates of actual power demand by different plants vary according to the composition of the wastewater and the type of treatment. According to the estimated value that the power generated by MW-WTP on average 69,500 MWh per year. Recovering of energy during wastewater treatment provides many environmental, health, safety and financial benefits, such as [63].

- Production of recycled clean water
- Provision of renewable resources
- Reduction of load on external grid
- Provision of supportable resources for farming and irrigation
- Elimination of CO_2 from the atmosphere, reduction in GHG
- Increase Power generation
- Reduction of Power Losses
- Reduction of Power Shutdown
- Failsafe Communication
- Increase plant automation

Therefore, considering its potential, engineers and researchers are working to find comprehensive solutions for wastewater treatment. Water treatment is a rolling stock that requires continuous power supply. The significance of this research is that it enables WWTP electricity cogeneration without unwanted shutdowns, providing advanced PMS with failsafe & redundant telemetric communication through SAS. IED and Smart RTU are modelled with

SCADA system to form an embedded system of the plant operations and working philosophy. Two-way power flow successfully achieves enhanced power generation and reduces load on external grid station. The research contributes to the knowledge of smart grid with protection relaying using IEC61850, IEEE standards with OSI layers to meet the requirements of power demand and efficient WWTP electricity cogeneration model.

1.9 ORIGINAL CONTRIBUTION

This research contributes to the development of Advanced Telemetric Communication System at WWTP for reliable control of power flow and PMS. The philosophy proposed in this research provides a perfect potential free contact for all the generated signals on-site to be communicated across in an orderly fashion. The research successfully integrates a renewable energy resource from the WWTP, the biogas, into its existing infrastructure and hence enabling the WWTP to become power redundant as well. Internationally recognised standards like the DNP3 employs SCADA to control and monitor the efficiency of IEDs through smart RTUs. IEC61850 provides full compatibility and interchangeability features between the IEDs, regardless of their manufacturer. It allows the existing conventional protocols, like Modbus and DNP3, to synchronise with the IEDs and HMI. Ethernet-based switches have provisions for fibre and copper interconnections. Every telemetric status signal is followed by an acknowledgment before any command instructions. Smart RTUs maintain connectivity of the relevant actions against them. Main contribution of the research is listed as follow:

1.9.1 Electricity Cogeneration

This research aims to create an opportunity in electricity generation at WWTP and to provide competition in the power generation market, which has highly efficient performance as compared to separate boiler system. It only makes sense to accumulate all the resources available on-site for WWTP electricity cogeneration. This research aims to develop smart RTUs using least cost and technically acceptable principles for each-sub-station in the power network to achieve [64]:

1. Increased efficiency in electricity cogeneration.
2. Lower emission to the environment of greenhouse gases.
3. Reduction of costs for fuel supply and waste disposal.

Figure 1.14 shows distributed electricity cogeneration at WWTP. The system is interconnected with SCADA system through smart RTUs and provides two-way power flow with advanced PMS.

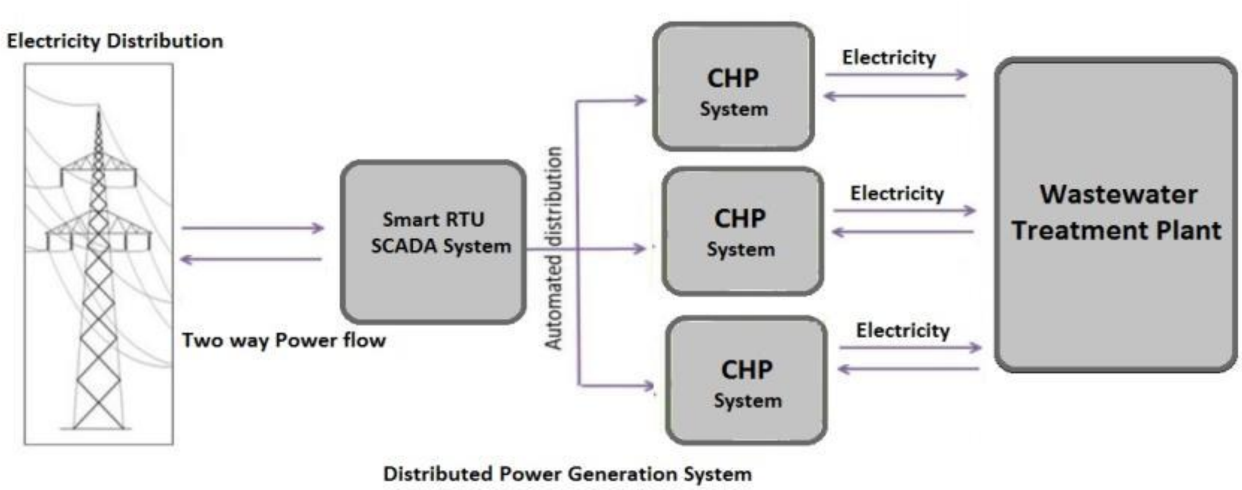


Figure 1.14 Electricity Cogeneration System with Power Flow

1.9.2 Electricity Trigeneration

This research also contributes to the management of excess heat emissions using Combined Cooling, Heat and Power (CCHP), also known as trigeneration. This method is the integration of two major technologies, which are Combined Heat and Power (CHP) technology and cooling CCHP technology through absorption system. CHP systems consist of a power system that can be an internal combustion engine or turbine, driven by biogas formed at WWTP and coupled to a generator, producing electricity. A heat recovery system recovers the thermal energy from the power system and exhaust gases for heating applications. Heat released from generators is utilised in absorption chillers. Figure 1.15 shows the generation of power and heat absorption by a chiller to produce cooling. This system is very useful especially in summer for chilling purposes, which in turn reduces load on external grids and provides financial benefits by reducing electricity bills [65].

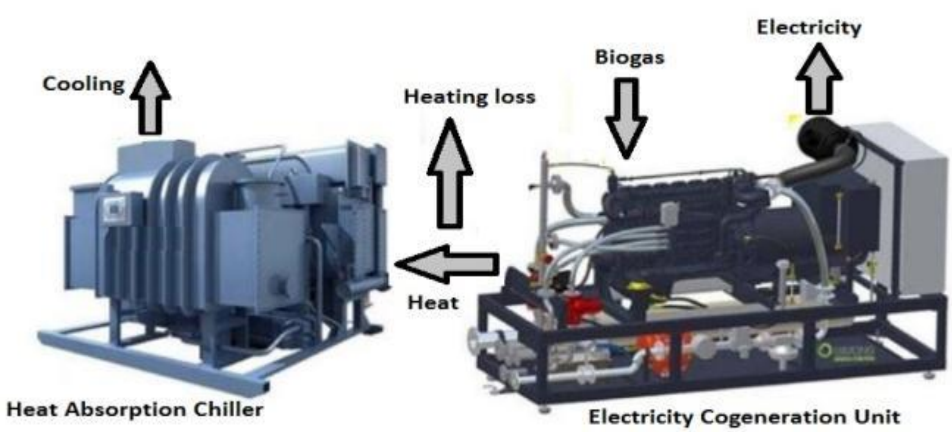


Figure 1.15 Electricity Trigeneration with Absorption Chiller

1.9.3 Distributed Power Generation

The advances in control system, transmission, distribution, direction and control procedures have made quick development in wastewater and irrigation systems. Power systems at the existing MW-WTP were old and did not have the capacity to handle abrupt variations in the power supply and demand of the processes involved. A centralized control system is proposed that can embed all the IEDs, SDs and sensor signals to a control room, where the operators can manage the whole treatment and the WWTP cogeneration process.

SAS and control systems technology is all the more generally accessible, easier to manage, more proficient and less exorbitant today than they were only 10 years back. In any case, the ascent of circulated control is additionally being driven by the capacity of appropriate control philosophy of WWTP, to beat the imperatives that regularly restrain the improvement of extensive capital ventures of transmission and distribution (T&D) lines.

In 2012, $150 billion was put towards expansion and utilization of resources into the WWTP PMS, including biogas turbines and solar systems in electric, control, mechanical drive and other SAS applications comprehensively [66].

142 GW in 2012 to 200 GW in 2020. That is a 58 GW increment and speaks to a normal yearly development rate of 4.4%. Interest in power distribution advances will ascend from $150 billion to $206 billion. As a perspective, amid this same period, worldwide power utilization will increase from 20.8 to 26.9 terawatt-hours (TWh).

The world is expanding at the rate of 3.3% annually. In this context, by the end of the decade, power distribution network will expand at a rate of about 40%. This research has demonstrated that expanding the infrastructure to optimally General Electric (GE) appraises that yearly circulated control limit increases will develop from utilize the available resources.
By 2020, $206 billion will be contributed every year to the renewable energy and power distribution industry [67].

1.9.4 Value Engineering

Such advancement towards an automated power distribution system becomes effective as far as both execution and cost of the PMS is valued against the outcomes. WWTPs are the need of time however features can be added as per the geographical limitations i.e. at congested zones where it is uneconomical to incorporate a massive WWTP. This will likewise mean more innovative work for new researchers, for example, power modules with a specific end goal to decrease the cost per kWh.

1.9.5 Asset Management Issues

There is always an issue of Operation and Maintenance (O&M) at large WWTPs. This research aims to provide an effective asset management system for the capital works at WWTPs. Limiting site movements to isolate parts or sections of a WWTP and a failsafe mechanism and philosophy implied via the smart RTUs provides a one stop shop for the asset managers to do predictive maintenance.

1.9.6 Ecological Effect

Dispersed gases from WWTPs cause a bad odour and a bad impact on the environment, especially neighbouring areas of the WWTPs. The research discusses ways to decrease the WWTP environmental footprint. Smart grid with smart RTUs enable utilization of all energy resources on site. This dispersed gas during the digestion process is collected under the covers and used to excite on site biogenerators for green electricity.

Dispersed system does not really mean clean system. In reality, diesel responding motors regularly utilized as go down circulated generators tend to be the most exceedingly awful entertainers regarding ozone depleting substance discharges [68]. Disseminated system, to be an economical elective worldview, will hence need to depend on the cleanest innovations or support productive utilizations amplifying vitality effectiveness and decreasing discharges, for example, cogeneration.

1.9.7 Sub-station Automaton Systems

Power System Automation is one of the critical perspectives of this research. In an electrical power distribution system, a deep study is required to come up with the right philosophy to enable WWTP cogeneration. This research proposes the smart RTU philosophy where engineers can easily incorporate the intertripping and power supply interlocking philosophies easily by designing the circuits accordingly and by programming of the relays.

The computerized data acquisition for metering and monitoring of power system automation can be separated into three general classes as; data gathering, smart metering and monitoring.

The data gathering framework gathers the information from the power system network utilizing the digital power monitors through the voltage and current transformers (CT/VT). The gathered parameters of the Power System and the figured power information can be checked on the screen of the digital power monitor. The qualities will be sent to the computer system utilizing the communication framework for intertripping down time, so that the whole plant is not isolated for a small fault at a distant location. FOCs are utilized to enable failsafe communication.

Automation, protection, local control, operator interfaces, communication, remote control and monitoring capacities are some of the key information that were already used with the PLC modules for each capacity. Smart RTUs philosophy enables multi-tasking of these power system parameters, which are interconnected in ring topology through SCADA system. This will enable the telemetric data transfer in an orderly fashion to control various power supplies at the WWTPs to enable trigeneration as well [69].

Smart sensing devices collect information from the power system equipment via their auxiliaries and transferred through CAT6 and FOCs. The data can also be communicated via the wireless communication network. This research provides solution for designing an advanced SCADA system with smart RTU and with a redundant communication system to transfer the data. Smart RTUs are modelled as part of the SCADA system to do all manipulations of the parameters and data of the WWTP power network system. This can be viewed in different forms like analogue, digital, graphical at the SCADA master control centre. Smart RTU is modelled for advanced control management systems with reliable communication to generate the reports for all the different types of control mechanisms like power failures, CT or PT fail low PF etc.

Smart RTU with IED interfaces can enable this on all existing or old infrastructure with minimum investment. Important benefits of automation can be listed as:
1. Improved quality of service and reduced manpower requirements.
2. Improved reliability with reduced system implementation costs.
3. Reduced operating costs.
4. High value service provider and reduced maintenance costs.
5. Easy to add advanced modification need of technology.
6. Improved access to information and also improved information for modification.
7. Improve health and safety parameters.
8. Reduced power outages at WWTP.
9. Smart grid development.

Sub-station automation is a system for managing, controlling and protecting the various components connected to the power network. It obtains the real time information from the system, local and remote-control applications with advanced electrical system protection. It has following components:
1. Electrical Protection.
2. Control.
3. Measurement.
4. Monitoring.
5. Data Communications.

1.9.8 Protective Relaying

This research also contributes in advanced protective relaying and protection of devices. Determining the protective devices for a power system and their right settings usually puts two important goals against each other. First goal that the system is available at all times without any interrupts. Second is to manage all power outages, due to maintenance or failures, which must be avoided. WWTP power equipment protective device ratings and settings selectivity can be accomplished with smart devices that are specific. That is, they work just on shortcomings inside their zone of security and do not normally detect faults outside that zone. When a fault occurs inside the zone, the SDs regularly react momentarily and trip breakers on the edge of that specific zone. When fault occurs outside the zone, proper coordination of relays is required for intertripping and isolating the fault.
Power outages and capital works are one major cause of financial burden on the owners. The proposed smart RTU philosophy proposes a standard driven approach to minimize shut downs at

remote WWTPs thereby increasing their efficiency as well as making it self-sufficient with their maximum power demand.

Time delay is a needful deferral in an inter trip task. Once the SDs detect the fault, time delays are utilized to give space interval to another overcurrent fault to work and clear the hazards. Appropriate SAS frameworks have been characterized for the WWTPs that empowers an electric utility company to screen, organize and workout segments of their network or in full in a continuous mode from remote areas. The power distribution philosophy is particular and might be actualized in systems to incorporate remote checking and control of substation, feeder and customer smart devices and demand loads [70].

The goals of Power Distribution Automation for WWTP discussed in this research are:

1. Reduced costs.
2. Improved service reliability.
3. Better consumer service.
4. Enhanced government relations.
5. Deferred capital expenditures.
6. Reduced operations and maintenance expenses.
7. Improved system response and restoration.
8. Enhanced system efficiencies.
9. Enhanced consumer satisfaction.
10. Improved data information.
11. Prevent outages.
12. Alleviate the need for a sound maintenance program.
13. Replicate good operation and maintenance practices.
14. Eliminate the need for daily planning.

As utility stake holders and engineers interested in effective approaches to increasing efficiency and productivity the latest “high tech” developments must be continuously reviewed by the utility. Increased competition has led large existing and potential commercial consumers to carefully evaluate both the direct cost of electric service and the monetary value of reliable electric service. These activities in conjunction with increased awareness by residential consumers of even the shortest loss of electric service have resulted in increased emphasis by regulatory systems in qualifying the cost to consumers. It is important to identify the costs and benefits of each project including the value of improved reliability to the consumer.

1.9.9 Telemetric Signal Communication

Sub-station telemetry systems enable the remote control and monitoring of our substations. The reliability of these telemetry systems is essential to maintaining visibility and control of the transmission network. The operation of the transmission grid increasingly requires a range of advanced capabilities that demand enhanced communications and data system functions at substations. Our future sub-station telemetry systems will be key elements in providing this improved grid capability. Asset management approach for sub-station telemetry seeks to achieve high standards of reliability, and to provide the capability required to meet emerging grid needs. Asset overviews of the MW-WTP existing sub-station telemetry systems are based on PLC units.

These PLCs provides the data gathering and communications capability at the substation. There are used to monitor digital and analogue signals from sub-station equipment and to transmit indications to a control centre.

The smart RTU also provides a pathway at the sub-station for commands from the remote-control centre to be directed to Sub-station equipment, such as for opening and closing circuit breakers. The loading of smart RTUs has increased significantly result of the progressive replacement of electromechanical protection relays with modern numerical relays. These numerical relays have a wide range of functional capability and produce far more signal outputs than the previous relay technology. The additional signals available from modern relays are valuable to Grid operators and engineers but cause increasing load on the smart RTUs.

1.9.10 SCADA System

SCADA systems at their fundamental level are industrial control systems. They are computer-based control systems that monitor and control industrial processes that exist in the physical world. SCADA systems can be found in manufacturing facilities, oil production and processing, pharmaceuticals, energy, water treatment and distribution, and the list goes on. They are the best control method for processes that have large amounts of data that need gathering and analysing, or are spread over large distances, or require critical control in fast paced processes [71].

Before any data collection or remote sensing can be achieved, information needs to be passed between the sensors and the communications system in a form that is compatible with the SCADA system. A field interface unit is required. The most basic of these units are known as remote terminal units, or RTUs. Modelled smart RTUs convert electronic signals received from field sensors into machine language, known as protocol, and transmit data over the communications network to the SCADA Master, where a human will interact with information. The smart RTUs have been modelled to provide all the features of SAS there by providing a level of local control. Smart RTUs for use with Supervisory Control and Data Acquisition (SCADA) systems typically consist of a box which contains a microprocessor and a database.

1.9.11 Redundant and Failsafe Communication

Smart RTUs with IEDs using different topologies like optical fibre, with IEC and IEEE standards provide failsafe and redundant communication. The research provides new scope for smart power networks that integrate its operations from all connected end users. This infrastructure provides bi-directional communications between end-users and the grid operator.
The wireless communications system will also be used to transfer control signals to different system components for supporting continuous, reliable and secure operations of the smart grid,

The smart grid will use and integrate different available wireless communications technologies, standards and protocols to allow the electrical grid to operate smoothly and robustly. Figure 1.16 shows ring topology in which smart RTUs communicate information, making the system failsafe and redundant [72].

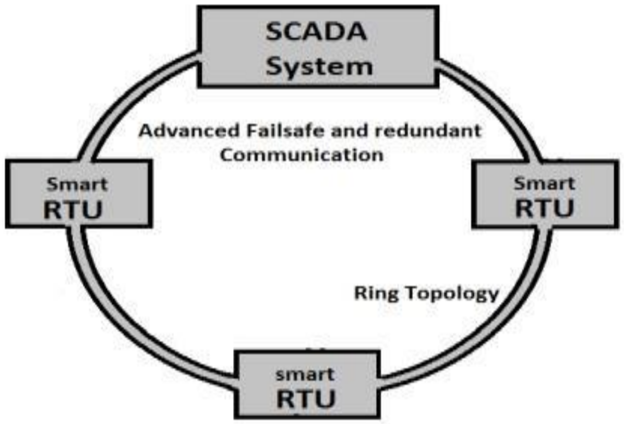


Figure 1.16 Communication of Smart RTU with SCADA System

1.9.12 Power Management System

Energy management is nowadays a subject of great importance and complexity. The complicated process includes choosing among a set of sources able to produce energy that will be sufficient to a set of loads by minimizing losses and costs. The sources and loads are heterogeneous, distributed and the reaction of the system, the choice of sources, must be done in real-time to avoid power outages. This research contributes to the concepts of energy management at WWTPs or on sites where a renewable energy resource is available.

Efficient energy management system is proposed by using sub-station automation through smart RTUs, controlled two-way power flow and sustainable power production during the variations in the biogas production at a WWTP [73].

1.9.13 Smart Grid

The utilization of sustainable power sources expanded incredibly soon after an oil emergency in the late seventies. Around then, monetary issues were the most imperative elements, consequently enthusiasm for such procedures diminished when oil costs fell. The present resurgence for this enthusiasm to utilize sustainable power sources is driven by the need to decrease the high natural effect of fossil-based power generation systems [73].
Wastewater is a sustainable power resource and asset, which is accessible in all the zones. This research gives an answer for wastewater and effective PMS. Biogas produced through anaerobic digestion is utilized during for WWTP electricity cogeneration. SAS with HMI and smart RTU provides the telemetric correspondence with cutting edge SCADA System, enabling all required

functionalities for WWTP cogeneration [74]. The smart grid at the WWTP can efficiently add the following features in the WWTP distributed power system.

1. Wastewater use as renewable energy resource.
2. Distributed power generation.
3. Smart RTU provide reliable telemetric communication.
4. Bidirectional power management system.
5. Increase efficiency of power generation.
6. Decreases power shutdown.

1.9.14 Occupational Health and Safety

The proposed smart RTU philosophy in this research has increased the OH&S standards of the MW-WTP drastically. The spring charge motors no longer require manual winding to reset as the control supplies are now fed from a redundant source via the smart RTUs. The HV operators can isolate the faulty parts of the plant from a control room. The GHG and carbon emissions for the MW-WTP are reduced. The bad odour around the MW-WTP is controlled and the hazards related to site access is eliminated. SAS will also ensure that any major upgrades can be performed easily.

1.9.15 Environmental Impact

The continuous flow of the sewage at the MW-WTP by minimizing shutdowns during fault scenarios means that the upstream piping is always well maintained and clean. The research proposes utilization of all gases formed in the water treatment process hence the carbon footprint of the MW-WTP is also diminished. The oceans are saved from all the rubbish and other non-biological components ensuring healthy marine life [75]. This research adds to many other natural arrangements. Efforts have been made to diminish ecological issues. Wastewater treatment has been intended to limit the ecological effects of releasing untreated wastewater. At any WWTP there is an approaching wastewater stream which treated before it is permitted to come back on the earth, lakes, or streams. Wastewater treatment plants work with the basic purpose of the water recycle. This thesis contemplates is to evaluate the natural effect of wastewater treatment plant, situated in Melbourne Western Wastewater Treatment Plant, and bolster WWTP outline limits for more productivity to give ecological arrangement and balance.
The purpose of this research is to provide an inter trip and inter locking mechanism from power company`s zone sub-station to the two WTP 22 kV power supply points of connection POC1 & POC2.

Background

The existing MW-WTP power supply agreement with the power company requires that a minimum 200 kW to be imported at each of the 22 kV point of connections (POC1, POC2). This requirement made it difficult to control the on-site power bio generators and to efficiently use all the available biogas. Agreement has been made with power company to allow power to be exported via POC1 and POC2, which will enable more efficient operation of the onsite biogas generators and maximize the use of the available biogas. To enable this, power company requires an automated intertrip to be established between their substations that supply MW-WTP, POC1 and POC2 to enable them to trip POC1 or POC2 in the event of faults in their system.

1.10 OVERALL SYSTEM REQUIREMENTS

1.10.1 Overview

This section outlines the overall system requirements for the provision of an intertrip between Power Company (PowerCor) and the two WTP 22 kV power supply points of connection (POC1 & POC2).

1.10.2 Scope of Works

This research includes the design, study and provision of POC2.

1. Design of communications cubicle inside POC2 for termination of Telstra cable modems and Powercor communication cables.
2. Designing control philosophy between POC2 and the POC2 Powercor equipment cubicle for circuit breaker trip and status signal cable, PLC input output cables and Telstra connection cables.
3. Designing of cabling between POC2 HV switchboard and the POC2 Powercor equipment cubicles for two intertrip signals and circuit breaker open and closed status signals.
4. Designing of Powercor equipment cubicle for Trip, communications fail time delay trip and generators not connected status signals.
5. Design study and evaluate POC2 Powercor equipment cubicle for R phase Amps, R-W Phase Volts, 3 phase MW and 3 phase MVAR.
6. Designing and evaluation of POC2 PLC cubicle and the POC2 Powercor equipment cubicle for 230 V AC power supply.
7. Designing ethernet and RS232 cable between the Powercor equipment cubicle and POC2.
8. This research includes the design, study and provision of POC1.
9. Designing and studying POC1 and the POC1 Powercor equipment cubicle for circuit breaker. trip and status signal cable, PLC input output cables and Telstra connection cables.

1.10.3 Functional Statement

This research allows PowerCor to isolate WTP's electrical supply system from PowerCor's network (intertripping) at POC1 and POC1. No change to MW-WTP sewage treatment function will occur.

1.10.4 Design Standards/MWC Specifications

Any installation shall comply with AS3000 Wiring Rules, Victorian Electricity Distributors Service & Installation Rules 2005, and all other related standards. The AGL Generator controls will require changes to enable power to be exported from site instead off controlling to import a minimum power of 200 kW on each supply feeder.

1.10.5 Monitoring Requirements

Additional points will be required on the SCADA database for alarm that the trips have been generated by Powercor.

1.10.6 Electrical Equipment Design

The design and installation of all equipment shall be done according to the relevant Australian Standards.

1.11 THESIS ORGANISATION

The thesis comprises of seven chapters and is organised as follows:

Chapter # 1 Covers a brief introduction of the key objectives, motivations and methodologies of the research, while providing insight into the research significance in the discipline of electrical engineering. Chapter # 2 Presents a comprehensive literature review exploring a synopsis of communication protocols and their development over time. Chapter # 3 shows Designing of a smart remote terminal unit at WWTPs to achieve optimised biogas production and electricity cogeneration.

Chapter # 4 presents modelling smart remote terminal units to achieve telemetric communication redundancy for electricity cogeneration at WWTPs. Chapter # 5 is about designing of smart RTU for redundant communication with SCADA system for smart grid in wastewater treatment site. Chapter # 6 explain about future works and recommendation to integrate renewable energy resources at WWTP. Chapter # 7 is about Conclusion of this research thesis.

CHAPTER 2: LITERATURE REVIEW

2. INTRODUCTION

The purpose of this chapter is to provide synopsis for the research work done on the wastewater treatment processes and power generation using biogas with smart telemetric communication and significance of standards for communication protocols within sub-station automation systems.
The importance of water as a primary source of life cannot be denied. Increased population has posed a serious danger to this natural asset because of increased need and demand as opposed to its availability. With the effects of climate change, reduced rains and melting glaciers are added factors that limit its availability to the living beings. Urbanization and population growth have also environmental implications which has not only threatened the water assets but also has affected the natural ecosystems. Contamination of water, polluting the oceans and increased wastewater production is some of the human actions which have severely affected its availability and purity. The world has so far not been able to critically plan for water assets administration due to which it has mostly become a political issue between nation states [76].

In order to address the increasing demand of water, social orders and national governments have separated unlimited quantities of it from waterways, lakes, wetlands, as well as underground aquifers to fulfil the water requirements of communities, farms and industries. It should not be neglected that water is also a social and economic entity. The need for water assets with satisfactory quantity and quality for human use, agricultural and industrial utilization will continue to increase if populations keep rising with same ratio and human development accelerates in same proportion. It is therefore very important that practices aiming for sustainable development must take into consideration the health and wellbeing of species dependent on water. It is also essential to evaluate the environmental importance of watersheds while taking economic and social development decisions on water allocation and utilization.

Any water used by humans and released in the environment is referred to as wastewater. In order to meet the increasing demand for water, wastewater is treated as a recycled product to make it usable before discharging it to the environment. Wastewater itself has high potential for renewable energy generation, which is attained during the process of treatment. With the application of creative methods for purification of wastewater, effluent quality improvement is attained. The fundamental notion of wastewater treatment is to gear up the natural methodologies designated to achieve pure water. Several fundamentally correlated problems have triggered the consideration of alternative approaches to conventional water treatment and distribution procedures, which include energy utilization, operational expenses and decreased water quality. Latest feasible solutions are applied for a decentralized water treatment to combat these issues.
Metropolitan wastewater is the blend of fluid or water carried squander released from homes, businesses and modern offices or organizations. Wastewater for most part contains natural materials, microorganisms, various supplements and poisonous mixtures [77].

2.1 THE IMPORTANCE OF WASTEWATER TREATMENT PLANT

Water deficiency is the one of the biggest problems being faced globally. Two-thirds of the earth's crust is made up of water but this water is not suitable for drinking or for other human activities. It has been found that 97% of the total water is salty, which is of no use to humans and animals (except marine animals) and only the remaining 3% is available as freshwater. More than half of this 3% is locked up in glaciers and less than 0.01% is available as usable water. Hence, water resources are scarce in comparison to the human demand for water [78].

A major percentage of consumable water is getting polluted because of human activities. This polluted and untreated water is causing abundant waterborne diseases. Furthermore, the world is facing huge climatic changes, which is further aggravating the situation. Some of the regions are getting more rain water than earlier and some are getting almost negligible. Experts believe that if these scarce water resources are not managed wisely and not reutilised, the world will eventually face water crisis in the coming decades.

An estimate of 884 million peoples are already deprived of safe drinking water and approximately 2.5 billion people do not have easy access to water for sanitation purposes. The problem of water crisis is expected to increase further due to the lack of water treatment. Agriculture is also overusing and polluting the ground water thus depleting its natural sources. Therefore, water treatment plants will play a crucial role in this regard.

According to the United Nations, water crisis is currently the biggest problem that is being faced by the world. Almost 25 countries of Africa, parts of China, Peru, Brazil, Chile, Mexico, Paraguay and parts of the Middle East like Iran are some of the countries lacking sufficient amount of water. Nature has its role but the major water problem is arising because of its increasing consumption and faulty usage. Most of these issues can be solved if the wastewater treatment is taken very seriously and precautions at every step are taken to improve the water quality [79].

This research provides solutions for many of these problems. It helps to recycle water and reduce risk of water crisis. If proper implementation of the proposed philosophy takes place in WWTPs according to the proposed philosophy, not only the water crises can be efficiently dealt with, but also can meet power demand by generating electricity using renewable energy resources and reducing load on external grid. Moreover, providing electricity to the external grids in case of excess electricity generation will prove to be very beneficial for the environment benefits.

2.2 WASTEWATER TREATMENT METHOD

An understanding of wastewater fundamentals is essential for WWTP infrastructure and effective treatment technologies. Wastewater originates from the usage of water by residential sectors and industries, together with ground water, surface water and storm water. Through the application of creative methods for purification of wastewater, effluent quality improvement is attained. The fundamental notion of wastewater treatment is to gear up the natural methodologies designated to achieve pure water. There are four basic levels involved in the treatment process, which are:

1. Preliminary
2. Primary
3. Secondary
4. Tertiary

Preliminary treatment handles the physical separation of solids from the waste flow to avoid mechanical destruction of equipment downstream.

Primary level deals with the settlement of unwanted solids. Oil and grease are removed from the wastewater through screening and sedimentation. The pH levels are also adjusted by neutralisation, which generally removes 40% of the suspended solids and 30-40% BOD in the wastewater.

The effluent from primary treatment usually carries substantial organic material, which is biologically processed at the secondary level.

Secondary level is where the water is further purified. Dissolved and suspended pollutants are removed with relatively high effluent treatments. Approximately 85% of BOD and TSS are removed at this level. The organic matter and residual suspended solids are eliminated using various microorganisms in a controlled environment.

The treated secondary effluent is then passed into huge sized ponds before being processed at the tertiary level.

The **Tertiary** level includes filtration and removal of nutrients (nitrogen and phosphorus) and toxic chemicals. Trickling filter (biological treatment) process is used in this level in which coarse media contained in the tank serves as a platform for biological growth. Wastewater trickle over the media and microorganisms removes the pollutants from the wastewater. Trickling filter then removes microorganisms, which are passed through the trickling filter media.

Figure 2.1 shows wastewater treatment at different levels in which different processes are applied in huge storage water tanks to produce recycled water [80].

Figure 2.1 Wastewater Treatment Processes

The idea of wastewater treatment emerged when contaminated water was discharged to the environment, posing high threats to health and life. Increased urbanisation and excessive population growth shrunk the land area for wastewater disposal, which resulted in an increase of wastewater. There are various ancient conventional methods for wastewater treatment in use but they are very costly. Over the years, focus is more towards green technical methods, which are more economical and use microalgae for its efficiency in reducing the toxic components [81].

2.2.1 Conventional Strategies

Though advanced sewage treatment strategies are becoming progressively common, there are some conventional methods that are still in practice for the treatment of wastewater at an earlier stage, which are listed below :

Coagulation: The wastewater is moved through rapid-mix tanks, which contain fast rotating paddles that coagulate chemicals (aluminium sulphate or polymer). It is then fully mixed with raw water, forming tiny unwanted particles in the water that stick together and form a huge element called flocs.

Flocculation: This method of treatment consists of a series of six chambers, approximately 14 ft long, 10 ft wide and 15 ft deep. These large chambers move slowly to promote the formation of floc, which is a cluster of impurities.

Sedimentation: The sedimentation phase is carried through sedimentation basins in which the water is passed slowly so that all unwanted dense floc settles down to form sludge, which is then pumped to another chamber.

Filtration: Water is passed through filters that restrict the flow of tiny dust particles. Customarily, the filter is composed of sand and gravel. However, in some places the grinded form of anthracite is also added, which filters out unwanted particles.

Disinfection: The disinfection of water assures that the water to be supplied is free from all viral and bacterial diseases. Proper concentration of disinfectants, such as chlorine and chloramines, are added and maintained in water distribution system so that it remains free from any infections.

Sludge drying: Just as heavy particles settle down at the bottom during sedimentation and filtration processes, the water under treatment is moved to drying lagoons for sludge treatment where it is dried and moved for further modification for use of agriculture.

Fluoridation: In this process, a fixed concentration of fluoride ions is added to water and is maintained to a safe level so as to prevent dental cavities in users.

pH Correction: To maintain the pH of acidic water, a solution of lime or sodium hydroxide is mixed with the filtered water in order to reduce the decomposition of the water distribution system and maintain its pH-7. These chemicals also reduce hardness in treated water [82]. Figure 2.2 shows different conventional wastewater treatment processes to produce recycled water. This method does not provide very efficient and adequate solutions relating to energy and the environment.

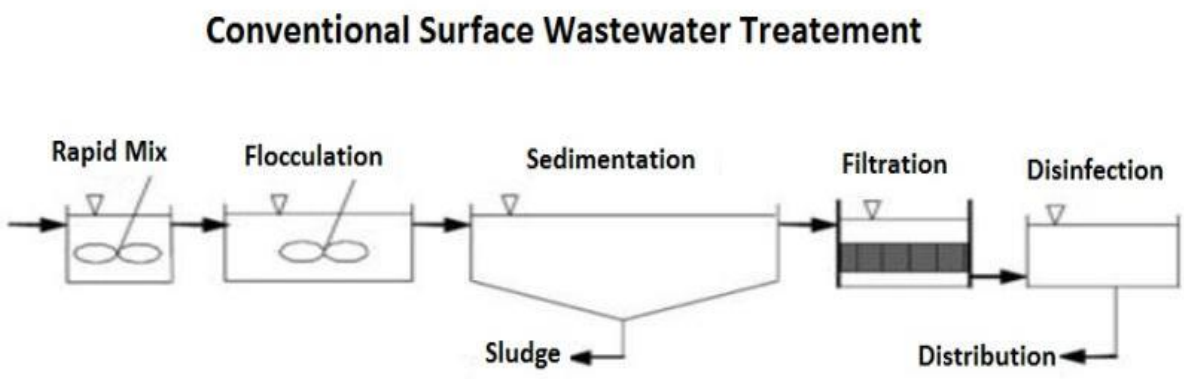


Figure 2.2 Conventional Wastewater Treatment

2.2.2 Modern Techniques

Modifications have been made for better use of energy resources in wastewater as discussed earlier. New techniques like UV disinfection system, chemical treatment system and biology (aerobic and anaerobic) treatment systems give fruitful results for different applications. Sewage treatment is a sequential process and WAS is a by-product obtained during wastewater treatment. It consists of a high content of spoilable organic matter, which must be treated to ensure its stability and to utilise it to its full capacity before disposal. There are two well-known digestion methods listed below that serve the purpose [83].

2.2.3 Biogas Production

Organic contents of sewage perform the energy recuperation process from anaerobic digestion of sludge and the resultant biogas produced is consequently utilized when connected with a power unit. Aerobic composting and anaerobic digestion methods are acceptable for bio-waste treatment, but aerobic composting uses extra energy while producing a poor-quality fertilizer and is also very costly.

Anaerobic digestion process on the other hand is a less expensive treatment which is drawing a lot of attention. In this process, various contents in the waste fluid such as cellulose, starch, fat or protein convert to a gaseous mixture of methane and carbon dioxide through absorption in a deep landfill or water.

This research has primarily concerned with the anaerobic digestion mechanism that takes place in the bio solids digester section which produces maximum amounts of methane gas through Combined Heat and Power (CHP) process. These primarily flammable gases are then burnt and converted into sufficient amount of steam [84]. This energy is optimized to produce electricity by exciting the generators. The sequential treatment process is described in Figure 2.3.

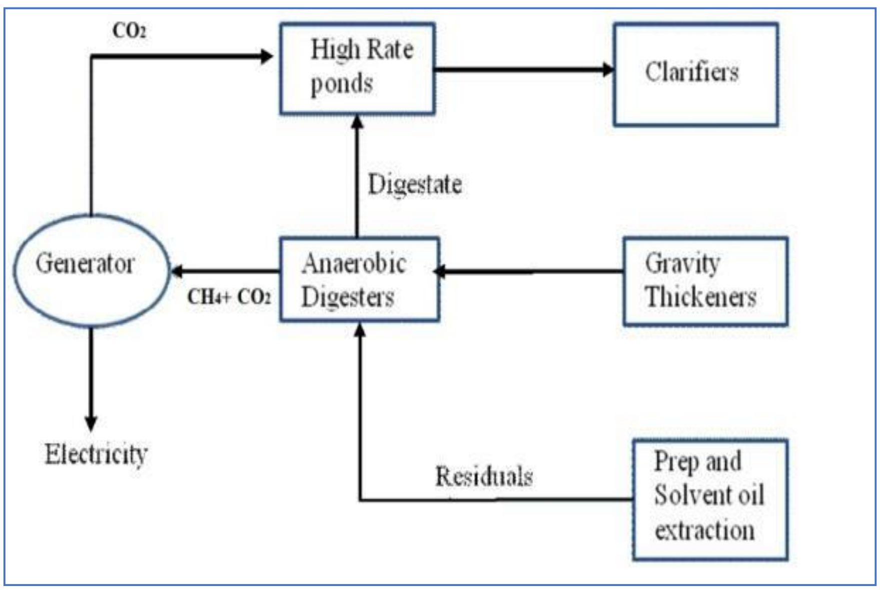


Figure 2.3 Wastewater Treatment Process through Anaerobic Digestion

Most of the larger wastewater treatment plants produce biogas through anaerobic processes. The biogas produced typically consists of 65% methane and 35% carbon dioxide. The biogas is captured and utilized for on-site electricity generation through an internal combustion turbine while the heat generated during the process is used for heating the anaerobic digesters especially in colder seasons. Thus, the process of electricity generation and on-site waste heat usage is called combined heat and power (CHP) process. Biogas undergoes combustion process to generate electricity. Anaerobic digestion is based on multiple processes each linked with other through multiple microbial reactions. Out of the three processes involved namely hydrolysis, acidogenesis and methanogenesis for anaerobic digestion, the last process is lengthier and defines the time required for total digestion process. Every product synthesized at a former stage acts as a substrate for micro-organisms in the next. One-stage nonlinear reaction method presenting the modelling of anaerobic digestion as shown by Abarghaz et al is as follows [84]:

$$dX/dt=\mu(S)X-DX \tag{2.1}$$

$$dS/dt=-k_1\mu(S)X+D(S_{oi}-S) \tag{2.2}$$

$$Q=k_2\mu(S)X \tag{2.3}$$

The factor μ(S) is defined through Monod bacterial kinetics as

$$\mu(S) = \mu_{max}(S)/(k_s+S)$$

Where:

μ: specific growth rate of methane production (1/day);
S: substrate (acetate) concentration (mg/l);
X: biomass concentration (mg/l);
D: dilution rate (1/day);
S_{oi}: concentration of influent organics (g/l);
Q: biogas flow rate (l/ day);
k_1 and k_2 are yields;
μ_{max} and k_s are kinetic coefficients related to the substrate.
Biogas technology has to consider the basic sizing parameters to achieve optimized performance. Since the biogas production varies, depending on above mentioned factors, the utilization of biogas becomes a complex task requiring proper control and monitoring to protect the equipment and achieve redundancy. These factors lead to three different scenarios described later, which should be properly monitored and controlled. For an activated sludge, estimation is necessary to ensure high biogas yield as well as quality. A single-stage mixed sludge mesophilic anaerobic digester and sludge volumes could be analysed using the following equations [85]:

$$\text{Sludge Volume} = \text{Production of TS}/\text{Specific gravity} \times \text{Water density} \times \text{TS concentration} \tag{2.4}$$

$$\text{Digester Volume} = Q \times \text{HRT} \tag{2.5}$$

Loading rate of solids could be estimated as

$$\text{Total production of VS} = (\text{Primary sludge produced} \times \text{VS \%}) + (\text{WAS produced} \times \text{VS \%}) \tag{2.6}$$

$$\text{VS loading rate} = \text{VS produced} / \text{Digester volume} \tag{2.7}$$

$$\text{VS removed} = \text{VS loading} \times \text{VS removal efficiency} \tag{2.8}$$

Where;

TS = Total solids per day (kg/day)
HRT = Hydraulic retention time (day)
Q = Sludge flow rate per day (m^3 /day)
VS = Volatile solids per day (kg /day)
WAS = Waste activated sludge (kg)

Aerobic digestion: Aerobic digestion uses oxygen to decompose the organic contents in the presence of bacteria. The process is based on endogenous respiration where microorganisms start digesting their own protoplasm to gain energy to create “Flock”, which is a stable sludge that settles down at the bottom and disposed of, easily.

Anaerobic digestion: Anaerobic digestion is a series of biological processes where the degradation of organic content takes place in the absence of oxygen to produce biogas and biofertiliser. Methanogen bacteria produced biogas (methane) through anaerobic respiration. It is further divided into two groups, which is hydrogen and acetic acid utiliser.

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2H_2O \qquad (2.9)$$

$$CH_3COOH \longrightarrow CH_4 + CO_2 \qquad (2.10)$$

Equation 9, 10 shows biological process for the production of biogas from acetic acid.

Figure 2.4 shows biogas production through WAS that is produced in the wastewater treatment process. Through anaerobic digestion, it produces biogas.

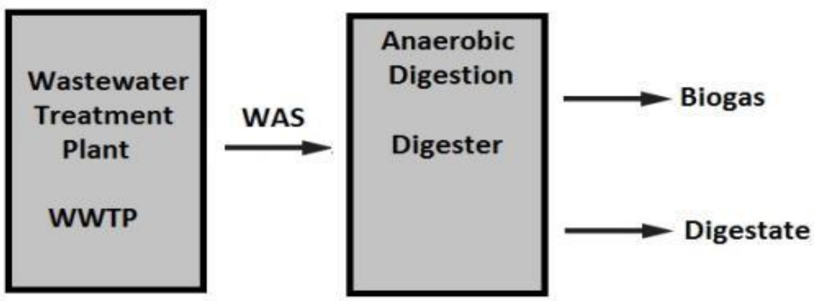


Figure 2.4 Biogas Production through Anaerobic Digestion

2.2.4 Energy for WWTP

The existing water treatment infrastructure is highly energy intensive which incurs huge costs to fulfil its load demand. Wastewater treatment plants produce biogas while treating the water through anaerobic process which is then utilized to produce heat and electrical energy. The infrastructure currently in use lacks certain important features that could enhance energy efficiency and utilize the bio fuels formed in an effective way. With certain modifications in the existing system, the extensive energy utilization of plants can be addressed. This thesis therefore aims to address these challenges by facilitating and enhancing cogeneration and achieving High Voltage/ Low Voltage (HV/LV) redundancy. It proposes to design a smart Remote Terminal Unit (RTU) whose implementation has been realized at the Melbourne Water’s Western

Treatment Plant. RTU panels provide proper signal monitoring, enables reverse power generation and distribution and reduces intertripping downtime between substations [86].

The design also suggests a failsafe mechanism by setting up an effective communication network by linking the system with Supervisory Control and Data Acquisition (SCADA) which aims for optimized remote control and performance monitoring. It is found that with proposed system up-gradation, intertripping downtime reduced to 20%, redundant and automated self- generation has been made possible which reduced the power demand from grid and leads to a safer transmission of power towards grid. Water and energy are closely linked in wastewater treatment. Wastewater treatment system is central to water and energy contacts because the process uses electrical energy for reducing the pollutants in wastewater. Likewise, water is also needed in production of electrical energy.

According to an estimate, wastewater treatment requires about 3% of electrical load requirements in developed countries and incurs high energy costs for treatment. To balance this energy consumption, it is essential to address the system's energy demands through cutting on load through various energy saving means [87].

In order to offset the energy requirements in WWTPs, certain strategies are adopted for efficient operation and energy consumption. Efficient utilization of biogas produced has been stressed upon which is reported as being relatively untapped source at national level in the US. It is estimated that biogas is produced by 52% wastewater treatment through anaerobic digestion where only 30% of which is utilized beneficially for energy generation. Mostly the remaining biogas is released to the atmosphere, which wastes this useful source of renewable energy.

Some of the suggestions to improve energy efficiency in WWTP are to reduce costs that the process entails through usage of efficient pumps and aeration equipment. It estimates in to save approximately 400 million and 5 billion kWh annually in the US with just 10% reduction in energy use. Improving the efficiency of system operations are suggested to be done via installation of Supervisory Control and Data Acquisition (SCADA) software, which enhances efficiency of process monitoring and operating control.

A wastewater treatment plant (WWTP) requires an electrical infrastructure that must not only ensure constant supply of low cost electricity but also facilitate quality improvement and technical advancements in water treatment thus bringing down the energy and operational costs. It is necessary to go beyond meeting health and environmental standards and to also ensure system compliance. There should be provisions in the system to address future up gradation strategies. With the increasing implementation of IEC 61850 standard, the Ethernet-based communication system facilitates complex automation of plant sub-station and enables it to perform secure transmission of data (e.g. tripping signals, synchronization messages, circuit breaker (CB) status etc.) for reliable operations and maintenance. This calls for the development of a customized remote terminal unit (RTU) that will efficiently control and manage the flow of power between zone sub-station and the biogas-fed generator(s) installed on the plant site [88].

2.3 PROBLEM STATEMENT

In order to achieve a redundant and failsafe power generation and optimization, certain important shortcomings of the existing wastewater treatment plants and energy infrastructure needs to be evaluated thoroughly. Following are the problems which the research aims to address through its recommendations.

2.3.1 Replacing the Old Equipment and Water Management System

Replacing of an already deployed sub-station equipment with a long operational period is a complex and challenging task. If latest technologies are adopted with an implementation of a new sub-station, it incurs high installation costs. This is why majority of sub-stations requiring automation are either up-graded or expanded to avoid replacement altogether.

Existing WWTP structures are not able to achieve advance requirement and system in which the administration choices are restricted. The real impediments of these frameworks are low working proficiency because of the imbalance between the supply of and demand of the energy.

These frameworks by and large utilize dams as water sources and after treatment the water is pumped and disseminated to all clients in the zone. The development of customized components and the transportation of water from a solitary source to the whole urban region are monetarily infeasible as well as inclined to spillages and pipe blasts along the transportation lines. Spillages and pipe blasts are regular occurrence in urban water circulation systems; when there is a noteworthy rush in the principle pipeline, a total shutdown of the water distribution process is unavoidable [89].

Decentralized frameworks are generally acknowledged as being all the more monetarily doable, less inclined to mischances, and a standout amongst the most encouraging methodologies for enhancing the water administration in urban regions. Decentralized frameworks are additionally appropriate for utilizing elective water sources, for example, recovered wastewater, rain, and ocean water. In any case, despite the fact that decentralized frameworks have real focal points over customary concentrated frameworks, they additionally have administration restrictions when water quality and amount are considered.

The unevenness between the supply of and interest for new water is another imperative urban water administration issue. Despite the fact that water utilization is higher amid sunshine hours than amid the evening time the supply of water is delivered at a moderately steady rate for the duration of the day, which at times makes oversupply or potentially water deficiency issues. A comparative issue additionally happens in squander water treatment frameworks. At the point when the gulf squander water stream rate is higher than the plant limit, the framework ends up inadequate; the treatment frameworks wind up infeasible when there is a low delta squander water stream rate, because of settled treatment forms. By thinking about these restrictions in water foundation, a shrewd water framework is proposed as a cutting-edge water administration conspire, one that incorporates data and correspondence innovation into the water arrange structure keeping in mind the end goal to build the efficiencies of all components in the water organize [90].

2.3.2 Energy Intensive Process

The clarifiers, pumps and aeration in a WWTP are energy intensive processes in operations which need to be considered on priority basis if energy conservation is intended
The existing WWTP are very power consuming which cause huge stress on external grids due to this reason WWTP become very expensive processes. WWTPs are not properly establish due to their high demand of electricity although its play very important role in water recycle and power generation. The latest examinations have meant to discover new procedures for water and slime treatment that enhance the contamination evacuation rate, in the meantime, decide a moderate cost increment or, all the more ideally, permit a cost investment funds. All things considered, the energy cost for wastewater treatment processes is very high hence a sustainable cost-effective solution needs to be implied. It is only logical and makes economic sense to utilise on site energy resources that are generated from wastewater treatment process [91].

2.3.3 Lack in Sub-station Automation

Existing WWTP have old automation system that comprises and depends primarily on relays, which are unable to perform efficient cogeneration and proper monitoring for power distribution. A sub-station a part of an electrical power system for power generation, transmission and distribution. The sub-station automation decreases the impacts caused due to human errors and expands the effectiveness. SAS provide proper safety and improves production. This system performs its tasks with synchronisation of devices duty cycle.

Sub-station smart automation system gives the control of energy system and allows control on power distribution. Insightful electronic smart IED information is utilized to convey remote clients and to control the power system through smart IED inside the SAS. The existing SAS system is unable to deliver information in require period of time. Essential measures can be used to rank and get the data about the danger of the occasions, segments, and framework structures.

2.3.4 Lack of Efficient Power Distribution System

The power transmission and distribution network system serve to gather electrical power generation and its transmission from sub-station to external power grid station. Existing power distribution in unable to provide effective power management system. Mostly it depends on external grid due to power outages. Electricity cogeneration is a very sensitive process which requires advanced monitoring system with efficient power distribution system to provide power or deliver power to external grid without any power outages. There is two-way power flow system in different buses of WWTP sub-station which must be very efficient power management system to avoided burning. Mostly existing WWTPs do not have advanced distribution network system. Due to this reason they have to relay on external power grid which make this process expensive. Secondly due to inefficient power distribution system generated power cannot utilised completely [92].

2.3.5 Lack of Optimized Plant Operations

In situations where wastewater treatment plants operate without optimization planning and processes, they are usually at a loss. An optimized treatment plant operation consumes less energy and if managed well with a lesser requirement of maintenance work, the life time of the processing units significantly increases. Most of the existing WWTPs have old infrastructure with manual operational task. Different operations, handled through plant operator without any automation system increases risk factors and reduces its efficiency.

Acknowledgement of different operations do not exist or not received in appropriate time interval. Manual operation through operator takes too much time which makes a WWT not suitable for electricity cogeneration. The devices are not interconnected with each other to work systematically. The devices are unable to transmission information completely at central control system [91, 92].

2.3.6 Lack of Optimized Energy Utilization

As mentioned earlier, water treatment is an energy intensive process which consumes high amounts of power during biogas production through anaerobic process. In order to address the energy requirements, the plant should have a means to fulfils its required load demand and must have reduced dependency on zonal energy providers. The WWTPs must therefore produce power through self generation. For an optimized energy performance if production is in surplus, there should also be a way for the energy to be delivered to the feeders of the main power distribution authority. This mechanism must be embedded in the process of cogeneration.

2.3.7 Lack of Effective Communication

One of most prominent drawbacks in the existing sub-stations is the lack of advanced and efficient communication capacity between distribution sub-stations of WWTPs and the power distribution authority. Existing/ old infrastructure achieves this communication from protection relays. The relay only performs local backup protective tasks for the entire sub-station and the interconnected transmission lines. These traditional mechanisms of protection and communication redundancy do not comply by the selectivity and sensitivity of advanced operational and maintenance requirements of water treatment. Lack of operational information in the control system causes unwanted plants outages and shutdowns. The field device status signals and power supply interlocking philosophies are hard to achieve causing safety hazards in the power system. Multiple errors exist due to old communication network system. The configuration and settings of different devices are unable to meet advanced requirement of WWTPs for advanced communication with acknowledgement. Existing WWTPs infrastructures do not have failsafe and redundant communication system. If error occurs in the system whole system information network will fail to transmit information; meanwhile relays operates and turn off the plant for safety purposes. Sometimes it will take time to operate which causes huge damages. The operational relays are not synchronised with different devices to act spontaneously.

2.3.8 Design Requirements of Effective Philosophies

There is also a need to design necessary control and monitoring philosophies to increase plant automation and bring I/Os to Human Machine Interface (HMI). The management of unreliable and low bandwidth networks and its communication to a remote SCADA system and local sub systems via redundant communication link is necessary.

2.3.9 Demand for Redundant and Failsafe Operation and Communication

Human interaction with the system needs to be reduced to address the associated risks, hazards, and manual dependency. Complex secondary wirings related to metering signals, protection relays, control gear monitoring, etc. also need to be minimized for a flexible, reliable a redundant infrastructure. An important aspect to consider for the automation of system to achieve enhanced performance, control, and monitoring requires advanced supervision and implementation of multi layered protection within various processes. This is done through implementing a redundant and fail-safe mechanism in the system for enhanced automation operation [93].

2.3.10 Lack of Advanced Protection System

Existing WWTP do not have advanced device protection system. The IEEE characterizes protective and time synchronised protocol. IEEE protocol has capacity to identify imperfect lines regarding errors or mechanical assembly or other power system states of a strange or unsafe nature with complete compatibility of different plant devices.

Existing WWTP communication system is inefficient which leads to increase down times and delays along with the loss of information about the plant status, downtime and loss of information, which is also a major contributor to the shutdowns at the WWTPs with older infrastructure. WWTP have capability to produce electrical power in megawatts and also it requires huge amount of power so protection must be required for different expensive devices and for safety. Improper management of power causes burning and heavy losses. Power outages occur mostly to prevent losses. There is no proper advanced system for busbar protection and switchgears. The efficient fast accessibility model is important to maintain a strategy for protection system and to provide safety to whole power flow arrangement system [94].

Advanced SCADA system with central control power management is required for protection. SACDA system with smart modelled RTU provides efficient communication and power management system. Smart modelled RTUs have great compatibility with existing and smart IEDs. Smart RTU provide time synchronised operations with real time application to support electricity cogeneration. Smart RTU also compatible with existing relays-based protection system. Upgradation of old infrastructure of WWTP with smart RTUs require small investment with multiple benefits.

2.3.11 Environmental Impact

Existing power plant working on coal and gas emitting greenhouse gases and cause one of the major global warming factor. Even existing WWTPs emit CO_2 in much more amount, which can be reduced through SAS with smart RTUs. The proposed research result in green electricity with multiple environmental solution.

2.3.12 Health & Safety

Existing WWTPs have manual operation. Operators require to operate sensitive task. Communication systems are not so advanced to provide complete information without any delay due to this reason existing WWTP need to improve their infrastructure through SAS and enhance health and safety parameters [95].

2.4 PROBLEM EVALUATION

2.4.1 CHP Process and Electricity Cogeneration

In order to address the energy requirements of water treatment process, there needs to be a sustainable way of power generation and transmission. The proposed methodology therefore suggests sustainable delivery of electricity required which can be attained through self-generation of power. There should also be a mechanism to channelize any surplus amounts of electricity produced by feeding it back to the zone sub-station. Same should be fed by zone sub-station in case of energy deficiency which is addressed through cogeneration. This is another drawback of the existing plant sub-stations as it lacks this communication system between distribution sub-stations present at site and the zone sub-station. Manual HV operator tasks also serve to increase risks and dependency. The complex secondary designs like telemetric signals, protection relays, control gear monitoring etc, need to be reduced to implement a flexible infrastructure with adequate redundancy. The objective of the proposed methodology is therefore to also add communication capacity to the distribution sub-stations while providing centralized power management to operate the plant. It will also address other aspects of automation such as enhanced performance, advanced supervisory control and reliability of power protection which is done through several protection layers.

Anaerobic digestion in biosolid digester's section produces maximum amount of methane gas which is used is combined heat and power (CHP) process for power generation. The sequential treatment flow process shows that flammable gases that are formed are burnt to produce sufficient amount of steam, which is further utilised to excite on-site generators for electricity generation. Figure 2.5 shows block diagram of electricity generation and cogeneration system [96].

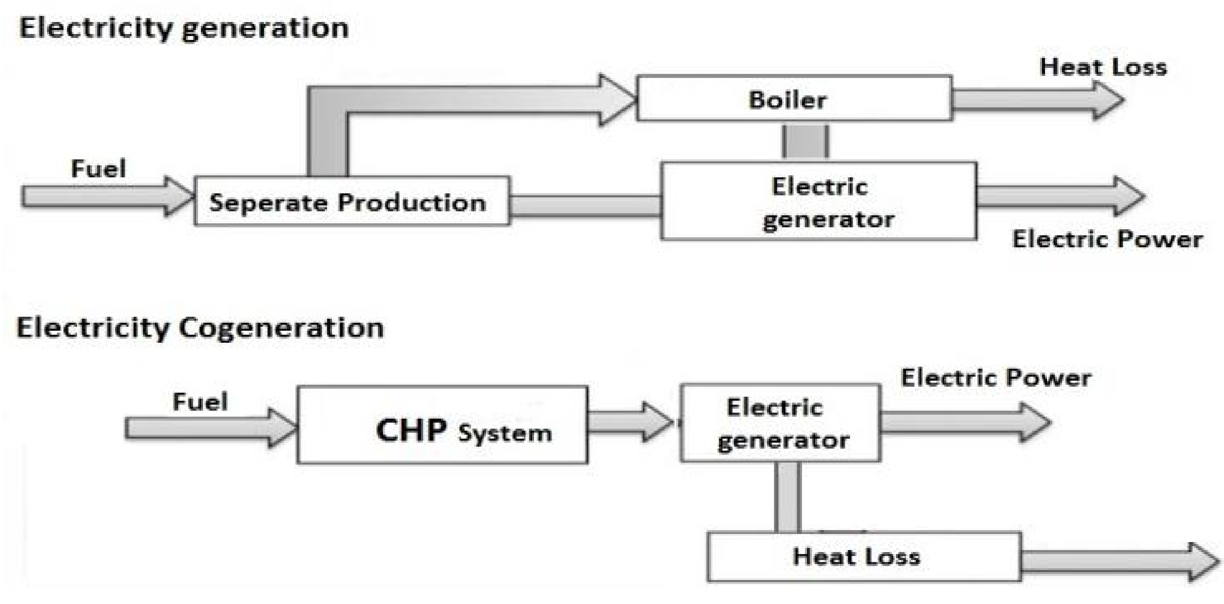


Figure 2.5 CHP Process and Power Generation

Biogas is captured and utilised for on-site electricity generation through an internal combustion turbine, while the heat generated during the process is used for increasing temperature of anaerobic digesters, especially in the winter, as higher temperatures favour this process. Electricity generation with waste heat usage is called the CHP process.

2.4.2 Electricity Trigeneration Generation

In a trigeneration system, thermal energy produced by the internal combustion engine or turbine and not used for heating applications will be used to power a thermally driven absorption chiller system. Figure 2.6 demonstrates the acquirement of electricity through trigeneration, which is an efficient way of generating power.

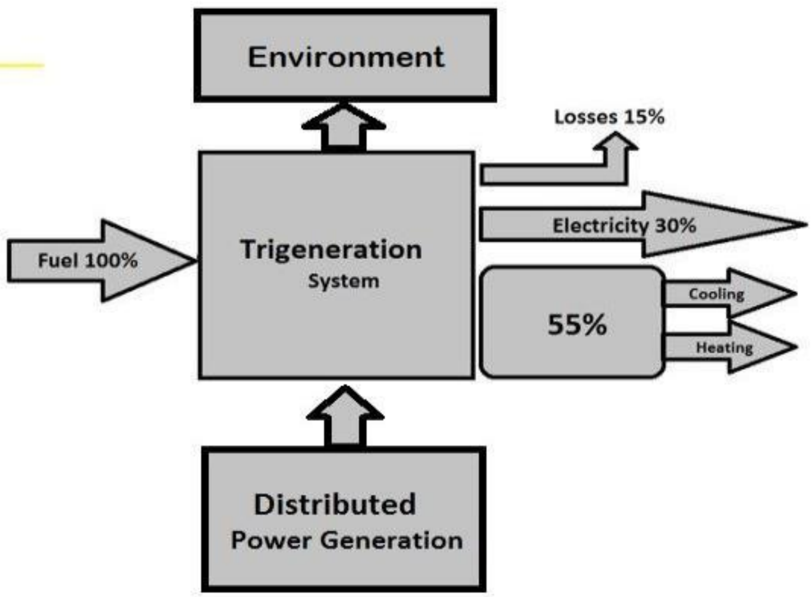


Figure 2.6 Electricity Trigeneration Outcomes

CHP systems is an efficient power system which consist of an internal combustion engine or turbine driven by a fossil fuel joined with a generator to generate electricity. A heat recovery mechanism process recovers the thermal energy from the power generating system and exhaust gases for heating applications. CHP system is capable of high efficiency, up to 80% at point of use, as opposed to 45% for electricity and heat produced separately.

In a trigeneration system, thermal energy produced by the internal combustion engine or turbine and not used for heating applications will be used to power a thermally driven absorption chiller system. With integration of the absorption chiller system, higher efficiency achieved as compared to a CHP system. CCHP systems are more than 90% efficient [97].

Absorption chillers are a practical alternative to the compression chillers. Their main advantage is that they do not require any electrical power consumption, except for the pump moving the solutes. They rely on thermal energy produced in power generation to power their systems.
An absorption chiller works with a mixture of two fluids. The fluid with the lowest vapour pressure is the solvent, while the fluid with the highest vapour pressure is the solute. Usually the couple of fluids used can be water (solvent) and ammonia (solute), or lithium bromide (solvent) and water (solute).

An absorption chiller system comprises of four main parts

Evaporator

It is the heat exchanger in which the refrigerant (the solute) absorbs heat from the surroundings at low temperature and becomes vapour. Considering the refrigerant is at low pressure, its boiling point is low and evaporates absorbing heat from the stream which needs to be cooled.

Absorber

It is the device where the refrigerant, in the form of vapour, is absorbed by the liquid solvent. The absorption process takes place here because of the affinity between solute and solvent. As refrigerant vapour is absorbed by the solvent, the partial pressure in the evaporator reduces, allowing more refrigerant to vaporise.

Generator

It is the solute-solvent mixture is heated by the heat source. In a trigeneration system, heat would be obtained from the combustion process of power generation. Application of heat causes the refrigerant to evaporate out and move to the condenser. The solvent is now directed back to the absorber.

Trigeneration

It is the heat exchanger in which the refrigerant vapour, produced by the generator, condenses releasing heat to the environment. The refrigerant flows back to the evaporator, completing the cycle.
The main benefits of trigeneration is its ability to cut energy cost due to its higher overall cycle efficiency which reduces the amount of fuel used to produce one unit of usable energy. This is opposed to conventional methods of separately generating electricity, thermal energy using a boiler, and cooling, each with its associated efficiency losses. Achieving WWTP trigeneration on existing infrastructure can remarkably enhance the following features, which can enhance the following features of the plant.

1. Lower greenhouse gases emissions.
2. Lower distribution losses.
3. Better power management system.
4. Improved security.
5. Lower network demand.

2.4.3 Power Management System

Power generation and distribution management is one of the important subject for electricity cogeneration and to handle complexity. Wastewater consist a set of renewable energy sources which are sources for electricity generation. Power management using SAS give minimum losses and costs. This system has to manage load and source, power generation and power distribution complete sub-station power control. The choice of sources, must be done in real-time to avoid power outage. The research proposes a system through smart RTU for PMS using IDE with advanced SCADA system which able control all operation of Sub-station with their power demand and power distribution. SAS has importance due to its the overall reliability and efficiency of the electric grid.

Electrical energy and energy management are vital for every industry of the world. Industry's dependence on scarce energy resources, the volatility of energy costs, the growing environmental consciousness and more stringent legislation are just a few of the factors influencing the global drive for improved energy management. MS prevents blackouts and disturbances of sub-station operations at the same time. It controls energy costs, enhances safety and mitigates both environmental and health impacts [98].

2.4.4 Ring Network Topology

In a ring topology, smart RTUs are connected in a ring and data travels in one direction using a telemetric control signal that uses the SCADA system.

Advantages

1. Multiple RTUs with substations can be added easily.
2. Relatively very low cost. Figure 2.7 shows smart RTU in ring topology to communicate telemetric signals with centralised SCADA system.

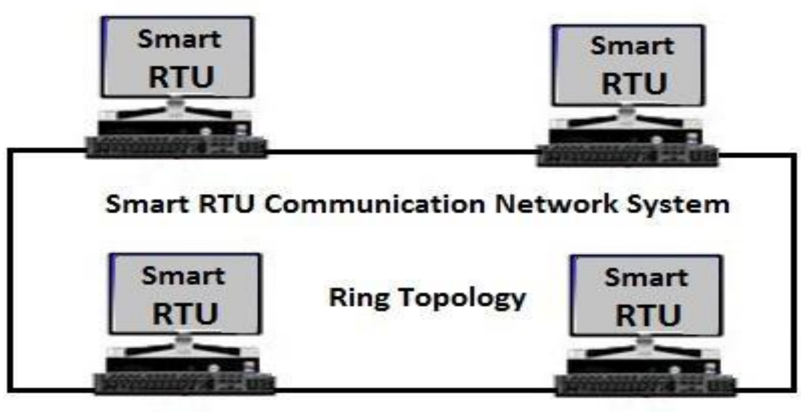


Figure 2.7 Smart RTU with Communication Network Topology

Disadvantages

1. Slower than a star topology under normal load.
2. If a cable fails anywhere in the ring, then the whole network will fail.
3. If any RTU fails, then the token cannot be passed around the ring.
4. The hardest topology to troubleshoot because it can be hard to track down where in the ring the failure has occurred.
5. In order for the nodes to communicate with one other they must all be switched on.

Star Network Topology

In this type of network, RTUs are connected separately with a central control system. A central control system usually forms the main node and the subsidiary nodes are connected to it and to each other through a network switch. Figure 2.8 shows the smart RTU's communications in a hybrid of ring and mash topology format to communicate telemetric signals with central SCADA system.

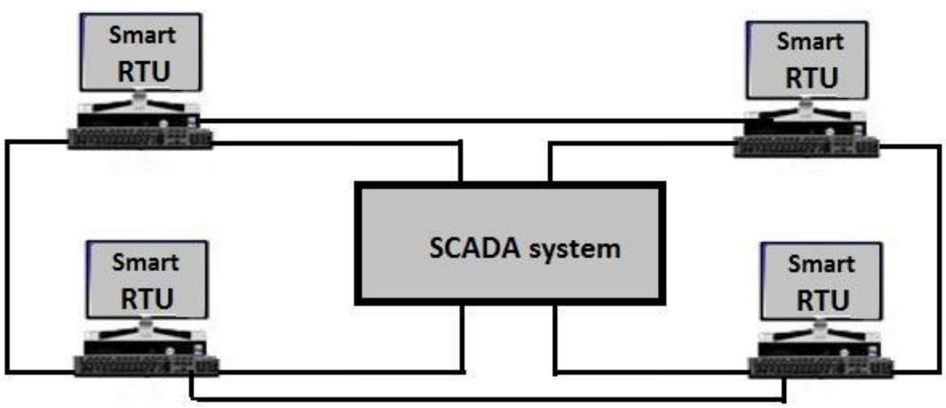


Figure 2.8 Communication of Smart RTU in Hybrid Topology with SCADA System

Advantages

1.The most reliable because the failure of an RTU or a node cable does not affect other nodes.
2.Simple to troubleshoot because only one node is affected by a cable break between the switch and the node.
3.Adding further RTUs does not greatly affect performance because the data does not pass through unnecessary nodes.
4.Easily upgraded from a hub to a switch or with a higher performance switch.

Disadvantages:

- Uses very lengthy cable route that makes it expensive to install other than ring topology.
- The extra hardware required such as hubs or switches further increases the cost.

Figure 2.9 represents the topology of the zone sub-station with two distribution sub-stations called Point of Contact (shown as POC1 and POC2). The single line drawing shows the conceptual approach of the interlinked plant generators G (which generate electricity from biogas) with the zone sub-station through Ring Main Units (RMUs). RMUs operate on High Voltage (HV) coming through step up transformers passing on to Wastewater Treatment Plant (WWTP) sub-station. Any number of sub-stations can be connected to the network using ring topology. Each sub-station is protected by providing fault inter-tripping signals to the protection relays [99].

The LV supply from G is interlocked with the LV supply of the sub-stations using non-essential electrical panels whose circuit breakers are mechanically and electrically connected to the circuit breakers of the main panels of any given sub-station. They serve to protect the distribution sub-stations during bidirectional flow of electricity by triggering signals to trip when required. This enables improvement in secondary distribution network performance. The bidirectional power flow is very sensitive task and therefore requires immense attention during cogeneration.

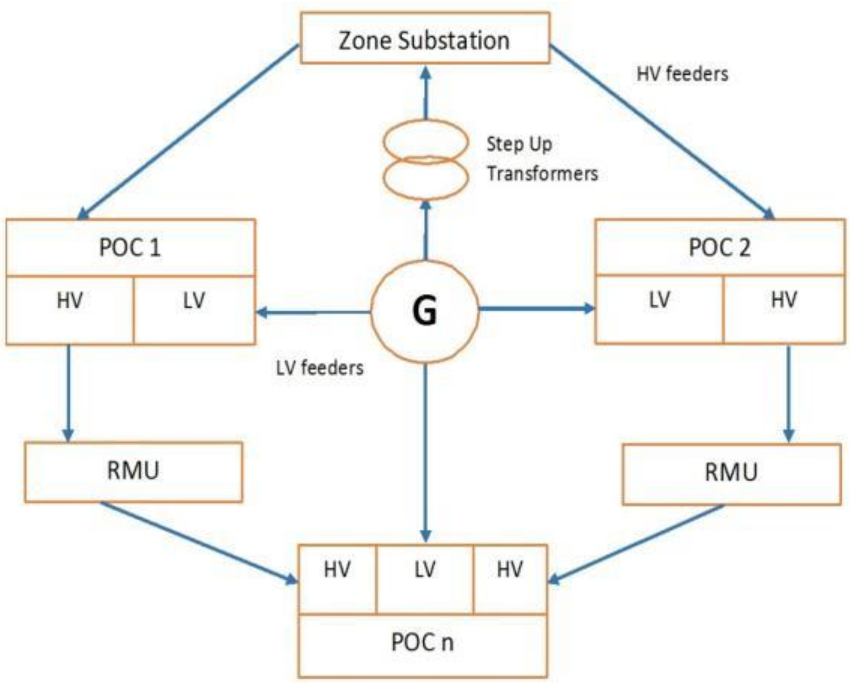


Figure 2.9 Failsafe and Redundant Co-generation of Power Supplies.

2.4.5 Design Requirements for a redundant, failsafe and interlocked power

The design of the proposed RTU need to have certain features to address the requirements mentioned above. It must have suitable configuration for effective reverse power transfer between the Zone sub-station and the water treatment facility. Most of the existing installations are not capable of this bidirectional flow of electricity which switches according to the change in energy demand [84]. A swift operational mechanism is a pre-requisite for sending alerts or signals to multiple systems simultaneously. The fault troubleshooting time depends on signalling time, operating time of protection relay, relay trip and circuit breaker present in the plant sub-station. The water treatment facility itself must be designed in a way in order to maintain a strong balance between power demand and generation and must also have a system to dispose of the heat produced during electricity generation [100]. The operating time must be highly efficient to ensure smooth running of the plant. The respective calculation and evaluation work should be performed as per standard electrical engineering practice.

2.4.6 Failsafe and Redundant Communication

The benefit of the ring topology is that fault isolation and fault recovery are simpler than for other topologies. Therefore, the ring topology is considered to be the most reliable topology for sub-station automation.

The proposed smart RTU philosophy has been realised at MW-WTP. It has a massive sewage and industrial waste treatment facility that produces a huge amount of biogas. Existing power infrastructure, through smart RTUs at MW-WTPs, POCs and power company`s zone substations, has resulted in the achievement of electricity cogeneration, power supply and communication redundancy with optimum usage of biogas by the CHP process. The zone sub-stations are directly connected to POCs via the smart RTUs that provide an interface to transfer data from relays and internal storage. To guarantee availability of MW-WTP status, the ring topologies are implemented with intelligent network-managed switches like Hirschmann switches. The smart RTUs interface has the ability to process telemetric signals from the POC-PLC, interposing relays, switchgear auxiliaries and communication bus to IEDs and HMIs [101].

Information accumulates in POC-PLC and is then sent to SCADA via the smart RTUs. The installation considers reduced cabling by segregating the centralised control and monitoring of the updated SAS. The proposed network philosophy, therefore, presents a flexible solution as opposed to conventional schemes in existing WWTP substations. Figure 2.10 shows the telemetric communication flow from sub-station to SCADA master control centre through which smart RTUs provide efficient and failsafe communication with advanced power management during power flow [100,101].

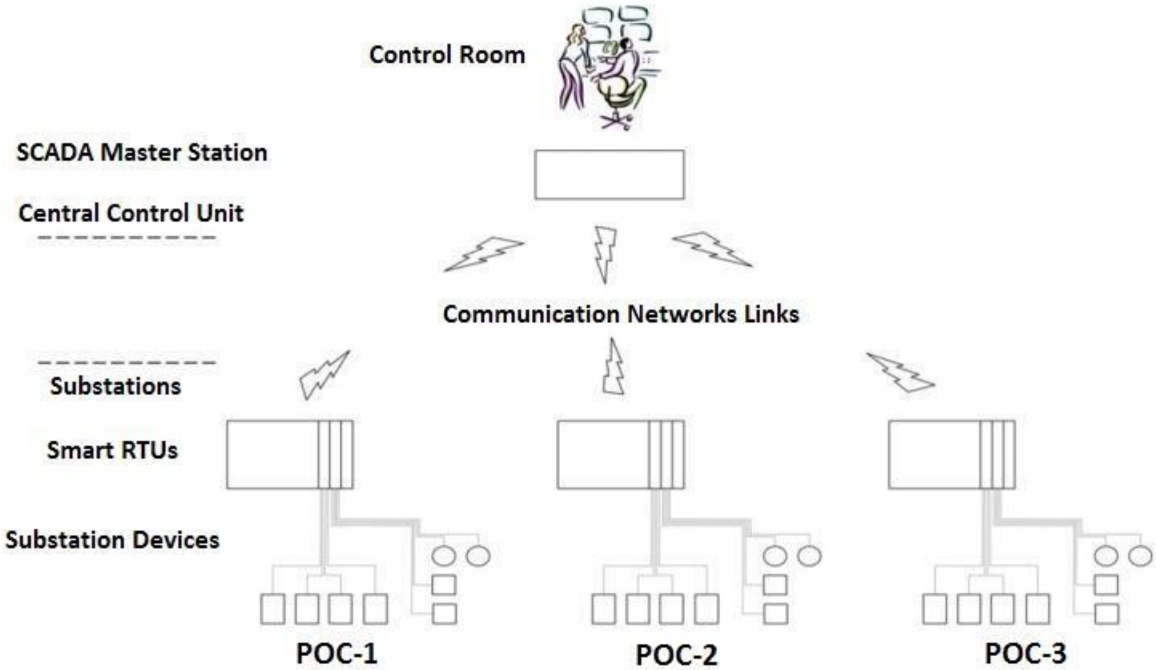


Figure 2.10 Communication Flow of Sub-station RTUs

2.4.7 Wireless Communication

Modern substations have advanced communication system for better PMS which consist of both wired and wireless communications are options. Wireless communication provides instant access on far off power plant. Smart wireless devices increase more efficient remote control for different operation. Smart RTU easily compatible with smart wireless devices to increase communication network for advanced control and enhances health and safety parameters. With these motivations from recent developments and ongoing activities, the efforts have been made for this work to implement on the various smart applications using standardized wireless communication technologies, e.g. IEEE 802.11 based wireless LAN, IEEE 802.16 based WiMAX, 3G/4G cellular, ZigBee based on IEEE 802.15, IEEE 802.20 based MobileFi, etc.

Different applications of these wireless technologies have been identified considering the latest available data rates, distance coverage, and other important technology features in smart grid environment. Smart grid communication system requires advanced communication system. Without proper communication network smart devices cannot coordinate and information cannot be executed hence without communication smart grid cannot be achieved.

IEEE 802.11 based wireless LAN provides robust, high speed point-to-point and point-to-multipoint communication. The spread spectrum technology was adopted in IEEE 802.11, because it allowed multiple users to occupy the same frequency band with a minimum interference to the other users. IEEE 802.11 legacy standard proposes the standard for wireless Local Area Networks (LANs) covering three non-interoperable technologie. IEEE 802.11b, also known as Wi-Fi, offers a maximum data rate of 11 Mbps. It operates on 2.4 GHz frequency

Further, currently available technologies based on IEEE 802.11a and IEEE 802.11g can provide data rates up to 54 Mbps. IEEE 802.11a operated on 5.8 GHz frequency band with Orthogonal Frequency Division Multiplexing (OFDM) modulation whereas, 802.11g, also known as enhanced Wi-Fi, operates on 2.4 GHz frequency bands with DSSS modulation technique. IEEE 802.11n based on Multiple Input Multiple Output (MIMO) technology is intended to increase data rates further, up to 600 Mbps. IEEE 802.11i (known as WPA-2) enhances the cyber security in wireless LANs using Advanced Encryption Standard (AES). Deployment of wireless LAN offers various benefits over wired LAN, as it is easy to install, provides mobility of devices and is less expensive [102].

2.4.8 Protocols

Node to node communication between the WWTP substations is driven by IEC61850 standards that define a standardised format for SCL. It includes various functions for SCADA, IEDs and for the network control technology. Distributed Network Protocol (DNP3) is a register-based protocol that stores data intended to be communicated in a register location of IEDs. Systems complying with these standards are most suited to provide protection and control for WWTP electricity cogeneration. IEEEC37-238 utilises FOCS with IEC61850. The IEEE1588 standard facilitates the usage of the Precision Time Protocol (PTP) to fulfil the clock synchronisation requirements in packet-oriented networks. Link aggregation control protocol (LACP) is implied for physical connection of the network nodes. The DNP3 protocol has compatibility with IEC62351-5 and is widely recognised as a communication standard for utilities and WWTPs. Figure 2.11 shows IEEE, IEC61850 and DNP3 protocol standards used in different layouts for the proposed smart RTU [103].

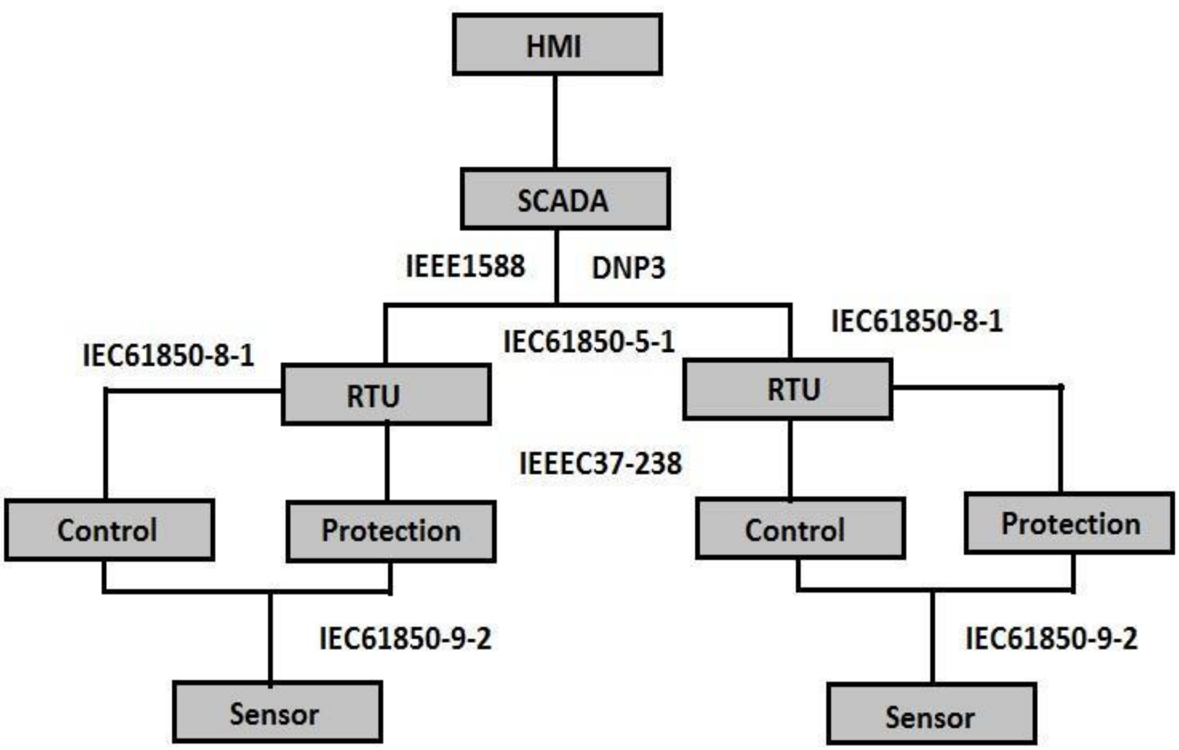


Figure 2.11 IEC, IEEE and Network Protocols for Various Layers of Protection

IEC61850-9-2 Standard

The IEC61850-9-2 standard described the model for accounting the configuration of a sub-station network covering the protection and control devices, their connections as well as monitoring topology of the sub-station while utilizing Sub-station Configuration Language (SCL). IEC61850 is an international standard which provides a description of the devices used in an electrical sub-station. The exchange method and criteria of data transmission by these devices depend on configuration time and run-time. This standard facilitates suitable and reliable data exchange between different devices. Connectivity suspensions and re-entering of data are no longer part of the system operation as it guarantees a uniform and seamless information flow throughout the network. In contrast to master slave models, the standard enables client-server models with methods which are adaptable and easy to upgrade. The IEC 61850 enabled intelligent electronic device IEDs receive power grid condition data in digital format through process bus and merge units [104].

Node to node communication depends on IEC 61850 based systems which are most suitable for providing protection and control. The IEDs connected to the sub-station network exchange the data where all are given equal priorities. The source IED sends messages to destination IEDs instantly because the IEC 61850 based systems are high speed systems between the trunks. The distributed network protocol (DNP) is utilized for enabling communication mode between SCADA systems i.e. RTUs. This robust and intelligent protocol facilitates reliable interoperability between system nodes.

Components of IEC61850

IEC 61850 has the following components:

1. An objective model for the description of the data available from primary equipment and sub-station automation functions.
2. Provides a description of services, information format and common data class and independent of protocols.
3. Specifies the communication between the IEDs of the sub-station and performs mapping of the services to the protocols.
4. Provides a specific language for configuration and communication configuration information.

Under this system, specific functionalities are allocated to indicate events occurring in the sub-stations such as Generic Sub-station Event (GSE) which has replaced hard-wired signals. GOOSE messages are also structured on a single message format which communicates relevant protection related information such as protection IED and minimizes the network traffic simultaneously during fault events. IEC 61850 defines a standardized configuration language called sub-station configuration language (SCL) which includes various functions for SCADA, Intelligent Electronic Devices (IED) and for the network control technology. The physical network nodes are connected via Link Aggregation Control Protocol (LACP) so the accumulated bandwidth of every trunk is accessible for transmission of information. In the event of connection failure, the remaining connections gain control of the on-going data transmission thereby guaranteeing redundancy. There is also an automatic load distribution mechanism [105].

OSI Network Layer

1. Application layer provides a cluster of interfaces to be utilised for getting access to network services.
2. Presentation layer mainly transforms the data of application into a generic framework for network broadcasting and vice versa.
3. Session layer allows two communicating parties to maintain ongoing exchange of data across a network.
4. Transport layer is to manage the data transmission over the network.
5. Network layer converts logical network address into the format to be used within physical devices and also controls the addressing for message delivery.
6. Data link layer initiates specific data frames between the physical layer and the network.
7. Physical layer converts data format from bytes into signals to be sent as outgoing messages and vice versa.

The Open Systems Interconnection (OSI) display is a reference device for understanding information correspondences between any two arranged frameworks. It isolates the interchanges forms into seven layers. Each layer simultaneously performs particular capacities to help the layers above it and offers administrations to the layers underneath it. The lower three layers focuses around the power system functions and the field devices. The top four layers come into play at the last framework to finish the process and mostly involve monitoring and control. This research uses these OSI layers for compatibility of smart RTU with different IED in sub-station. This improves the power network communication quality with a centralized control SCADA system.

Every one of these layers depends on the layers underneath it to give supporting capacities and performs support to the layers above it. Such a model of layered usefulness is likewise called a "convention stack" or "convention suite". Conventions, or standards, can do their work in either equipment or programming or, as with most convention stacks, in a blend of the two. The idea of these stacks is that the lower layers do their work in equipment or firmware (programming that keeps running on particular equipment chips) while the higher layers work in programming. The Open System Interconnection is a seven-layer structure that indicates the prerequisites for correspondences between two PCs. The ISO standard 7498-1 characterized this model. This model enables all system components to work together [106]. Some key advantages of implementing the OSI on existing WWTPs are:

1. Helps clients comprehend the master plan of systems administration
2. Helps clients see how equipment and programming components work together
3. Makes investigating less demanding by isolating systems

IEC61850 standard explains the model for accounting configuration of sub-station networks covering protection and control devices along with their connections. It also defines monitoring topologies utilising SCL for SAS. IEC61850-8-1 protocol uses object-oriented configurations for reliable remote operations. IEC61850-9 standards are compatible for conventional and modern CT/VT with converging devices. IEC61850 with IEEEC37.238 performs reliable intertripping and interlocking of power supplies. Second and third Layer of Open System Interconnection (OSI) provides protection and reliable control. The Smart RTU proposed philosophy should incorporate all these standards for a safe and successful WWTP electricity cogeneration. Figure 2.12 shows four OSI layers of protection used in the proposed philosophy for this research. Smart RTUs are implemented in the second layer.

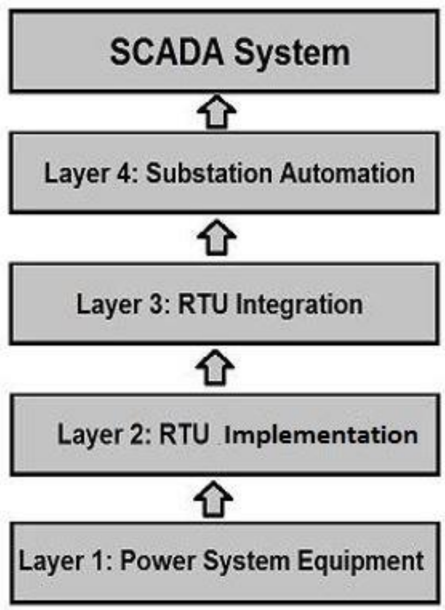


Figure 2.12 Four Layers of OSI Protection via Smart RTUs

2.4.9 Sub-station Automation

The structure of sub-station automation is comprised of three basic levels which is defined by the IEC 61850 standard as mandatory which needs to be discussed. In this context the structure of sub-station automation is shown in Figure 2.13. The three levels are:

Station level

The station level is a shielded control room which receives data from various bay levels for necessary data exchanges.

Bay level

Bay level is located near the switchgear and is responsible for protection, control and monitoring of IEDs such as circuit breakers, transformers etc. installed at different bays. It also facilitates in exchange of relevant information between bay and station levels.

Process level

This level provides an interface between the functions and the bay level. It deals with switchyard section of the sub-station such as current and voltage transformers, remote I/Os etc. and thus transfers instantaneous and time critical messages such as status signals and control data between the process and the bay levels.

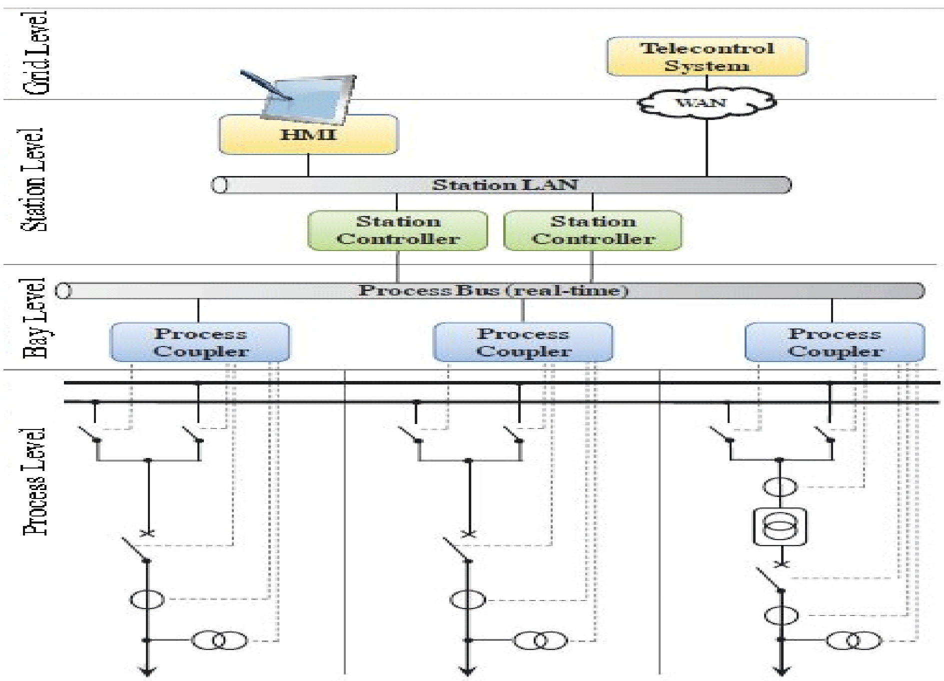


Figure 2.13 Structure of Sub-station Automation

The connectivity between the zone sub-station and distribution sub-stations (POC1 and POC2) in the form of ring topology is made through RTUs installed at each site to increase redundant and failsafe communication. The implementation of the above-mentioned levels is mandatory for the swift flow of designed I/Os via RTUs. SAS is a supervisory management and control system for industrial electrical distribution systems. The interest on SAS has been increasing rapidly due to its numerous benefits to utilities. It has advanced further than a traditional SCADA system providing additional capability and information that can be used to further improve operations, maintenance and efficiencies in substations. The most significant elements of a SAS system include relays and smart IDEs that perform various control, monitoring and protection related operations. The electrical grid undergoes a fundamental change with the introduction of the Smart Grid. Installation of end consumer smart meters, deployment of distributed renewable energy generation through wastewater, and interconnection of operation and information systems require new solutions that can intelligently monitor and manage the infrastructure. The Smart Grid aims on raising operational efficiencies of operators by increasing the flow of information and automation in order to enable better and faster decisions, hence reducing operational cost. In order to achieve this, utilities are facing some challenges to improve the power delivery methods and utilization, including the integration of control room systems for better workflow, new power demands, and security of supply. Additionally, The Smart Grid enables future ability at WWTPs where they can cater for trends and developments in operations and maintenance, as well as any other major upgrades [107].

The trends in electric utility automation, specifically sub-station automation, have converged upon a common communications architecture with the goal of having interoperability between a variety of intelligent IEDs found in a substation. This initiative was begun back in the late 1980s driven by the major North American utilities under the technical auspices of EPRI (Electric Power Research Institute). The resulting standard that emerged is known as the Utility Communications Architecture 2.0 (UCA2.0) and is now becoming an international standard as IEC 61850.

This research provides solution to many issues and requirements especially telemetric communication in the sub-station environment and for sub-station automation applications requiring real-time performance. New standards introduced by the IEC and IEEE establish new HMI and environmental requirements specifically for communications networks (i.e. Ethernet) in substations, critical Layer-2 features of modern Ethernet switching hubs (i.e. switches) which enhance real-time deterministic performance as well as fault tolerant loop architectures and network redundancy The proposed SAS is a system which enables an electric utility to remotely monitor, control and coordinate the distribution components installed in a substation. Modelled smart RTUs with IDEs are used for sub-station automation and protection. These IEDs are installed in strategic locations for collection of system data and automatic protection of sub-station equipment. Data communication between the control centre and IEDs in remote locations and among the IEDs becomes an important issue to realize the sub-station automation functions. Various protocols are used for telemetric control purpose, but none of them fully supports the interoperability among IEDs supplied by different vendors in the substation. These protocols are Modbus, Modbus Plus, DNP 3.0, and IEC 61850.
Though these protocols are used at the utility level, there are still some shortcomings. Modbus and Modbus Plus are suitable mainly for serial data communication and not optimized for communication over ethernet. IEC 61850 is a standard specifically designed for implementing SAS systems. The main features of the standard are data modelling, object oriented platform-independent modelling of all the functions, fast transfer of events and messages and GOOSE and

GSSE for the peer-to-peer communication mode. Setting groups- control blocks allow the user to switch from any active group of setting values to another. Value- transfer of sampled data from modern switchgear and nonconventional CT/VTs are represented in the substation and are stored in XML format using the sub-station configuration Language (SCL).

2.4.10 Advanced Monitoring System

AMS with SCADA system improves routine management, quality of service, reliability and security. AMS is the deployment metering solution that provides bidirectional communication. This system also gathers information on voltage, current and power. AMS has three main objects, which are measurements, controlling device communications and data processing centres that enhances safety and provides redundancy.

2.4.11 Intelligent Devices Sub-station

Conventional substation's transformer, switchgear, controls and monitoring are independent to all other devices, while communications are based on a cable connected with the device. On the other hand, intelligent substations share all information on control, monitoring and protection through just one bus by the use of digital and information technology.

2.6.12 Sub-station Sensors

Sub-station distribution faces a number of challenges, such as lack of communication and insufficient operations. Sub-station sensors are a solution to many distribution problems and provide many different applications for asset safety, monitoring, continuous communication of equipment, and increase in utilisation of the grid with SCADA system. Power generation side sensors enable high-efficiency base load operations and more efficient biogas and thermal power plants processing through improved monitoring. The combination of sensors is used to measure voltage, current, chemicals, gas, humidity, time synchronisation and intelligent electronic devices.

2.6.13 Remote Terminal Unit (RTU)

The RTU is connected to the physical equipment for advanced control. It converts all electrical signals coming from the equipment into digital values like – open/close – from a valve or switch, or the measurements like flow, pressure, current or voltage. By converting and sending the electrical signals to the equipment, RTU controls the equipment, like closing or opening a valve or some switches [108].

2.5 SUB-STATION COMMUNICATION SYSTEM

There is a lack of advanced and efficient communication capacity in the already deployed traditional sub-stations. The communication and protection of existing/old infrastructure depends only on relays. A relay performs protective tasks such as local backup for the entire sub-station and the interconnected transmission lines. The backup protections and communication redundancy offered by these traditional infrastructures have coordination issues with respect to selectivity and sensitivity of advanced operational and maintenance requirements of a WTP. The available I/Os must be communicated and should be made redundant in order to increase automation. It is needed to design necessary control and monitoring philosophies for enhanced plant automation and transmission of I/Os to Human Machine Interface (HMI). The management of unreliable and low bandwidth networks is essential and a platform for communicating to remote SCADA system through redundant communication link is necessary within existing infrastructure.

A redundant network setup is essential for management of treatment plants because still many of WWTPs are based on legacy system by either having a stand-alone deployment or own the traditionally used star topology Ethernet network. Valuable data from the field devices have greater chances of loss if the station encounters a fault within. The ring topology introduces a flexible performance by re-building the network and route data immediately through a substitute path. Redundancy is one of the fundamental necessities for power system infrastructures because it provides intensive protection and automation to treatment process so that water treatment should not shut down. Redundant systems ensure constant resource availability and control to address single point connection failures.

2.5.1 Fibre Optic Cable System

FOCs facilitates in attaining the required electrical isolation in order to reduce electrical hazards under faulty conditions. WWTPs must have broad network coverage for equipment placed at distant sites and substations. FOCs are the most suitable choice while extending to long distance point-to-point connections. The FOC channel strengthens electromagnetic interface and control, which provides secure and reliable communication in harsh weather conditions. This advanced networking setup demands adoption of a network with wide bandwidth that will make it possible for the SCADA system to command execution of a remote status from a centralised control centre at WWTPs.

WWTP substations consist of different operations which require advanced monitoring of transmission and distribution lines, including many complex high-voltages electrical equipment and their protection [109].

Power systems will inevitably have short circuits, disconnections, ground and many other faults caused by external factors such as lightning, birds and internal factors, such as equipment aging, improper operation and maintenance regime, non-compliant procedures and bad management practices. Shutdowns and outages of the plant has adverse effects on the production. They also cause damage to the device or even the grid system, which are mostly irreparable. In order to reduce the probability of these faults occurring, strict regulations are needed for equipment's procurement, installation, operation and maintenance. Appropriate protection and instrumentation should be installed to achieve this level of automation and safety.

Protective relay devices are installed on power systems for sensing faults and abnormal operation. These protection devices are usually installed on remote sites of a plant and away from each other. Hence, it needs to be ensured that the signal transfer and formation is valid and in correct order for a systematic operation. Therefore, the relay signal transmission is essential for the normal operation of a power and communication system of a plant. SAS with integrated OSI layers can solve such technical issues that may occur on existing or older WWTP infrastructure.

In an optical fiber communication system, the light waves frequency acts as a carrier, which is higher than the radio frequency and can be considered as transmission medium. Fiber losses are much lower than cable and can further improve the safety and reliability of WWTP sub-station transmission. In WWTP sub-station operations, the optical fiber communication has many advantages. It has a high rate of recognition error and good transmission quality, which the protection devices need. Transmission received at its final terminal are exactly the same with the original information; there is no lack, loss, noise, distortions or change of the transmitted information. It also has high anti-interference ability and can effectively avoid the system-generated electromagnetic interference due to lightning and other natural phenomena [110].
FOC can carry wide frequency bandwidth and can accommodate large transmission.

2.5.2 Smart RTU and SCADA Systems

SCADA refers to the centralised control system that controls and monitors an entire WWTP. This system provides remote monitoring over a large area and all the control actions are automatically performed by RTUs. Figure 2.14 shows a screenshot for the SCADA system's advanced control in biogas production and water flow to improve production, health and safety parameters.

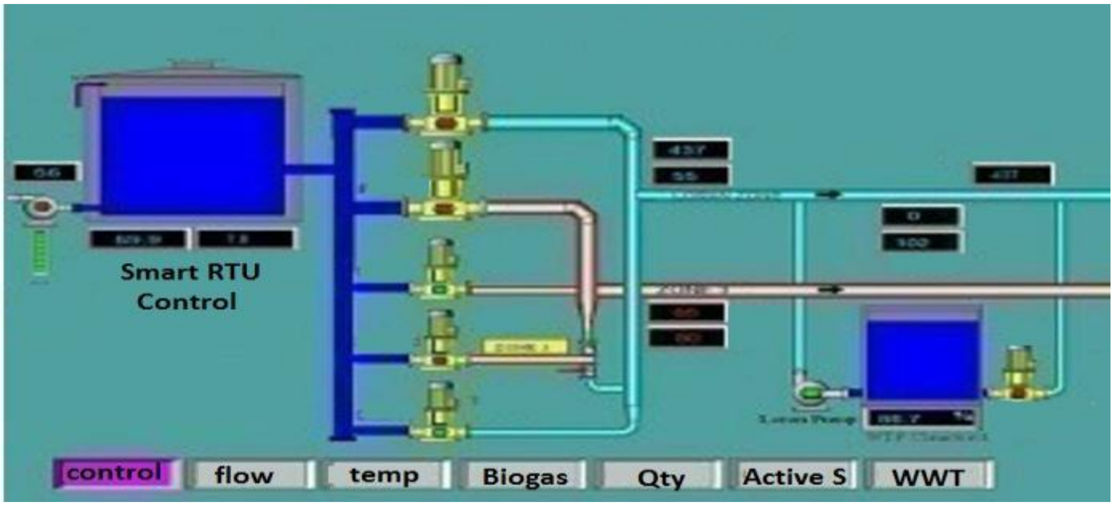


Figure 2.14 Smart RTU SCADA Control Panel for Biogas Production

The HMI, or Human Machine Interface, is an apparatus that gives the processed data to the human operator. A human operator uses HMI to control processes. The information provided by the HMI to the operating personnel is graphical; in the form of mimic diagrams. This means that the schematic representation of the plant that is being controlled is available to the operator. The picture of the WWTP that is connected to the pipe shows that biogas is running from the amount of effluent fluid entering through the pipe at that particular moment.

The operator can then switch off the pump. The software of the HMI shows the decrease in flow rate of the fluid in the pipe in real time. Mimic diagrams both consist of digital photographs of process equipment with animated symbols, or schematic symbols and line graphics that represent various process elements.

Out of many opportunities provided by the wastewater treatment infrastructure, there is also a need for a tool to evaluate the state of entire infrastructure. This can be achieved by having a centralized Supervisory Control and Data Acquisition (SCADA) system that could be used for monitoring and controlling of the plant. Remote Terminal Units are normally utilized as a part of SCADA system with a goal to reinforce the correspondence between SCADA point and the distribution sub-stations. The SCADA system needs to assemble the data of various generation systems in order to ensure the availability of the entire sub-station’s information at a centralized location for common use. The proposed RTU design aims to set up suitable configurations and connectivity based on cost effectiveness, adequate ingress protection, reliable implementation and performance. The proposed design philosophy utilizes remote and on-site controls for monitoring metering data, protection trips, condition monitoring, supervision and fault indication. This network extension would seamlessly integrate with the existing infrastructure. An intertripping and interlocking mechanism is developed with required inputs/outputs made available to the proposed RTU at a potential-free contact to optically isolate different control voltage levels.

2.5.3 Role of Smart RTU Panels

The proposed RTU aims to facilitate the process of energy cogeneration by performing the following functions:

1. Assembling and processing the digital status inputs, analog inputs, integrated values and forwarding them to the master station.
2. Receiving input and processing both digital and analog control commands.
3. Accepting the generated polling messages from the master station simultaneously through separate logical databases for each relative master station.
4. Perform communication activities simultaneously on available communication ports and using multiple concurrent protocols as per the layout, including the IEC standards and MODBUS protocols.
5. Must be able to support relevant data transmission rates.
6. RTU must comply with IEC 61850 Standard for communication with IEDs associated with each communication level.
7. RTU must be capable to automatically restart and initialize during restoration of power after an outage with no dependency on manual restart. The restarts must be reported to the attached master station.
8. RTU must have time synchronization feature through messages received from the master station.
9. It should facilitate downloading of RTU database from the master station.
10. It must also possess the SOE (Sequence of Events) feature.
11. Must act as a data concentrator for acquiring data from other RTU panels and facilitate the provision of necessary supervisory controls.

Figure 2. 15 is a representation of the proposed RTU panel. Some I/Os are coming from feeder of zone sub-station and some from the distribution sub-stations of the plant, details of which are explained as in the sections below.

The design philosophy utilizes remote and on-site controls in the form of different telemetry status and metering signals that monitor the status of electrical flow, protection trips and faults. The wiring of each POC is based on the design, interlocking and intertripping philosophy of the plant sub-stations. These telemetry signals and I/Os are mapped via PLC and then onto a Human Machine Interface (HMI) for proper monitoring and control of the plant. These terminals are mounted in the proposed smart electrical panel RTU and are energized by an external redundant source.

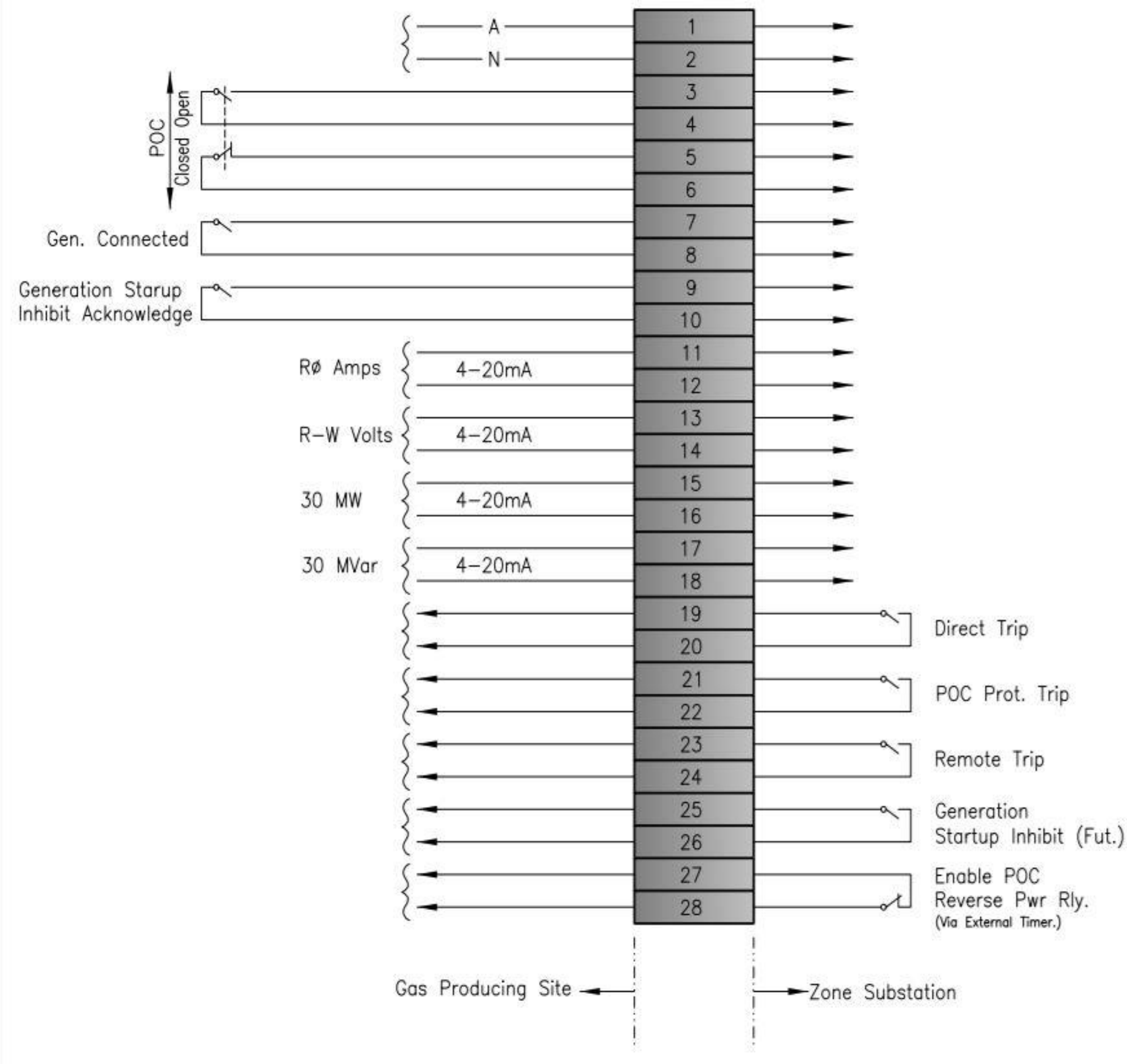


Figure 2.15 Smart RTU Panel

2.6 PHYSICAL REALIZATION

Implementation of the proposed smart remote terminal unit and its communication and data networking has been physically realized in Melbourne Water's Western Treatment Plant which is the largest water treatment facility and hence biogas producing station in the southern hemisphere and has a huge sewage and industrial waste treatment facility. It has two distribution sub-stations, POC1 and POC2. Following philosophies were done to achieve cogeneration and HV/LV redundancy and failsafe power network.

2.6.1 Power Distribution Flow

Figure 2.16 presents the implementation of power distribution flow between the zone sub-station with Distribution Sub-stations (POC1 and POC2). The generators are linked with the zone sub-station through interlocking philosophy.

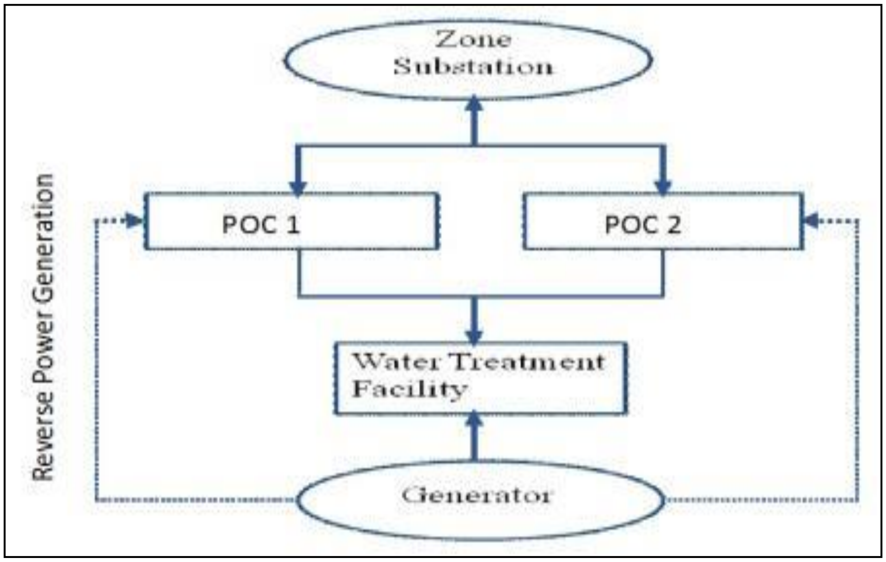


Figure 2.16 Melbourne's WWTP having two Distribution Sub-stations POC1 and POC2

The power distribution network is designed to overcome high energy demands. POC1 and POC2 supply power to water treatment facility. Both the distribution sub-stations were initially powered solely from the zone sub-station rendering the process highly energy consuming. It was thought that a strategy must be devised for on-site production of power and its optimal usage. Keeping in line with the objective of this research, smart RTUs were designed for POC1 and POC2 so as to enable the bidirectional flow of electricity through intelligent intertripping and interlocking philosophy. With continuous improvement in renewable energy sources usage, the design of energy consumption should satisfy the principle 'generation following demand' as per future perspective.

The distribution network establishes three possibilities for the power flow which are described below.

1. If the generators produce more energy than the power required for operating water treatment plant then power is supplied from the plant generators to the zone sub-station via POC1 and POC2 through circuit breakers.
2. If the generators are not meeting the average demand of the water treatment plant then the zone sub-station delivers the additional power required to the POC1 and POC2 sub-stations.

3. The third possibility presents the condition when the on-site produced power is equal to the power required to drive the treatment plant. In that case, the power coming from zone sub-station is not used to operate the treatment facility.

It is evident that proper power intertripping and interlocking philosophies must exist between zone sub-station and site generators. Control, monitoring and system management are becoming decisive elements for power maintenance and to add efficiency and safety parameters for the distribution process. This monitoring and control philosophy shown in Figure 2.17. It is therefore strongly suggested to consider advanced management strategies for monitoring and control to protection on modern distribution schemes in order to achieve optimization. The available source capacity can be determined after tracking the source power.

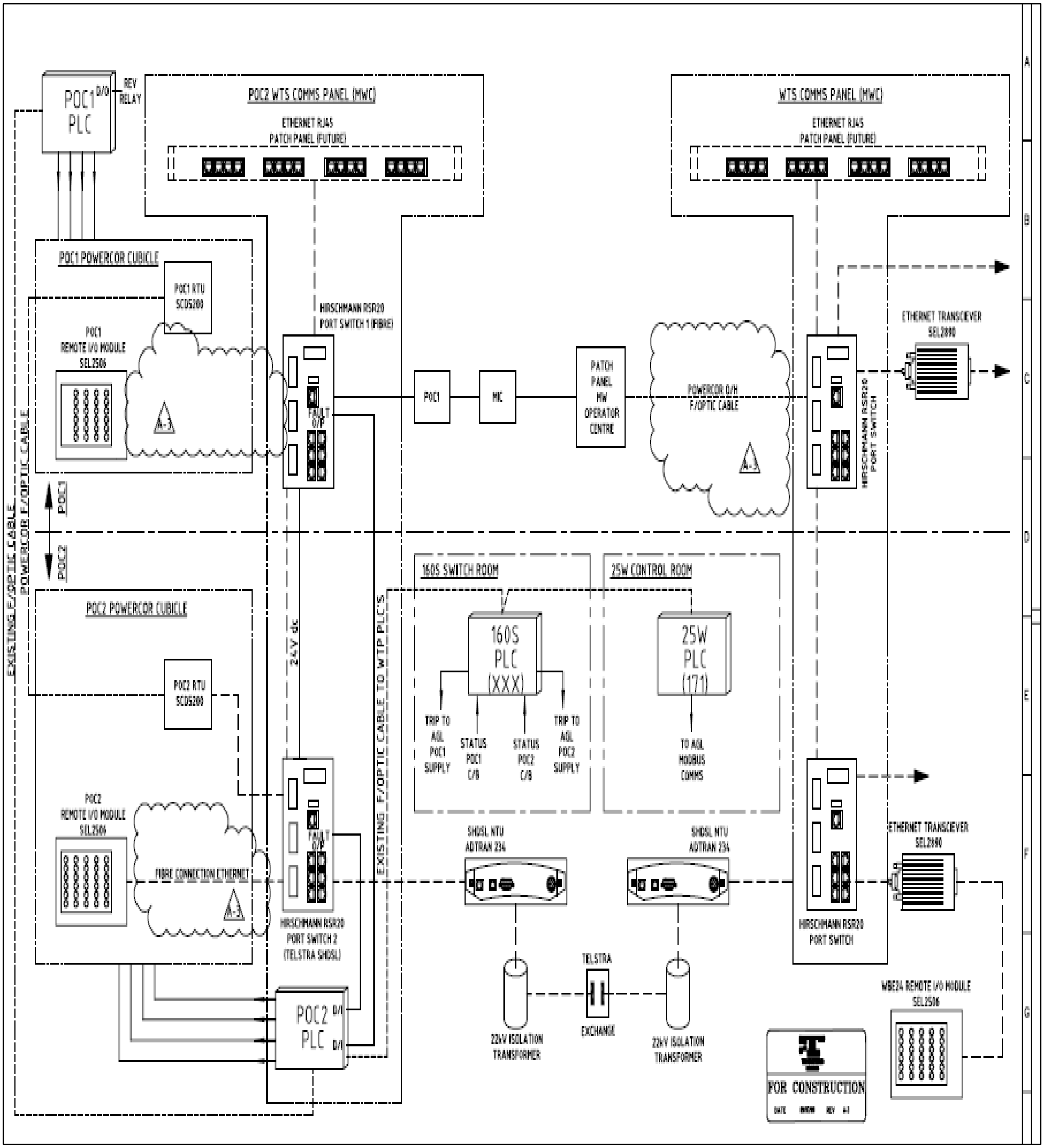


Figure 2.17 Network Arrangement for Control, Monitoring and System Management

2.6.2 General Arrangement of Distribution Substations

Figures 2.18 and 2.19 represent the equipment layout of POC1 and POC2 with front elevation. It elaborates on the telemetric functions communicating via PLC and other relays that are responsible for efficient RTU panel operation. Two modes namely sink mode and source mode define the connectivity between the I/O coming from the smart panel and I/O of the PLC. Hirschmann RSR-20 managed switch is specifically designed with consideration of industrial automation to show compliance with industry standards. The switch is capable of operating under severe surrounding conditions with reliable and long-lasting performance.

Residual current device (RCD) provides protection to deal with electrocution and power quality issues. These devices act as circuit breakers (CBs) enabling automatic circuit opening at the point of placement.

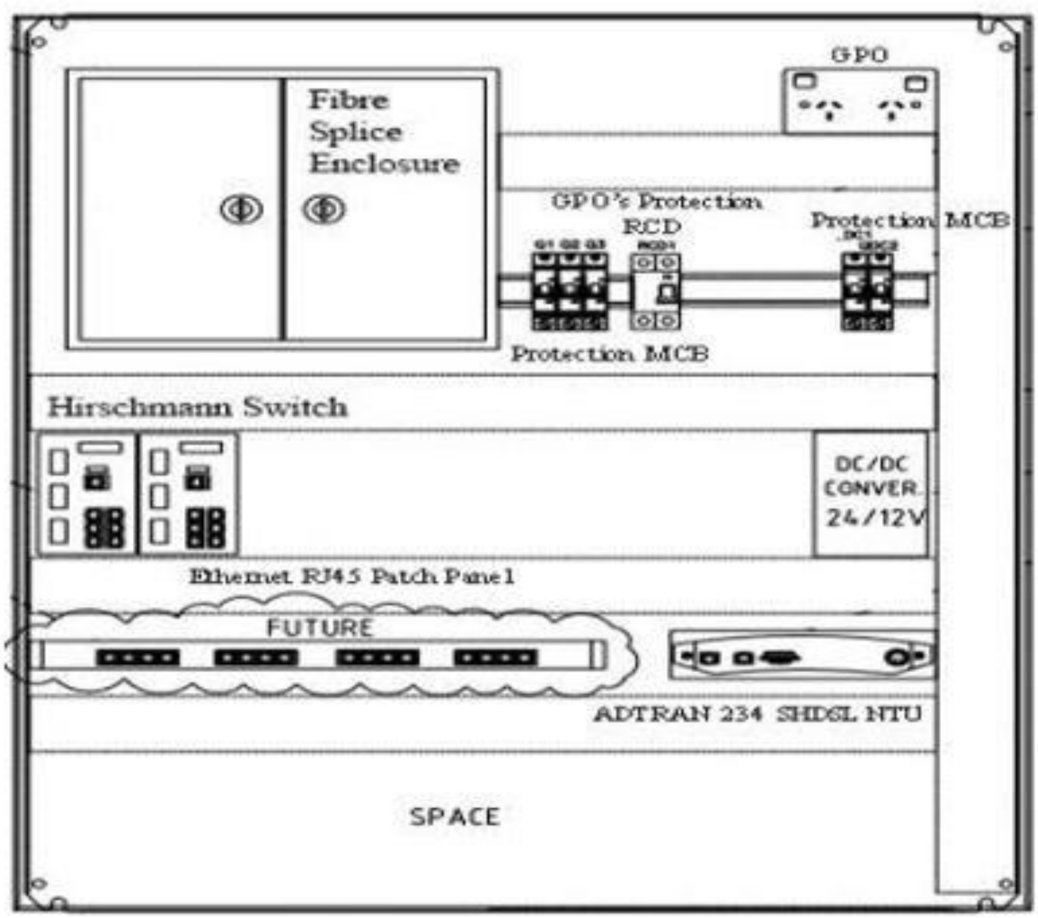


Figure 2.18 General Arrangement for PowerCOR RTU

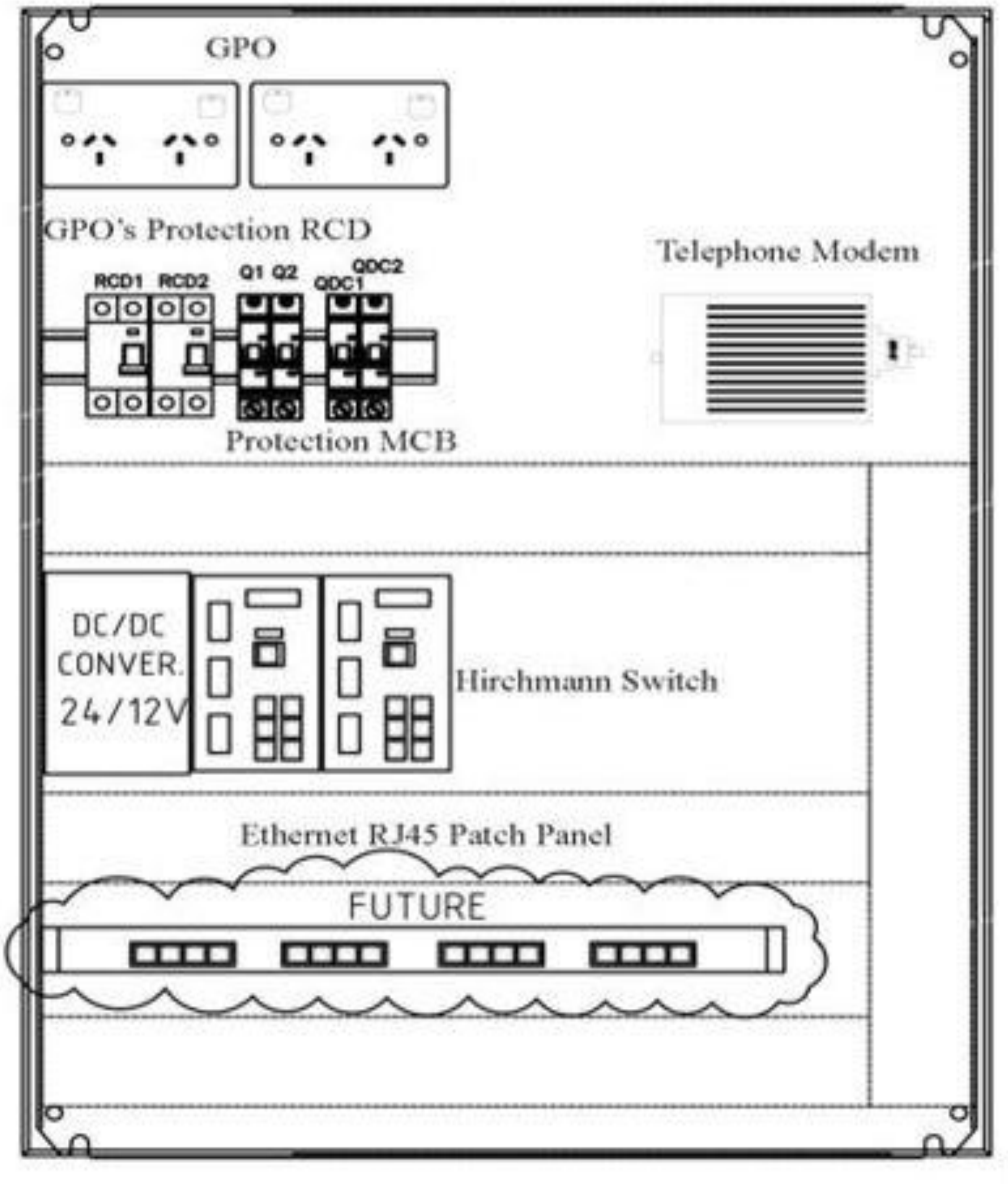


Figure 2.19 RTU POC1, General arrangement for POC1 RTU

Figures 2.20, 2.21 and 2.22 show general arrangement of PowerCor and its preliminary setup for PMS. When the residual current arising due to circuit failure crosses a specific threshold the POC2 has an additional component; a modem to create networking between equipment.

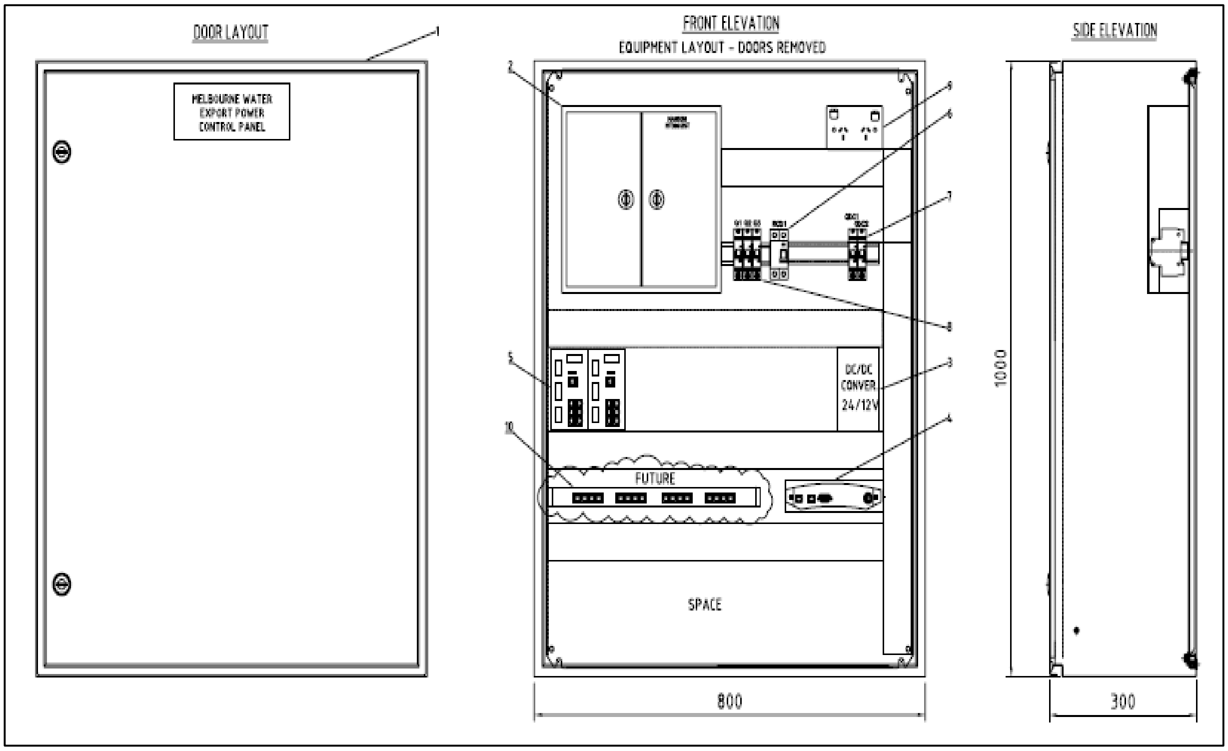


Figure 2.20 General Arrangement of POC2 RTU

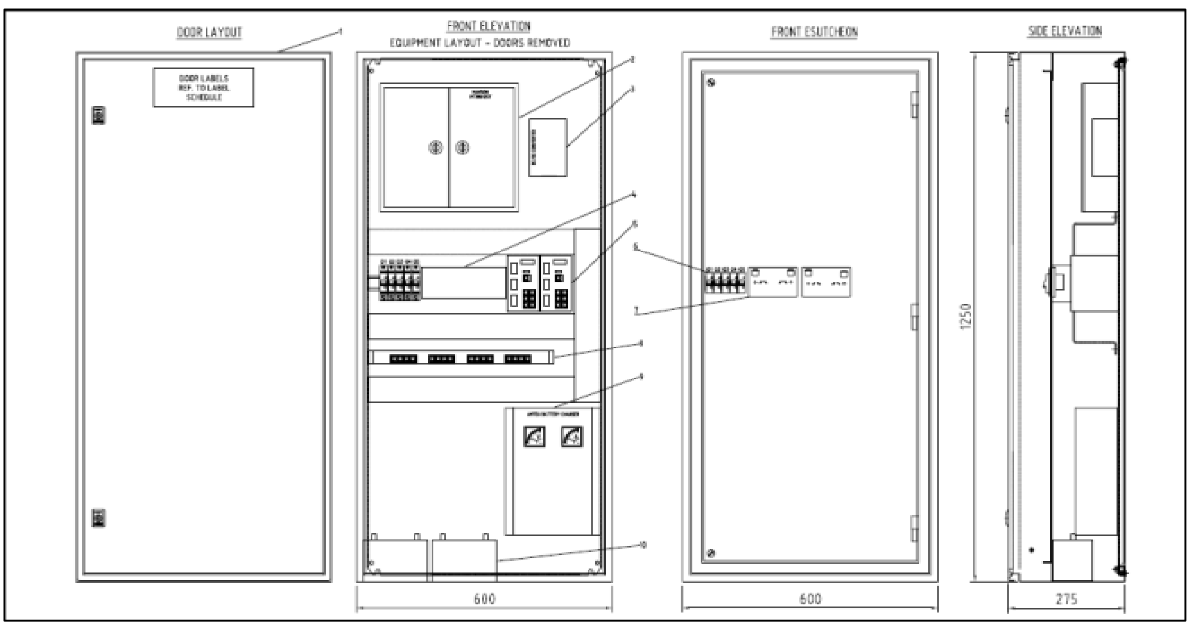


Figure 2.21 Preliminary Setup for POCn

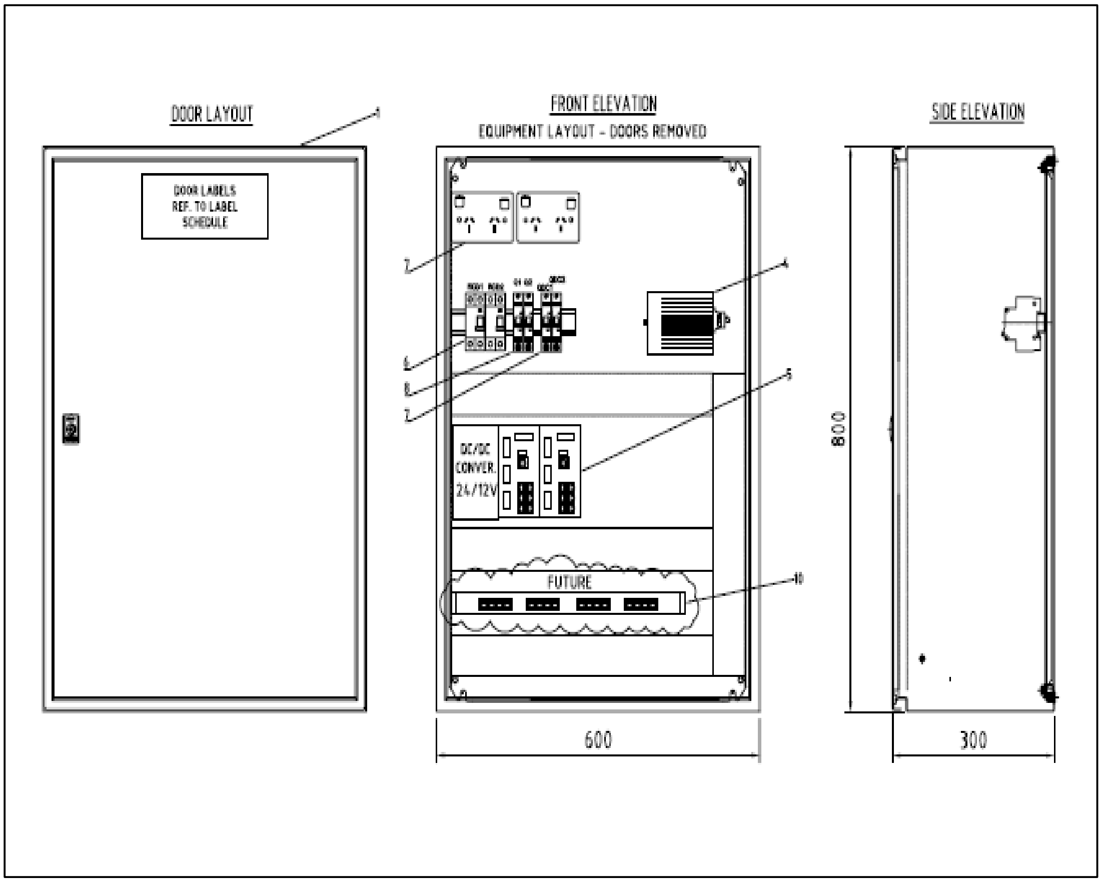


Figure 2.22 General Arrangement of typical RTU

The network Quality Of Service (QOS) is analysed to maintain signal integrity and efficiency. The telemetric signals from various field devices analyses the performance parameters through IEC standard defined transfer time functions and logics.

2.6.3 Smart Grid

The smart grid provides efficient control and power management with green electricity. Smart grid is a term used to describe the rapid infrastructure replacement of the electrical wiring system through smart devices [111]. The proposed SAS system provides advancement in technology by implementing a reliable power, control and monitoring system. This will also enable all communication features across the WWTP sub-stations, which is fail safe and redundant. These features do not exist in the existing or older infrastructure. Smart RTU enables a sub-station to be part of a smart grid with updated technology of green electricity generation and electrical distribution systems. The proposed system is capable to balance electrical loads of a WWTP and power generation using biogas produced in wastewater treatment in anaerobic digestion process.

One of the main features of smart grid is the capability to control load management system automatically through smart IDEs with modelled Smart RTU.

It can deliver power as per demand of the WWTP. The smart grid is adaptive, with less reliance on operators, particularly in responding rapidly to changing conditions, predictive in terms of applying operational data to equipment maintenance practices and even identifying potential outages before they occur, integrated in terms of real-time communications and control functions, optimized to maximize reliability, availability, efficiency and economic performance these factors make it most suitable as per future demand of a WWTP. Updated smart grid is designed to support large generation plants that serve faraway Wastewater plant sites via a transmission and distribution system that is essentially one-way. The proposed designed smart RTU enables a smart Grid that meets all the necessary protection, automation and communication protocols by enabling a two-way power flow system. The power generated by different sources is distributed with minimum losses. This research provides the philosophy to develop an efficient energy management methodology and a platform to utilize and modernize existing or older infrastructure. The necessity of considering energy management in a two-way power flow system is an innovation in supplying load to permit a more powerful penetration of renewable energy of wastewater usage. Smart grid enhances power generation with energy saving and reduces CO_2 emissions in the environment.

The smart metering and advanced communication factors enhance the current power distribution, and the benefits concerning smart grids. This research proposes an advanced power management system considering all parameters of WWTP substation, and the demand-side management and distributed on site control actions [112].

2.6.4 Overview of the Set up at Melbourne's Western WTP

The authorities of modern WWTPs face strong challenges over several issues. Necessary follow-ups are therefore mandatory to verify the expected performance of the systems. Through modifications done in the existing infrastructure of Melbourne Water Treatment Facility, smart RTUs and designed I/O philosophies were successfully implemented. The concept of cogeneration presented an economically feasible solution which not only addressed the electricity requirements of the treatment facility thereby reducing the costs associated but also implemented reverse power generation. The deployment of 8 generators at Melbourne' Water's treatment facility with a net generating capacity of 1.5 MW each, led to production of a total of 12 MW of power. Since the site's maximum electricity consumption is 8 MW, therefore 4 MW is produced in surplus which is fed back to the zone sub-station i.e. PowerCOR. With this research work, optimum usage of biogas produced at WTPs has been achieved through its efficient utilization to excite on-site generators and provision of a basis for control and monitoring philosophy which effectively feeds surplus power back to the supplier`s grid in different scenarios of biogas production. It also provides the level of protection and automation that achieves redundancy and a failsafe system for any biogas producing site such as race courses, dairy farms etc. Since this research can be applied to existing infrastructures and sub-stations, it therefore saves the cost of developing new infrastructures and decreases pressure on Operation and Maintenance (O&M) capital works budgets while providing same level of protection and reverse power generation. The redundancy and failsafe mechanism that the system ensures also increases on-site safety standards by minimizing operator`s interaction with the HV apparatus.

2.6.5 HV Reticulation

Figure 2.22 shows the HV reticulation mechanism applied to Melbourne’s Western WTP. The smart RTU philosophy installed is comparatively easy to implement and reduces the need for complex secondary wiring in the distribution sub-station(s) for attaining interlocking and intertripping and interlocking of power supply equipment. The figure describes the power flow from main feeder to the distribution sub-stations POC1 and POC2. The treatment plant utilizes self-generated power on first priority and the surplus power is passed through high frequency transformers to feed to the zone sub-station (PowerCOR) via POC1 and POC2. The intertripping and interlocking mechanism ensures that power can only be supplied through site generators when there is sufficient capability while the power coming from zone sub-station is being shut down and vice versa.
It should be noted that biogas yield evaluation is also a mandatory activity to ensure smooth power generation. The required functionality of all telemetric signals was achieved at Melbourne’s Western WTP. The proposed scheme of telemetric signals has ensured the stability of sub-station ring topology by providing an effective control and monitoring philosophy at varying relative biogas yields.

2.6.6 Schematics for HV and LV Reticulation

The Figure 2.23 below represents the HV and LV reticulation through HV/LV transformer and breaker terminology. As shown in

Figure 2.23 eight generators at Melbourne’s WTP feeds LV current to LV feeders of the plant’s distribution sub-stations (POC 11 and POC 2) and thus provides the power required for the plant’s operation. The excess supply of power is being fed back to zone sub-station through reverse power relay step up transformers.

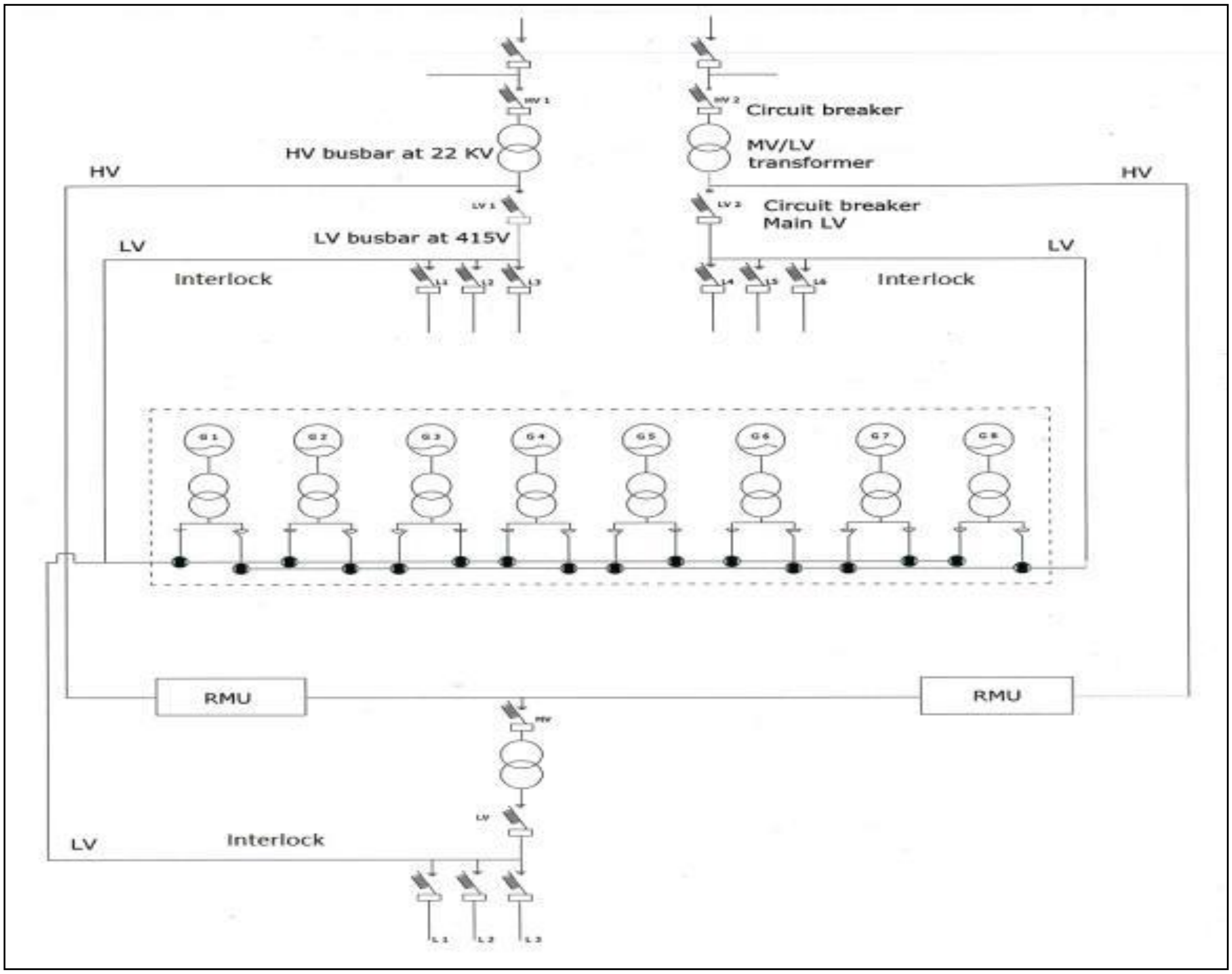


Figure 2.23 HV/LV Reticulation of the Main Panels Between POC1 and POC2

2.6.7 Bus Bar Protection

Figure 2.24 shows busbar protection characteristic curves. The bus bar protection is mandatory during the commissioning process. It is required that the feeder fault or transformer connected with busbar should not alter the busbar system. CTs are connected to the busbar systems to ensure protection in case of faults.

As shown in the graph, the busbar connected with Melbourne's Western WTP reduced the intertripping downtime up to 20% at POC1 and POC2 with increasing current magnitudes. The thermal overload protection relay shuts off the fault electrical current, thereby increasing the reliability of the sub-stations with RMU unit.

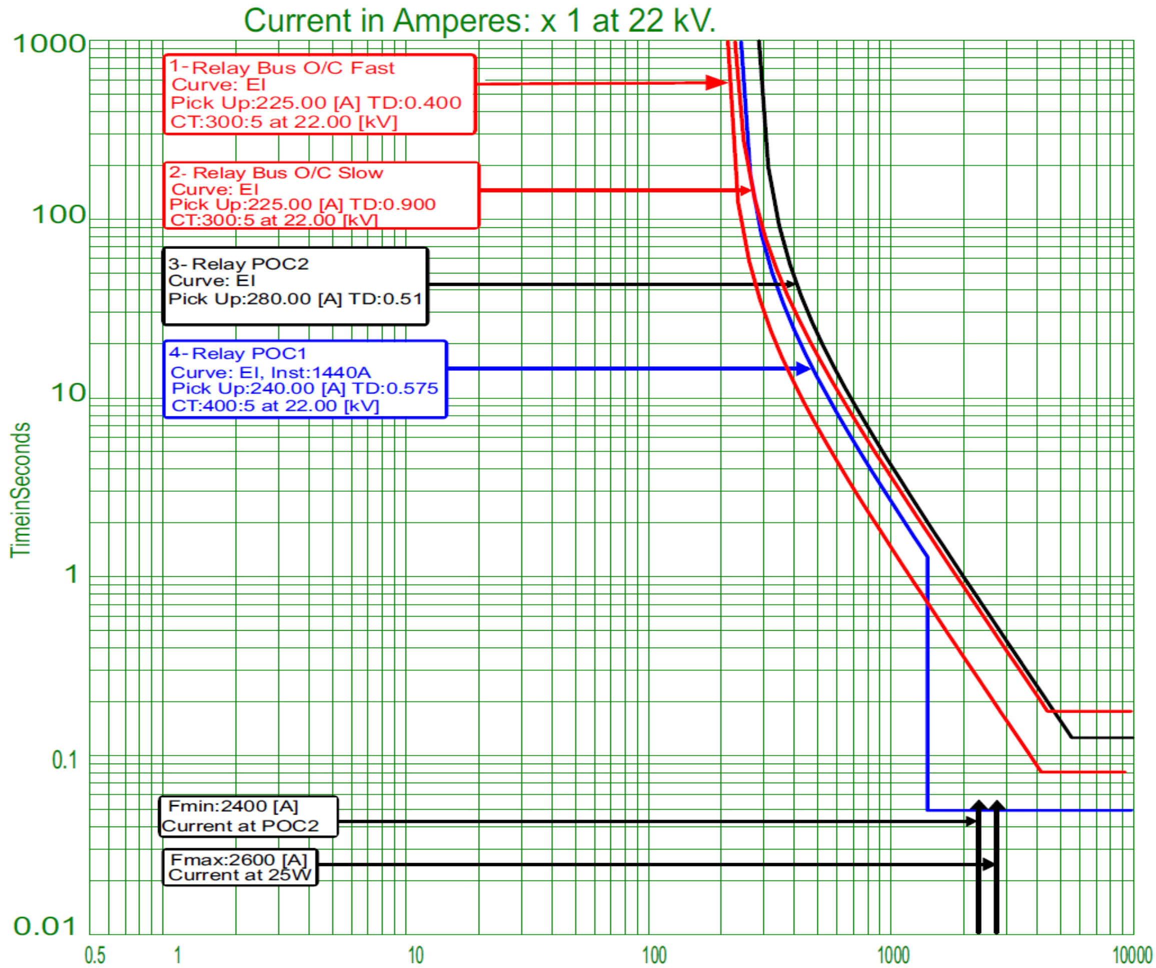


Figure 2.24 Busbar Protection Curves for the POC1 and POC2- For Relevant CB

2.7 CONTRIBUTION TO WATER AND POWER INDUSTRY

The proposed research is very important for water sustainability. All WWTPs are very energy intensive and they can cause enormous amount of load on the grids. The over whelming energy demand of the WWTPs id due to the heavy machinery involved in the process. This exploration encourages all water treatment plants to produce their own green energy with increased monitoring and control systems.

It only makes economic and environmental sense to implement this renewable model into the existing WWTPs. In this way, this proposed extra layer of protection will ensure compliance to the relevant IEC and IEEE standards. The positive aspects of sub-station automation system (SAS) implements advanced power administration, repetitive and adaptable arrangements while considering water treatment requirements. The exploration likewise ensures ideal utilization of biogas created.

2.7.1 HV/LV Redundancy

The research not only provides a mechanism to accomplish HV/LV access for a water treatment plant but it also executes multiple layers of security to the plant hardware by commissioning interlocking and intertripping and interlocking and activation of ring topologies between the power produced and the request stack.

2.7.2 Plant Operation and Maintenance

With the execution of electrical boards and the topologies discussed in this research, the necessity to close down the plant amid capital work or system up-gradation has been minimized. The methodology encourages disengagement of the plant section where the works are being done without influencing the entire water treatment processes and activities. This lessens the load on O&M assets minimizing the costs utilized on system maintenance.

2.7.3 Fail Safe, Redundancy and Reliable Power Flow

The proposed philosophy has been rehearsed and found reliable for interlocking methods giving a dependable and repetitive power supply a any biogas generating site. The philosophy guarantees a ceaseless stream of dark water at the treatment destinations and a successful method for checking and controlling force supplies.

2.7.4 Renewable Energy Benefits

Biogas being one of the important renewable resource assets compensates the energy intensive treatment operation and supports innovations. The ideal utilization of anaerobic processing increases the capacity of waste treatment and creation of power through biogas. This research looks into a modified and advanced arrangement of distributed power system from a renewable resource that needs to be integrated into the existing infrastructure. It will urge the stakeholders to adopt renewable resources as their primary source of energy, that are available on site, to get the most value for the money by optimal utilization of the processes involved.

2.7.5 Environmental Benefits

The environmental benefits of the process are the efficient utilization of biogas produced which was otherwise released in the environment, not only polluting it but also was a wastage of this important resource. The process of biogas generation itself is the conversion of wastes item into a profitable resource. This consistent treatment of wastewater brings about appropriate asset administration. The research provides an approach which limits natural dangers by giving environment friendly energy generation to water treatment plant and the power zone.

2.7.6 Health and Safety Benefits

Many cases appear due to electric risks faced by the operators and electricity personnel. The conceivable outcomes of electrical dangers faced by engineers, circuit testers, control line labours and related staff to electric stun, electric shock, wounds, and blasts are enormously decreased because of safeguard, access, and dependable execution. HV administrator assignments are limited to keep away from dangers, and manual reliance as the usage is consistent with electrical wellbeing principles.

2.7.7 Operational Benefits

The RTU boards give access and safeguard to operations and maintenance of water treatment plants. The cogeneration guarantees that the plant operations are not dependent alone on biogas or the energy originating from power conveyance organizations. The usage of this examination on destinations will lessen the need for HV and LV administrators to frequently contact the electrical departments or zone power stations.

2.7.8 Financial Benefits

The expansion of savvy board turns out to be a viable substitute to address the requirements of treatment plant operations thus reducing the establishment, substitution and stock costs respectively. The budgetary evaluation demonstrates that charging and tax assessment costs partnered with power conveyance organizations are promptly limited with the on location power era while using biogas.

2.7.9 Reliability of Communication System

It is important to have a dependable communication network which is designed according to the plant requirements. The proposed smart RTU panels and the corresponding communication network provide a potential free point to the system. The panels provide the system experts with the opportunity to deal with locking capacities on location with a safeguarded correspondence arrangement.

2.7.10 Asset Management

Water treatment facilitates are made up of assets which are key to the treatment process and which age overtime. The quality of treatment is also compromised which affects biogas generation and consequent production of energy. With the proposed automation and networking philosophies, the life span of assets would increase and hence operational and maintenance costs would reduce.

2.7.11 Energy Management

With this energy optimization process, the WWTPs can also gain a lot of benefits through management and optimization of energy used to operate the plant. This depends on the size of the plant and the optimization mechanisms of the plant owners.

2.7.12 Reduction in Labour Requirements

Wastewater treatment being operated automatically and unattended will also benefit the facility service providers by reducing labour requirements and thus saving labour costs.

2.7.13 Reduced Travel Time

Interconnectivity of the system with SCADA would also reduce the travel time of the personnel to remote parts of the treatment plant as the data could be remotely achieved from the network system implemented.

2.7.14 Room for System Up-Gradation

The existing systems with the proposed RTU interface and SCADA linking can also provide more room for the future up-gradation and expansion of the treatment facility because this methodology is applied to existing infrastructure and does not require heavy investments for a new plant design. Thus, in short, with the additional RTU panel, I/Os have been implemented as per the designed philosophies. This redundant, failsafe and reliable solution is subject to the fact that the treatment process is constant and that the excessive energy produced through on-site biogas generation must be fed to the power distribution company as part of an asset management procedure. The successful results of communication assessment obtained shows that the designed I/Os, smart RTU panel and their connectivity have enhanced the capacity of the sub-stations. I/Os are provided through a potential free point so that these could be easily communicated to HMI through the smart panels. The HV operator could observe the HV feeding process without being physically present at the sub-station which serves to reduce the operator’s tasks. Thus, the proposed smart RTU methodology provides an innovative solution for enhanced energy efficiency and productivity of the existing network/ infrastructure whilst complying with IEC 61850-8 standards. The research therefore provides a failsafe and redundant communication solution for telemetric I/Os decreasing the probability communication network failure for power equipment.

Even if the network fails in a worst-case scenario, a level of protection is provided to the equipment till the problem is resolved. This research shows the potential of anaerobic digestion for WWTP. Biogas production has successfully addressed the energy intensive demand and has made electricity cogeneration economically viable. Implementing smart RTUs and improving the mapping philosophy of telemetric signals functionality have considerably enhanced the safety of existing WWTPs equipment during cogeneration. This has effectively added to the required communication between the zone and distribution substations, which the old/existing infrastructure lacked. Not only HV/LV redundancy was achieved, but also different layers of OSI protection were added to the WWTP through an automated intertripping and interlocking mechanism. This system also ensured a failsafe and reliable multidirectional power flow with minimum losses. Sections of WWTP requiring maintenance or upgrade works can be isolated without affecting power supplies to other segments of the plant.

This research concludes that the existing power infrastructure at WWTPs requires an advanced and reliable communication network, which should transmit telemetric signals from distant nodes to a control centre and vice versa, in a timely and efficient manner. Network modification and upgradation is required to meet relevant IEC/IEEE WWTPs electricity cogeneration standards. The proposed smart RTUs implemented at MW-WTP POCs provide the perfect platform to achieve an isolated point that can be replicated in existing infrastructures without any major upgrades and investments to the switchgears or substations.

The existing power infrastructure at WWTPs requires smart grid for reliable power generation and communication network, which distributes electricity with maximum real power generated. Relay coordination with smart RTUs enables effective power management, fast fault identification and clearances, electricity trigeneration and environmental solutions. The proposed smart RTU panels implemented at MW-WTP POC provide a potential-free point, which can be replicated in existing infrastructure without any heavy investments. Smart RTUs relay coordination enhances equipment protection systems, efficiency, reliability and control on intertripping and interlocking functions of WWTP from a centralised location. This enables a failsafe and redundant WWTP communication network with increased OH&S standards.

CHAPTER 3: DESIGNING SMART RTU FOR ELECTRICITY COGENERATION AT WWTP

3.1 INTRODUCTION

Water is the main resource that plays a significant and predominant role in the existence of life on earth. It is also an important source of electrical energy. With the ever-increasing population and immense pressure on existing water resources, there is a universal realisation towards innovating new sources of energy and its conservation. Electrical engineers are working towards achieving sustainable solutions for enhancing energy production and efficiency methods by integrating renewable energy for daily usage. WWTPs consume high amounts of energy. The energy consumption in the USA for the movement and treatment of water and wastewater has been estimated to be 3% to 4% of the total electricity consumption [113]. The existing and old WWTP infrastructure lacks certain important features like monitoring, controlling, equipment protection and power supply redundancy that could enhance energy efficiency and optimally utilise the biofuels formed in the treatment process. Implementing proper control and modelling philosophies with the help of smart RTUs at WWTPs and power company`s zone substations of the existing power distribution network can address the issue of extensive energy utilisation.

This paper aims to address these features by proposing a technology driven approach to optimise WWTP electricity cogeneration on existing infrastructure by enhancing protection, monitoring and control levels for smart metering and two-way power flow between the grids and WWTPs or, any site where biogas or any other renewable energy resource is available. Typical arrangement for cogeneration at a WWTP in ring topology is shown in the power flowchart of Figure 3.1. Biogas is produced and then utilised to excite on-site generators with controlled two-way power flow between distribution and zone substations.

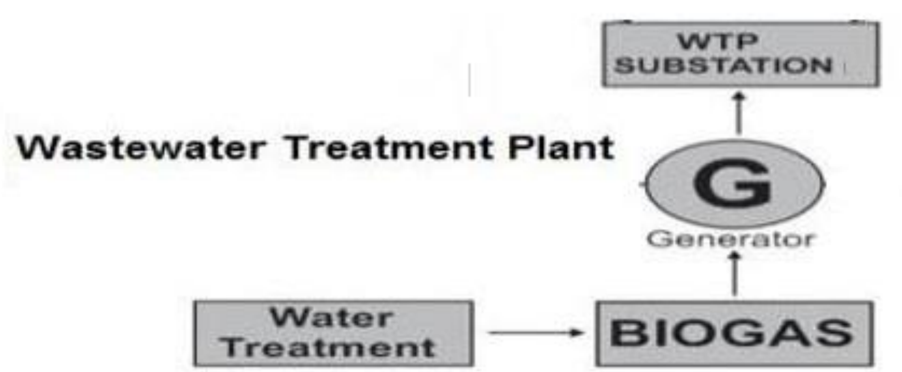


Figure 3.1 Typical Arrangement for Electricity Cogeneration at WWTP

3.2 SLUDGE AND BIOGAS PRODUCTION

The four defined basic levels involved in wastewater treatment are shown in Figure 3.2. which has been elaborated in chapter 2, article number 2.2. The tertiary treatment level is where the sludge is produced. Waste Activated Sludge (WAS) process offers efficient removal of Chemical O_2 Demand (COD) for biogas production [114].

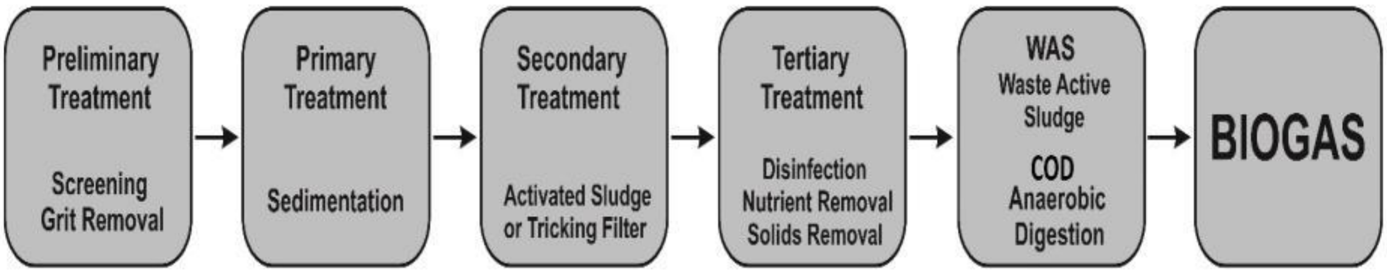


Figure 3.2 Sludge and biogas production

Mathematical model for biodegradable fraction of WAS [115] is represented in equation (3.1).

$$X = X_{active} + X_{active}(1 - f_d)K_d^{AS}SRT^{AS}$$
$$f_d^{WAS} = f_d \frac{X_{active}}{X} \qquad (3.1)$$

Where;
f_d^{WAS} = biodegradable function of WAS
X_{active}, X = total concentration of the volatile suspended solid(kg/m^3)
f_d = net biodegradable fraction of active biomass
K_d^{AS} = decay coefficient in the active sludge (day^{-1})
SRT^{AS} = solid retenion time applied in the active sludge process (day)

WAS has a high spoilable organic matter content, which is treated to ensure its stability and utilisation to full capacity before disposal. Two well-known digestion methods that serve this conversion are aerobic and anaerobic digestion.

3.3 BIOGAS PRODUCTION

3.3.1 Aerobic Digestion: Aerobic digestion uses O_2 to decompose organic contents produced in the presence of bacteria. The process is based on endogenous respiration where microorganisms start digesting their own protoplasm to gain energy and create "Flock", which is in the form of stable sludge that settles down at the bottom of huge ponds and can be disposed of easily.

3.3.2 Anaerobic Digestion*:* Anaerobic digestion involves series of biological processes where degradation of organic content takes place in the absence of O_2 to produce biogas and biofertilisers. A Methanogen bacterium produces biogas (methane) through anaerobic reparation [114, 115]. The generated biogas acts as a fuel for production of electrical energy through on-site generators. Figure 3.3 explains the type of gas produced during aerobic and anaerobic digestion. Biological process in WAS converts sludge into COD, which is a substrate utilised by the anaerobic digesters.

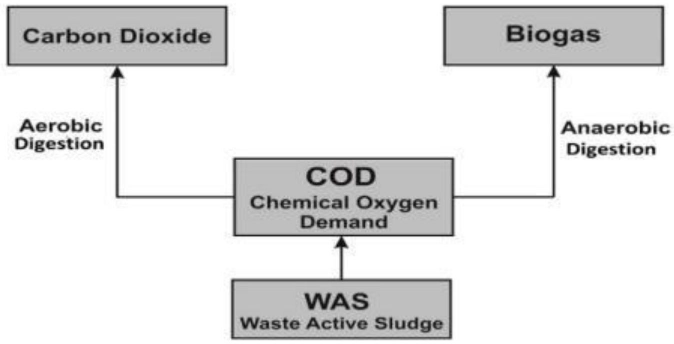


Figure 3.3 Aerobic and Anaerobic Digestion

3.3.3 Mathematical Modelling for Biogas Production

The amount of biogas produced [116] can be calculated by equation (3.2).

$$s_o = COD_{in} f_d \left(\frac{X_{biod}}{X}\right)$$

$$specific\ gas\ production\ (SGP) = 0.23e^{-0.028SRT} \tag{3.2}$$

Where;

$\mathrm{s_o}$ = substrate influent ($\mathrm{kg/m^3}$)

$\mathrm{COD_{in}}$ = Chemical oxygen demand ($\mathrm{kg/m^3}$)

$\mathrm{X_{active}}$, X = total concentration of the volatile suspended solid($\mathrm{kg/m^3}$)
$\mathrm{f_d}$ = net biodegradable fraction of active biomass
SRT = Solid retenion time (day)
specific gas production = ($\mathrm{m^3/day}$, $\mathrm{V_s}$) , $\mathrm{V_s}$ volatile substrate influent feed

Through multiple microbial reactions, different products are being synthesised at the prior stages of water treatment process. This acts as substrate for microorganisms in the next stage. One-stage nonlinear reaction modelling for anaerobic digestion [117] is shown in equation (3.3).

$$Q = K_2 \, \mu \, S \tag{3.3}$$

Where;

$Q = biomass\ flow\ rate\ (day^{-1})$

$K_2 = yield\ \ coefficient$

$\mu\ = Specific\ growth\ rate(C^0/day)$

$S = Substrate\ (acetate) concentration\ (gl^{-1})$

Biological kinetic equations (3.4) and (3.5) shows microbial growth and substrate consumption rate [118.119].

A) Grau et al kinetic model

$$S = \frac{S_o(1 + bt_{SRT})}{\mu_{max} t_{SRT}}$$

$$-\frac{dS}{dt} = \frac{\mu_{max} XS}{YS_o} \tag{3.4}$$

B) Monod kinetic Model

$$S = \frac{K_s\ (1 + bt_{SRT})}{t_{SRT}(\mu_{max} - b) - 1}$$

$$-\frac{dS}{dt} = \frac{\mu_{max} XS}{Y(K_s+S)} \tag{3.5}$$

Where;

μ_{max} = maximum specific growth rate coefficent

X = micoorganism concentration (gl^{-1})

b = specific microorganism decay rate (day^{-1})

y = growth yeild coefficent

S_o , S = concentration of the growth limiting substrate in the influent and effluent (gl^{-1})

t_{SRT} = solid retention time (day^{-1})

K_s = half saturation coefficient

K_{max} = maximum specific substrate use rate (day^{-1})

Equation (3.2) indicates that biodegraded substrate in the anaerobic digestion process is time dependent. Equation (3.3) shows that the production of biogas varies with temperature. Equation (3.4) and (3.5) states that production of biogas depends on the amount of substrate produced. Hence, three main factors directly effecting the WWTP biogas production through anaerobic digestion process are time, temperature and the amount of substrate produced, which needs to be taken in.to account while designing an efficient WWTP and its electricity cogeneration process.

3.4 CHP PROCESS AND ELECTRICITY GENERATION

Anaerobic digestion in biosolid digesters section produces maximum amount of methane gas through combined heat and power (CHP) process. The sequential treatment flow process is shown in Figure 3.4 Flammable gases formed are burnt to produce sufficient amount of steam, which is further utilised to excite on-site generators for electricity generation [120].

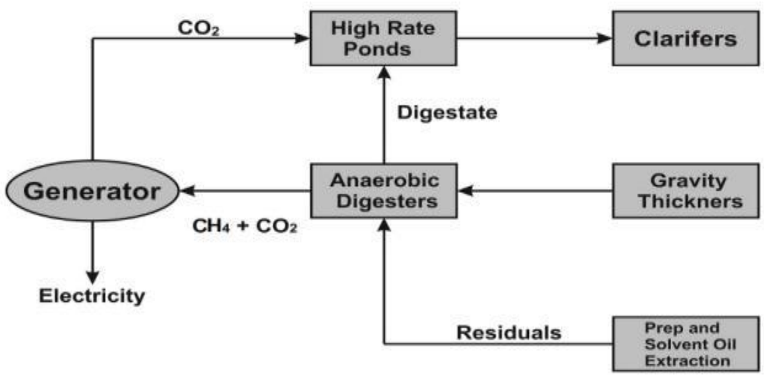


Figure 3.4 CHP Process and Power Generation

Biogas is captured and utilised for on-site electricity generation through an internal combustion turbine, while the heat generated during the process is used for increasing temperature of anaerobic digesters, especially in the winter, as higher temperatures favour this process. Electricity generation with waste heat usage is the CHP process, as shown in Figure 3.5. This is the most efficient way to generate electricity at WWTPs. Heat required for CHP process is shown in equation (3.6) and clearly indicates its dependency on digester temperatures and WAS [121].

$$Q_{start} = cm\Delta Tt + Q_{lost} \tag{3.6}$$

Where;

Q_{start} = Heat need to start anerobic process (kWh)

c = Heat capcity of feedstock (kWh/t/ h)

m = mass flow t/h

ΔT = change in feedstock temperature, before and after feeding into digester

Q_{lost} = heat losses through digester surface (kWh)

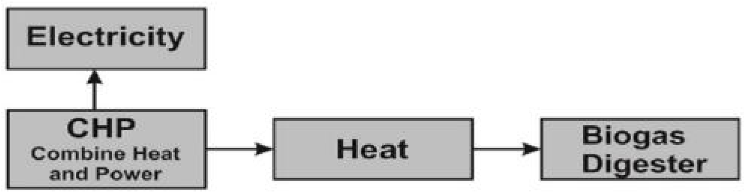


Figure 3.5 Heat Flow in CHP Systems

CHP process provides sustainable means of power generation thus fulfilling the energy intensive requirements of the water treatment process. Equation (3.7) presents power generation model using biogas [122] and indicates that power cogeneration system depends on the production of biogas and is directly proportional to each other.

$$m_{biogas} = f_d^{WAS} \times Y$$

$$MW = m_{biogas} \times y \times S \times \rho_{CH_4} \times LHV_{biogas} \times 1.165 \times 10^{-5} \times \eta_{el} \quad (3.7)$$

Where;

m_{biogas} = mass florate of biogas (m^3/h)

f_d^{WAS} = biodegradable function of WAS
Y = biogas flow rate m^3/h
m_{biogas} = mass flow rate of biogas (m^3/h)
y = biogas yeild (m^3/kg)
S = methane fraction

ρ_{CH_4} = density of methane (tons/m^3)

LHV_{biogas} = lower heating value of biogas (MJ/kg)

η_{el} = Efficiency in percentage

The calculation of total system efficiency that evaluates power cogeneration with consumed energy [123] is given by equation (3.8).

$$\eta_o = \frac{W_E + \Sigma Q_{therm}}{Q_{fuel}} \tag{3.8}$$

Where;

$\eta_o = total\ system\ efficency$

$W_E = electrical\ output\ \ (Watts)$

$Q_{them} = thermal\ energy\ output\ joules\ per\ second\ (heat\ transfer\ rate\ Watts)$

$Q_{fuel} = fuel\ consumption\ Joules\ per\ second\ (energy\ tranfer\ rate\ is\ Watts)$

Figure 3.6 evaluations taken through statistical calculations of conventional and CHP power systems at various WWTPs [124].

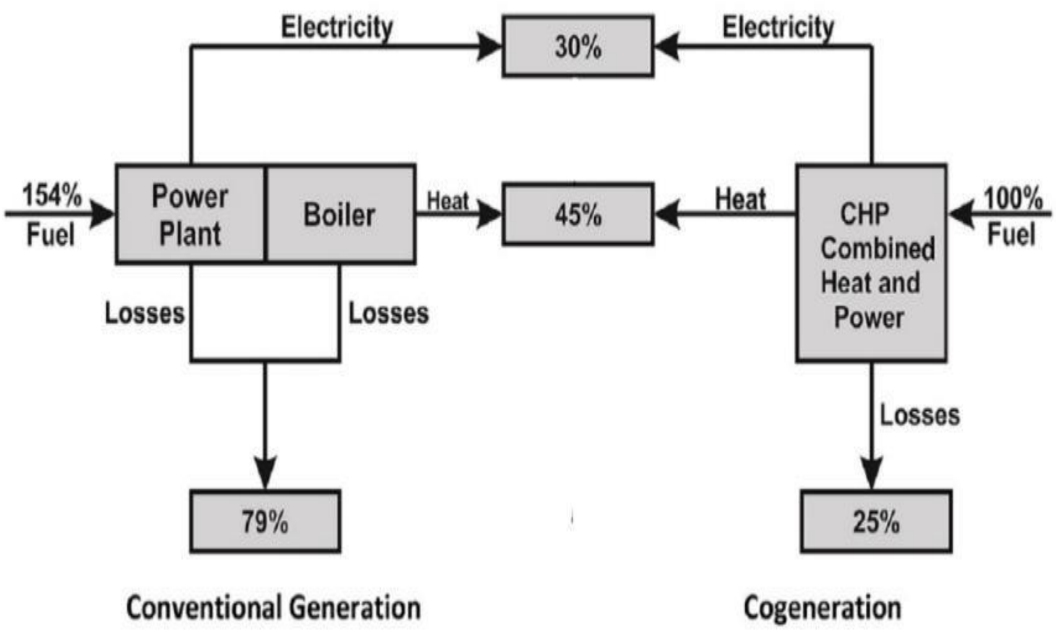


Figure 3.6 CHP System Efficiency

3.5 PROBLEM STATEMENT

3.5.1 Variations in Biogas and Scenarios for Electricity Cogeneration

Dependency of WWTP electricity generation on biogas production develops three different scenarios of electricity cogeneration:

A) WWTP Power Generation < Demand Load
B) WWTP Power Generation = Demand Load

C) WWTP Power Generation > Demand Load

Therefore, WWTP requires a robust automated system to manage these scenarios that also provides a systematic and layered protective system to the sub-station equipment. Simulation results at MW-WTP show that the production of biogas is not consistent with time and temperature in Figure 3.7.

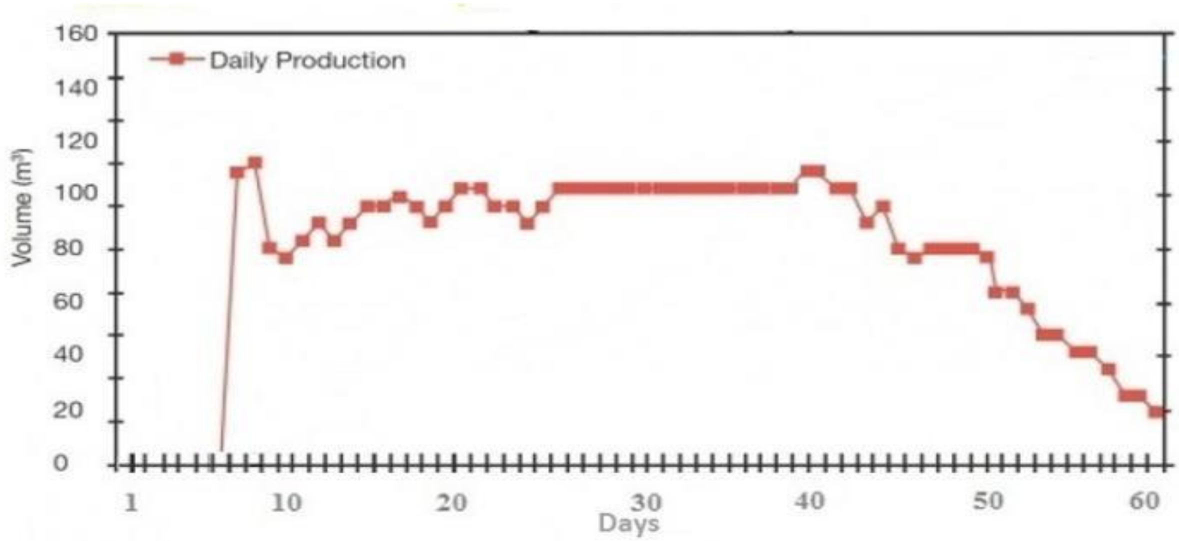


Figure 3.7 Daily Production of Biogas

In Figure 3.8 simulation data have been presented at 25 ^{0}C temperatures for anaerobic digestion process at MW-WTP. Results show that high temperatures favour anaerobic digestion and relative biogas yield increases with the increase in temperature and stabilises after reaching its peak value [125].

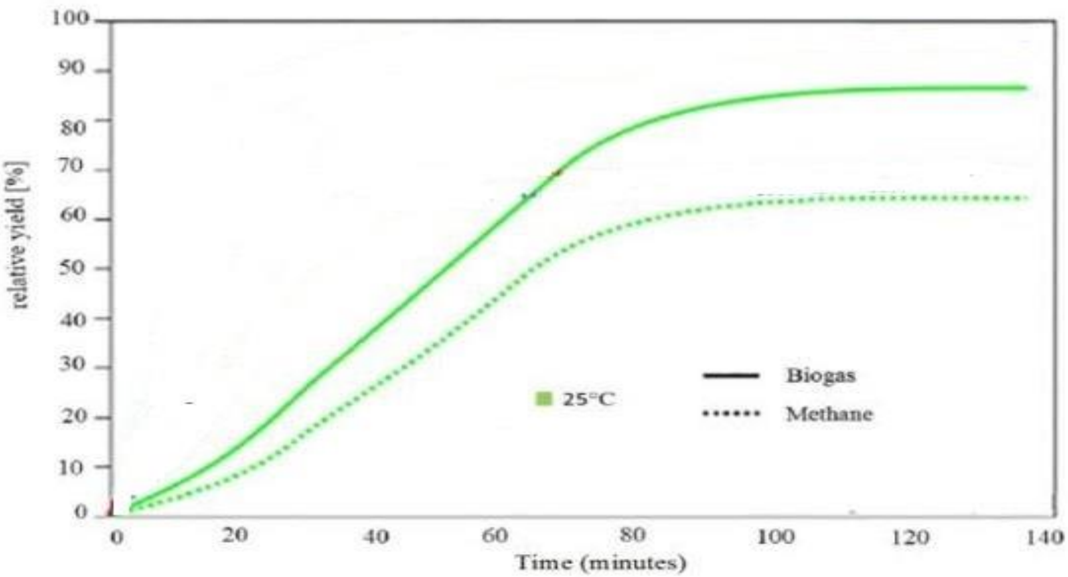


Figure 3.8 Relative Biogas and Methane Yields for at 25 ^{0}C Temperatures at MW-WTP

3.5.2 Existing and Old WWTP Infrastructure

Varying amount of biogas production reduces efficiency of existing WWTP infrastructure due to an inefficient communication network system and lack of a protection coordination, centralised metering and monitoring system during electricity generation process, which provides interlocking and intertripping mechanism with the power company`s zone substation. Complex secondary designs like telemetric signals, protective relaying and control gear monitoring needs to be reduced for implementing a flexible infrastructure with adequate redundancy [125, 124].

3.5.3 Power Management Issues

Water treatment is an energy intensive process that puts an enormous amount of load on the power company`s grid, making it very expensive. Existing WWTPs require alteration and upgrades to reduce this excessive load. Figure 3.9 shows power demand load at different levels of water treatment process at Melbourne Water Western Treatment Plant (MW-WTP) in Australia, which is the largest treatment facility in the Southern Hemisphere. It is clearly noted that the demand is very high, especially during the preliminary phase. It requires an automated, failsafe and redundant way for WWTP electricity cogeneration. Existing MW-WTP substations have no proper system to supply surplus generated electricity to the power company`s grid [125].

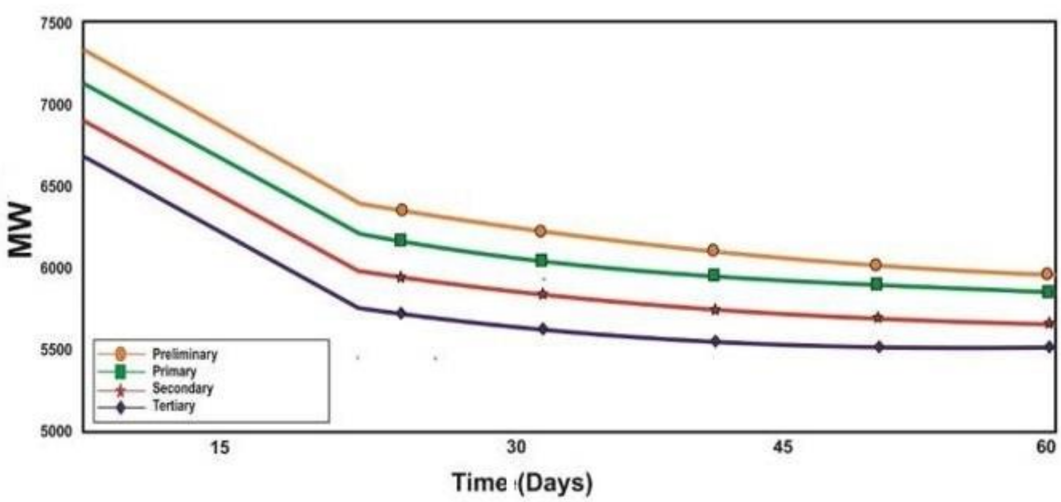


Figure 3.9 Demand Load for Water Treatment Process Levels at MW-WTP

Figure 3.10 shows average demand load versus power generation at MW-WTP existing infrastructure. Simulation results show that power demand is mostly higher than its generation because of an inefficient power management system (PMS) at MW-WTP. This generated electricity needs to be managed properly. It requires a failsafe monitoring and controlling system to effectively utilise WWTP biogas production to its maximum efficiency. WWTPs should be able to generate enough electricity through heat and waste energy to meet its own demand and, under ideal conditions, also be able to do reverse power generation.

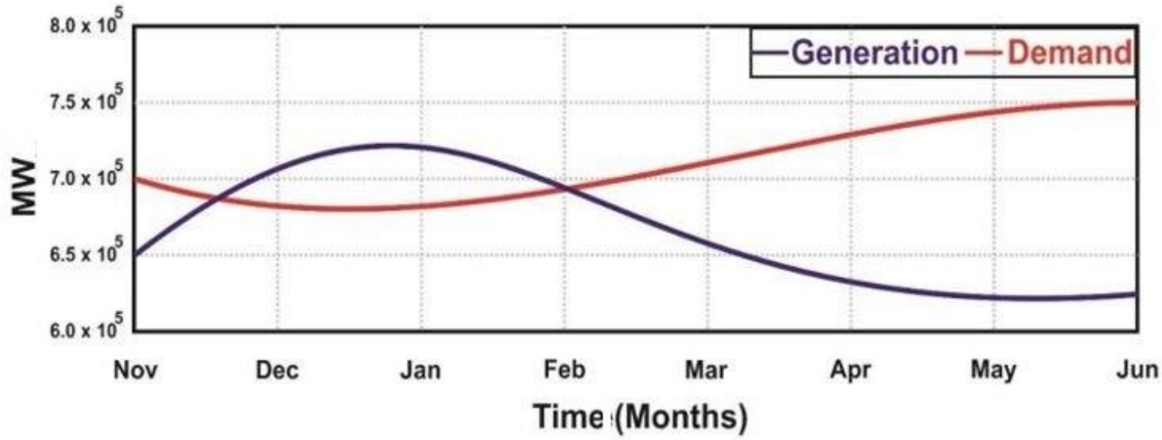


Figure 3.10 Existing MW-WTP Demand Load vs Power Generated

3.5.4 Intertripping Downtime

Efficient interlocking and intertripping philosophy between the WWTP and power company`s zone substations is required to handle different volumes of biogas produced for electricity cogeneration and abrupt variations. Intertripping downtime must be reduced for a swift and reliable operational control on WWTP equipment to achieve electricity cogeneration. Traditional secondary wiring of protection relays takes more than the required time to perform intertripping under faults and are extremely unreliable [126]. A philosophy must developed to implement HV/LV interlocking of supplies to achieve redundancy, which existing WWTP infrastructure doesn`t offer.

3.5.5 Occupational Health and Safety (OH&S) Issues

Manual operator tasks in the existing WWTPs during HV switching for maintenance shutdowns and power outages serve to increase risks. Physical interaction with HV equipment needs to be minimised during the complex task of electricity cogeneration [127].

3.5.6 Environmental Issues

Greenhouse gases (GHG) produced during the water treatment and electricity cogeneration process must be prevented to enter into the atmosphere to reduce environmental footprints of WWTPs. Existing infrastructure creates a bad impact on the odour and quality of the atmosphere. A redundant process is, therefore, required that can constantly monitor, control and utilise the biogas and produced heat [128].

Results in Figure 3.11 show that the existing MW-WTP emits 80,000 tonnes GHG per year (approx.) into the atmosphere, which can be reduced by more than 30,000 tonnes by implementing proper electricity cogeneration and management model.

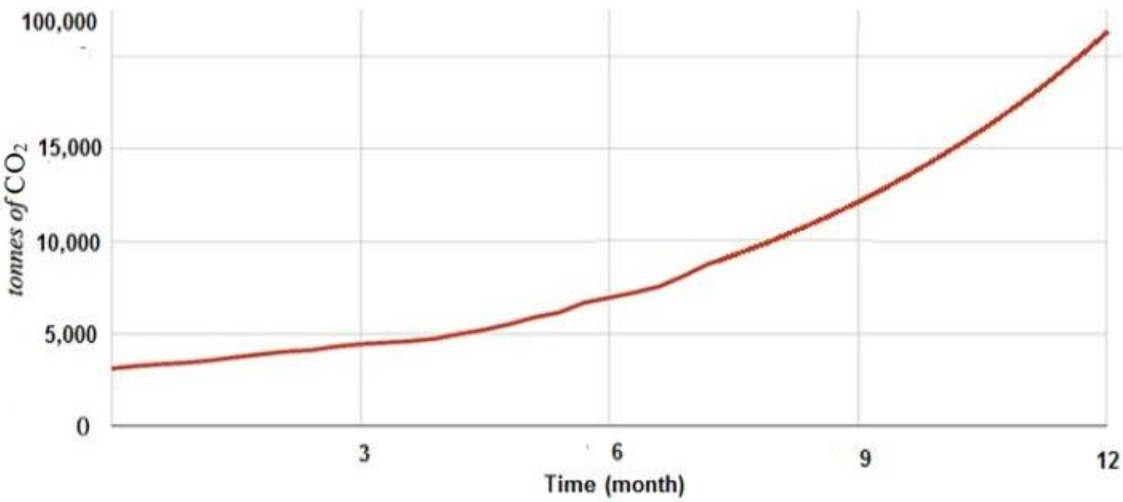


Figure 3.11 GHG for the Existing MW-WTP

3.5.7 Asset Management Issues

Making existing WWTPs energy efficient and sustainable has been an expensive and challenging task for the stakeholders and asset managers. Replacing substations, synchronising new systems with existing or old systems, WWTP maintenance, shutdowns and power outages put enormous burden on the budgets and profitability. Hence, an affordable system is required, which is easy to implement and maintain, to achieve electricity cogeneration and energy sustainability at existing WWTPs.

3.6 DEVELOPMENT OF PHILOSOPHIES

3.6.1 IEC and IEEE Standards Implementation

IEC61850 standard explains the model for accounting configuration of sub-station networks covering protection and control devices along with their connections. It also defines monitoring topologies utilising sub-station configuration language (SCL) for SAS. IEC61850-8-1 protocol uses object-oriented configurations for reliable remote operation. IEC61850-9 standard is compatible for conventional and modern CT/VT with converging devices [129]. IEC61850 with IEEEC37.238 performs reliable intertripping and interlocking of power supplies. Second and third layers of open system interconnection (OSI) provide protection and reliable control. The smart RTU philosophy should incorporate all these standards for a safe and successful WWTP electricity cogeneration. Figure 3.12 shows four OSI layers of protection used in the proposed philosophy for this research project. Smart RTUs are implemented in the second layer.

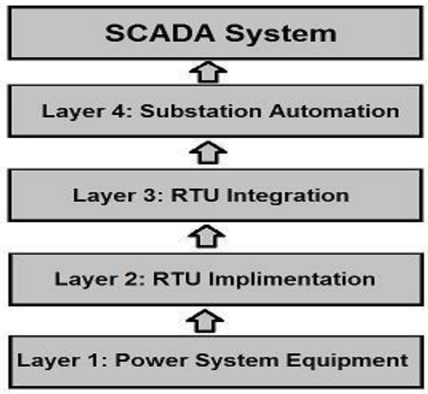


Figure 3.12 Four Layers of OSI Protection via Smart RTUs

3.6.2 Power Management System (PMS)

Efficient WWTP power distribution network through self-power generation using biogas or any renewable resource, must have a failsafe mechanism of a two-way power flow. Adding redundant communication capacity to WWTP distribution substations does this whilst providing a centralised PMS. This will address aspects of sub-station automation systems (SAS), such as enhanced and reliable protection, supervisory control and reliability of power. Ethernet-based communication system can facilitate complex intelligent automation of WWTP and power company`s zone substation. It also enables secure transmission of telemetric signals (tripping signals, synchronisation messages, CB status) for reliable operations and maintenance (O&M). This calls for development of customised smart RTUs that will efficiently control and manage power flows between the power company`s zone sub-station and the WWTP biogas-fed installed generators by providing the required layers of protection.

3.6.3 SCADA System

To avail opportunities presented by the WWTP infrastructure, various tools and human machine interfaces (HMI) like SCADA system are used for monitoring and controlling. Smart RTUs are utilised as part of SCADA system with a goal to reinforce correspondence between the WWTP distribution substations, generators and power company`s zone substations. SCADA needs to assemble telemetric data of various power generation systems in order to ensure the availability of the entire substation’s information at a centralised location for common use. Advanced monitoring system (AMS) with SCADA system enhances quality of service, reliability and security. AMS is deployed for continuous monitoring and metering solutions. It also provides a redundant two-way communication and is able to gather information on voltage, current and power [130].

3.7 METHODOLOGY – PROBLEM EVALUATION

3.7.1 Power Network of Zone and Distribution Substations to Achieve HV/LV Redundancy

Figure 3.13 represents two-way power flow in ring topology and typical equipment terminations of power company`s zone sub-station terminal with the two on-site WWTP distribution substations, termed as point of contact (shown as POC1, POC2 and POCn), for electricity cogeneration. Any number of substations can be connected to this network via Ring Main Units (RMU) for HV switching. The smart RTUs are connected with each POC and then interlinked with each other via a communication protocol.

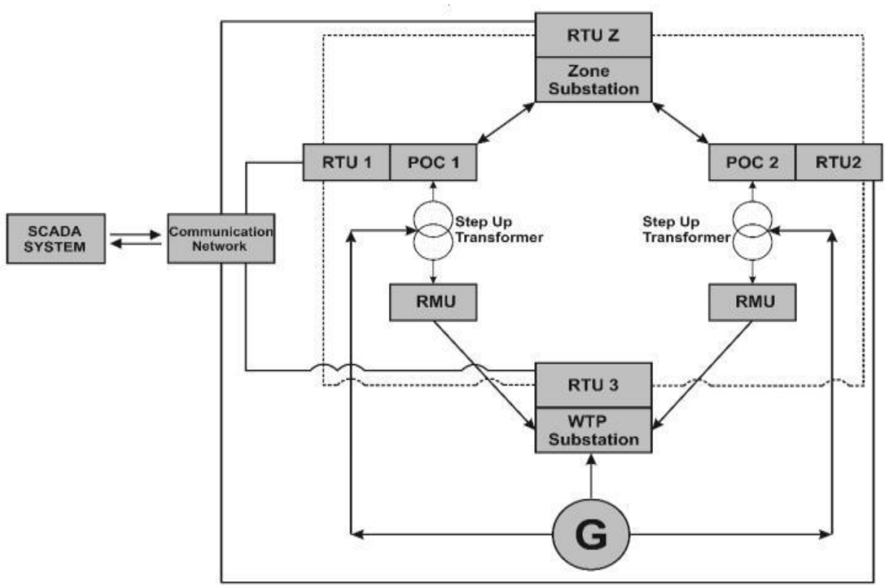


Figure 3.13 Ring Topology of Sub-station Network at WWTP

3.7.2 Intertripping Philosophy

Protection Trips

Swift and efficient provision of protection trip signals to the relays and shunt trip coils of relevant circuit breaker (CB) protect each substation. These signals are generated from auxiliaries and contactors of various power equipment at WWTP and the power company`s zone substation. Controlled intertripping mechanism is necessary to direct tripping commands, in the form of telemetric signals, in order to protect the power systems during various scenarios of electricity cogeneration. Mapping and communication of these telemetric signals can be achieved by installing smart RTUs at each POC of the WWTP and the power company`s zone substation.

Zone Sub-Station Trip

Tripping signals are used when WWTP power generation is equal to its demand load so that the feeders are disconnected from their respective POCs. Operating WWTPs at any given instance of electricity cogeneration scenario requires a robust and a swift way to communicate this tripping command, to and from power company`s zone substation.

Fault Trip

Fault current must be stifled rapidly so that the equipment's tolerance does not exceed its threshold and the restart/reconnect action of WWTP generators with the power network can be triggered at the earliest opportunity. Faults due to short-circuiting can be managed by tripping the power supply from the associated sub-station unit so that it is isolated from the faulty part of the circuit. With the aim of rapid fault detection and system restart, it is necessary to plan detailed protection relay coordination beforehand. This mapping philosophy then needs to be communicated across the power network for appropriate safety actions, in a sequential way.

Remote Trip

This signal acts like a field isolator and is able to trip any specific sub-station manually when required. When power company`s zone sub-station wants to perform maintenance related tasks, the design philosophy of the WWTP electrical cogeneration modelling must ensure triggering of a remote trip signal. In response, power generated at WWTPs must be tripped to prevent reverse power generation process, as the grid is not ready. For a smooth and safe operation, the design philosophy at power company`s zone sub-station ensures that a remote trip signal conveyed from WWTP distribution substations will not cause the relevant POC to trip unless at least one of the WWTP generators is operating parallel to that particular feeder coming from the power company`s zone sub-station.

Intertripping Downtime

Intertripping of HV and LV CBs of WWTP power network must be automatically activated and operated with a reduced downtime. Reducing intertripping downtime between power equipment increases their safety and protection during the electricity cogeneration process. Smart RTU philosophy must incorporate a communication network that is able to transmit the tripping signals in the form of telemetric I/Os (Input/Output), rapidly and efficiently. HV intertripping is achieved by activating the shunt trip coil in the switchgear via the smart RTUs telemetric fault signals installed at each substation.

3.7.3 Interlocking of HV/LV Power Supplies

Interlocking of HV/LV power supplies at WWTPs ensure that the network components (CBs, isolators, generators, feeders) operate without any manual tasks and commands during the electricity cogeneration process. Automation of this sensitive system requires status information of CBs (open, close or trip) at POCs, in order to provide redundancy through smart RTUs. Disconnection of WWTP generators should ensure that a trip and successful auto-reclose of power company`s zone sub-station feeders restore supply to their respective POC. Hence, it must also inhibit the operator initiated remote trip for the incoming feeders when generators are not connected to them. WWTP generators are interlocked with the zone and distribution substations via smart RTUs. RMU provides HV switching point and enables improvement in secondary distribution network performance by providing HV redundancy to the POCs via an alternate feeder when required [131, 132].

LV supplies from the WWTP generators are interlocked with LV supplies of the POCs using auto-transfer-switching (ATS) panels, CBs of which are mechanically and electrically interlocked to the CBs of each POC’s main LV switchboard. ATS serves to protect the distribution substations during WWTP electricity cogeneration by triggering signals to make or break a contact via smart RTUs, when required. HV/LV power supply interlocking philosophy and scenarios are highly dependent upon biogas production on-site.

3.7.4 HV and LV Power Supply Redundancy Using Ring Topology

Schematics for the MW-WTP HV/LV reticulation and the interlocking are shown in Figure 3.14 and 3.15.The eight MW-WTP 1.5 MW generators supplies LV to POCs. Surplus power is being fed back to the power company`s zone sub-station though high frequency transformers and reverse power relay (RPR). The mechanical and electrical interlocking of LV supplies between the plant generators and POCs provide a protection layer and LV redundancy during the electricity cogeneration process. HV redundancy is achieved by connecting feeders at POC1 and POC2 with all the other WWTP substations in ring topology via RMUs, which also provide HV switching points.

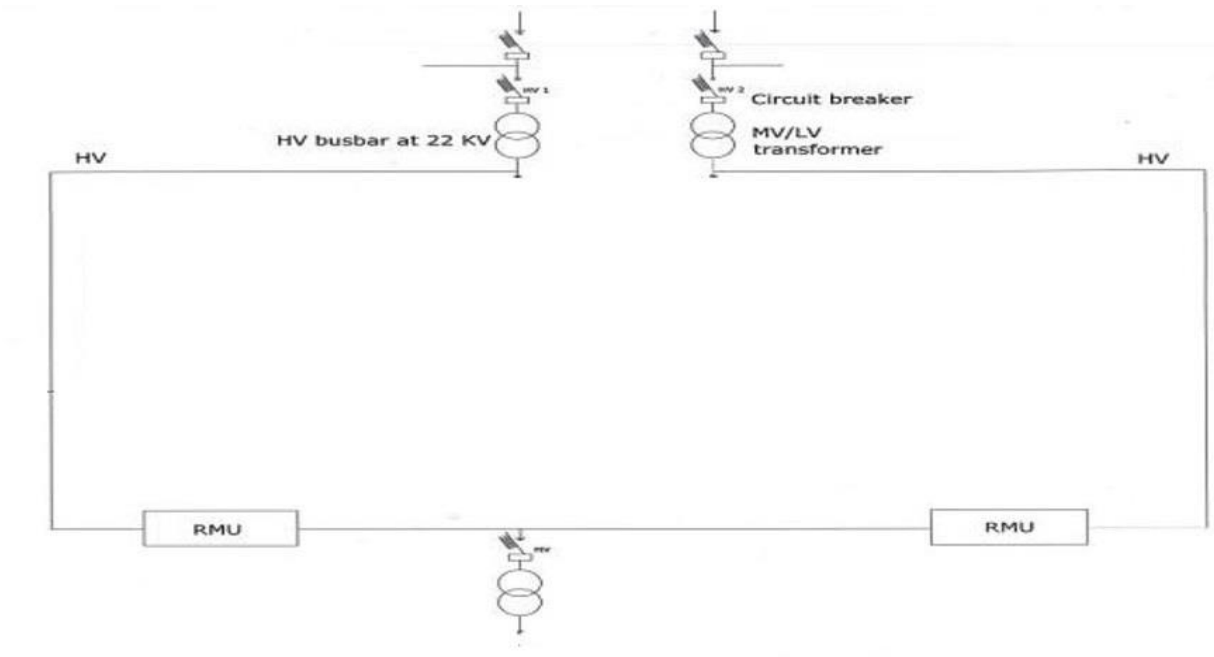


Figure 3.14 Ring Topology for HV

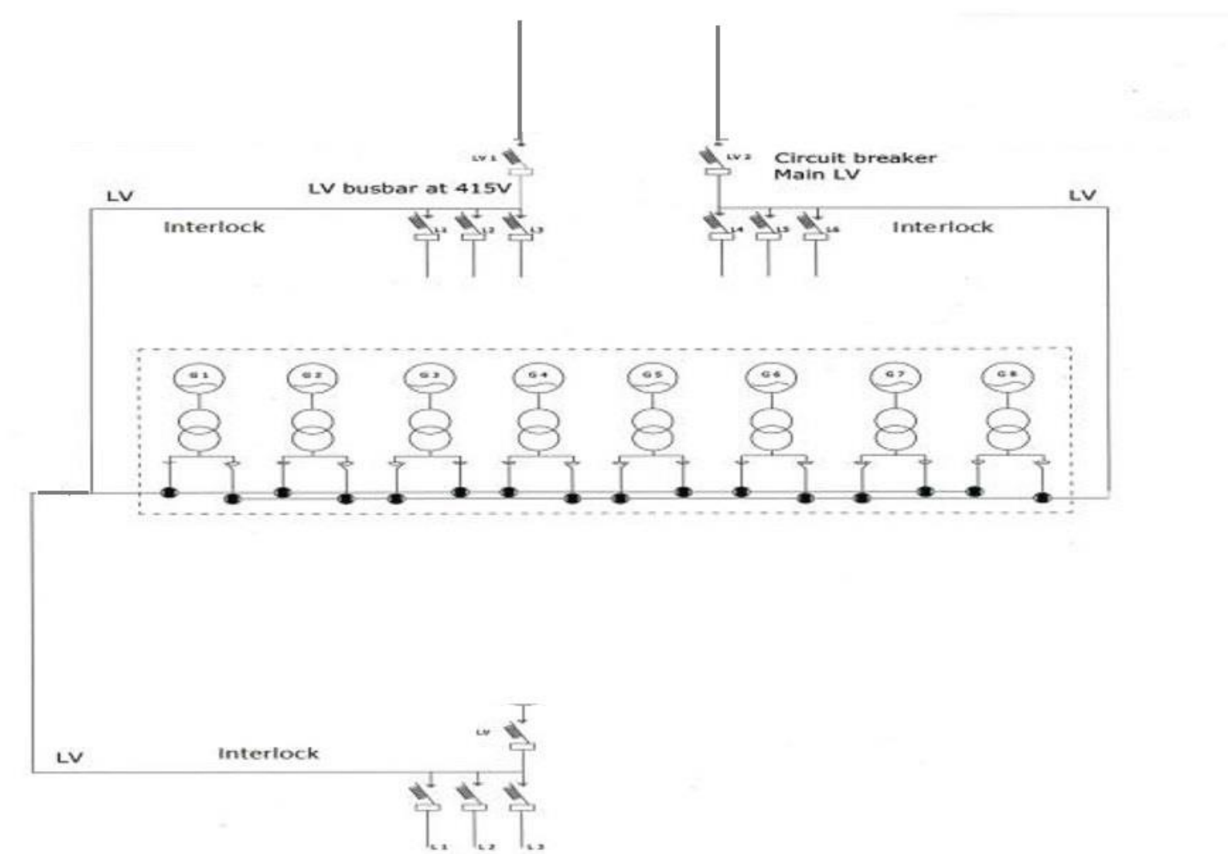


Figure 3.15 Ring Topology for LV

3.7.5 Enable POC Reverse Power Relay (RPR)

RPRs are utilised to detect power spill outs of generators. POCs RPR becomes functional when WWTP generates surplus or less electricity than its demand. A timer is initiated by this I/O, which at the end of a defined period enables the associated POC's RPR. This relay comprises of three parts namely directional, delay and hold. Current transformer (CT) and voltage transformer (VT) signals are changed over to a pure square wave shape having two levels, +1 and -1 respectively. For overlapping and non-overlapping sessions, +1 and -1 are obtained. The result is also subject to integration. In case of electricity cogeneration, this I/O attains threshold value. The delay component provides protection for relays by averting false trip signals delivered to the CB of the respective POC. The hold block provides stability to relay state and the power network system on getting tripped. Smart RTUs enable these functions when required, providing a layer of protection.

3.7.6 High Frequency Step-Up Transformers

When a WWTP is generating surplus power, higher power frequency is maintained to reduce line losses during the WWTP reverse power generation to grid. High frequency step up transformer uses Ferrite toroidal cores to increase frequency of the reverse power. These frequencies range between 1 KHz to 100 MHz the three-phase 415 V supply system from WWTP generators are connected with these transformers, which step-up potential to 1 kV and increases the frequency of power during reverse power generation. These transformers distribute power efficiently where cogeneration is being implemented. Mathematical model for proposed philosophy in which the frequency of transformers can be calculated for effective reverse power generation is shown in equation (3.9).

$$f_t = \frac{V_h}{2.d.\pi^2.L_h.p_o}(\pi - \emptyset) \quad (3.9)$$

Where;

f_t = frequency for transformer (Hz)

V_h = high voltage input (V)

d = voltage regulation (V)

L_h = leakage inductance (Henry)

p_o = out power (Watt)

$\emptyset$ = phase shift angle (radian)

Figure 3.16 shows power distribution with high frequency for reliability to overcome inrush current in busbars of the POC switchgears due to two-way power flow, reducing overheating of busbars.

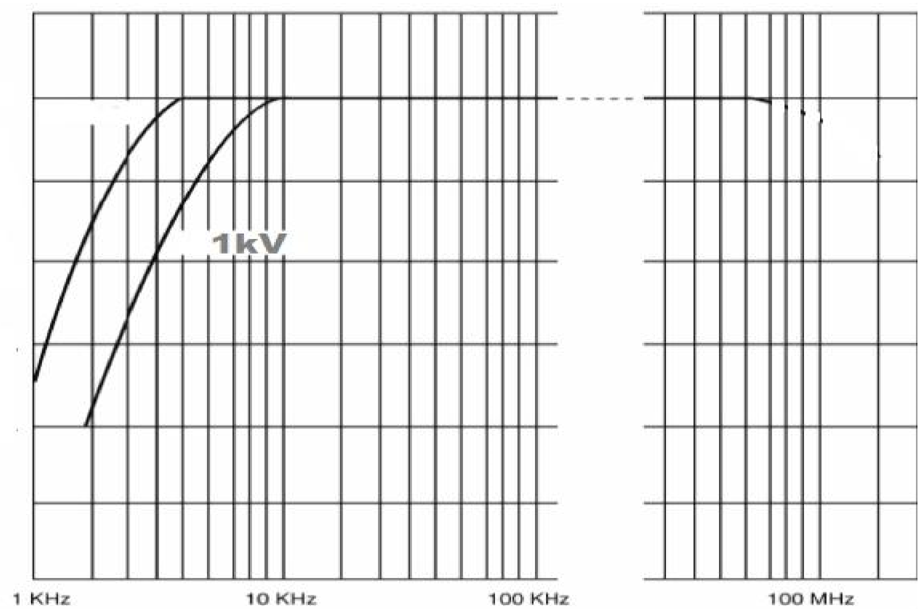


Figure 3.16 High Frequency Curves for Reverse Power Generation

3.8 PROPOSED SMART RTU INTERFACE AND WWTP ELECTRICITY COGENERATION

The proposed smart RTU philosophy aims to set up suitable configurations and connectivity based on cost effectiveness, adequate ingress protection, reliable implementation, performance, and maintenance. The proposed design utilises remote and on-site controls for monitoring, managing protection trips, plant condition, supervision and fault indications. This network extension will seamlessly integrate with any existing or old WWTP infrastructure. Intertripping and interlocking philosophies are then developed with required telemetric signals made available to smart RTUs at a potential-free contact to optically isolate different control voltage levels from their respective substations [132, 133]. Figure 3.17 represents the proposed smart RTU interface. Telemetric signals are generated from the power company`s zone sub-station and WWTP. The wiring of each POC is based on design, telemetric I/O mapping and flow, interlocking and intertripping philosophy. These telemetric signals are calibrated via PLC and then onto an HMI via smart RTUs, for proper monitoring and control of WWTPs. The smart RTU contacts are energised by an external redundant source and communication redundancy is achieved by implementing FOC patch panels with a backup ADSL link [134].

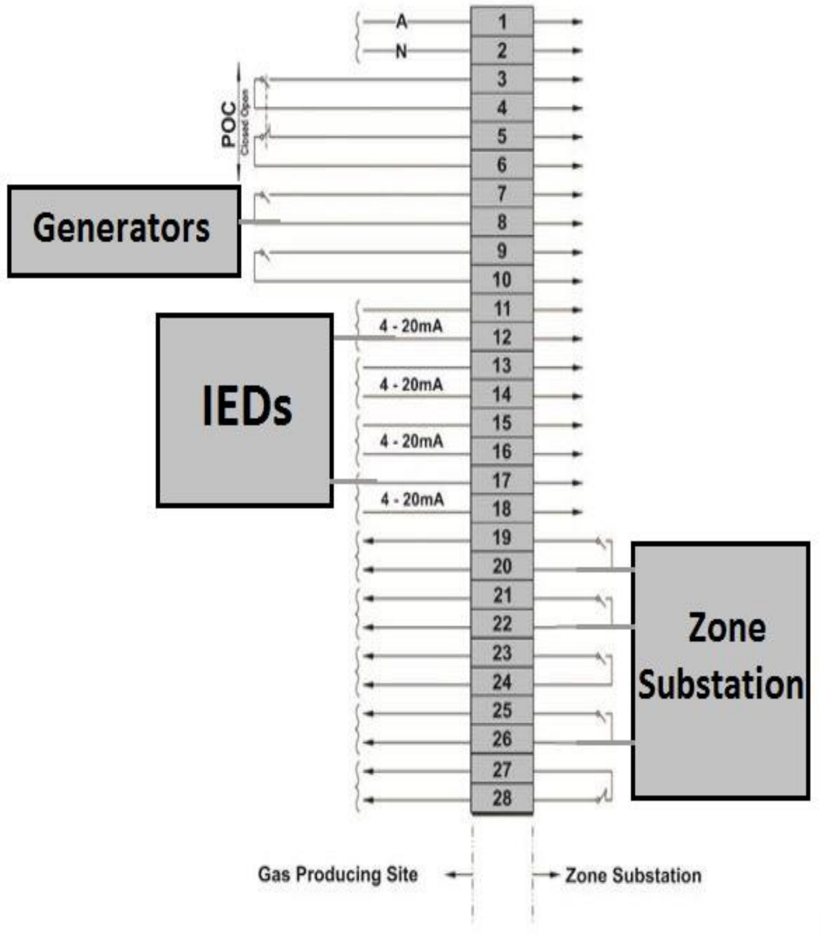


Figure 3.17 Proposed Smart RTU Interface with Telemetric Signals

3.9 SCENARIOS

3.9.1 Scenario One: WWTP Power Generation < Maximum Demand Load

Figure 3.18 shows power flowchart for scenario when the amount of power generated from WWTP production of biogas < the demand load. In this case, the LV power supply from WWTP generators is interlocked to the priorities already allocated to the POCs. The CB of the top priority POC and the feeder is tripped. In this research, POC2 is given the first priority, assuming lesser demand load on its feeder. This calls for a situation where power must be supplied by both, WWTP generators as well as power company`s zone substation. The WWTP generator then supplies power to first prioritised POC, POC2 in Figure 3.18, and any remaining power supply is directed to the next priority POC. The power company`s zone sub-station supplies remaining power as per WWTP demand load requirements via POC1 feeder. There could be a number of distribution substations (indicated as Ponca) at WWTP. In this scenario, the LV switchyards of any POCs receive power supply from the WWTP generators based on pre-set priorities and interlocking philosophies. POCs with lower priority are fed from the power company`s zone substation. The protection relay trips HV feeders of the first priority POC, POC2 in this case, so that WWTP generator supplies power to its LV panels. If, for any reason, the generators are still connected to tripped feeders at the time of reclose, CBs of the first priority POC and its feeder will remain open as it is interlocked with the 'Generator Connected' status for the respective POC. The scenario usually occurs on cooler days and night when the temperature is low and the digestion process is slow.

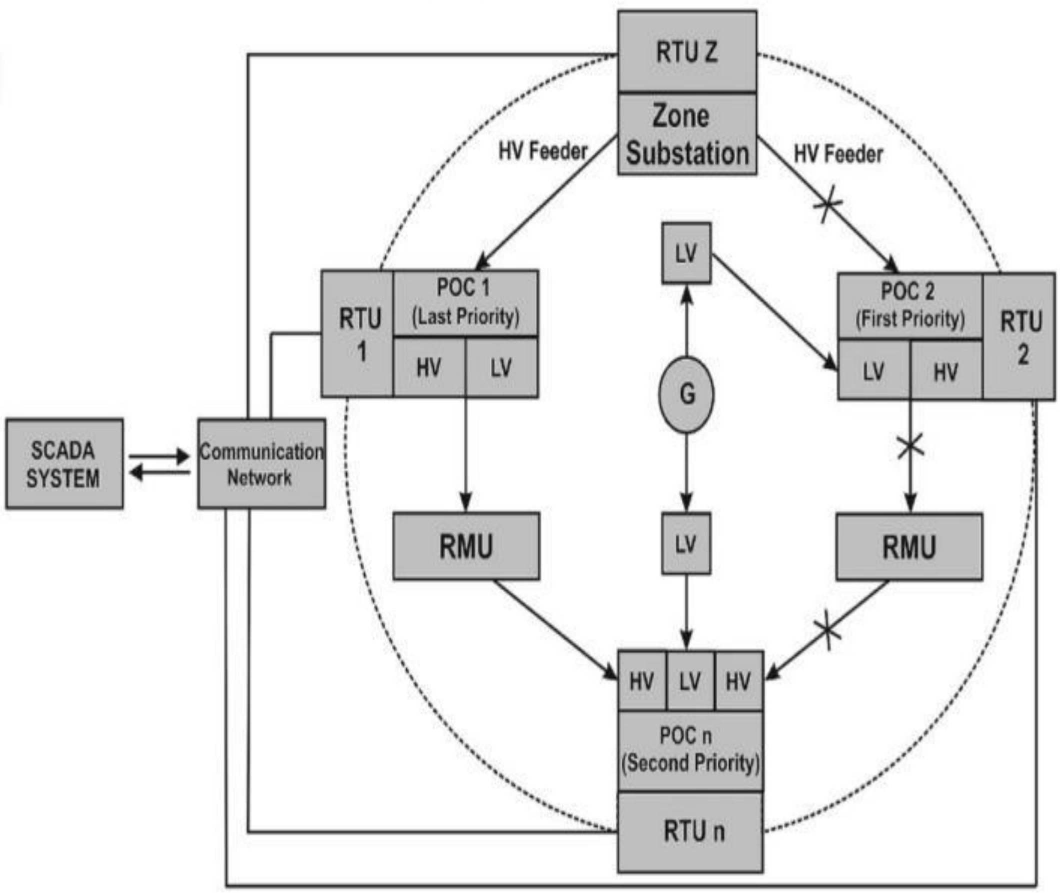


Figure 3.18 Scenario One: WWTP Power Generation < Maximum Demand Load

3.9.2 Scenario Two: WWTP Power Generation = Maximum Demand Load

In this scenario, the power company`s supply is not required. Figure 3.19 for this scenario shows that the WWTP generators interlock with LVs of the POCs (POC2 then POCn then POC1), providing the first layer of system protection, where it sends a signal to power company`s zone sub-station tripping CBs of all the HV feeders connected to POC2 and POC1 respectively, ensuring a second layer of protection. Tripping signals generated from the auxiliaries of WWTP generators and POC switchgear are communicated via the smart RTUs installed at each POC and the power company`s zone substation.

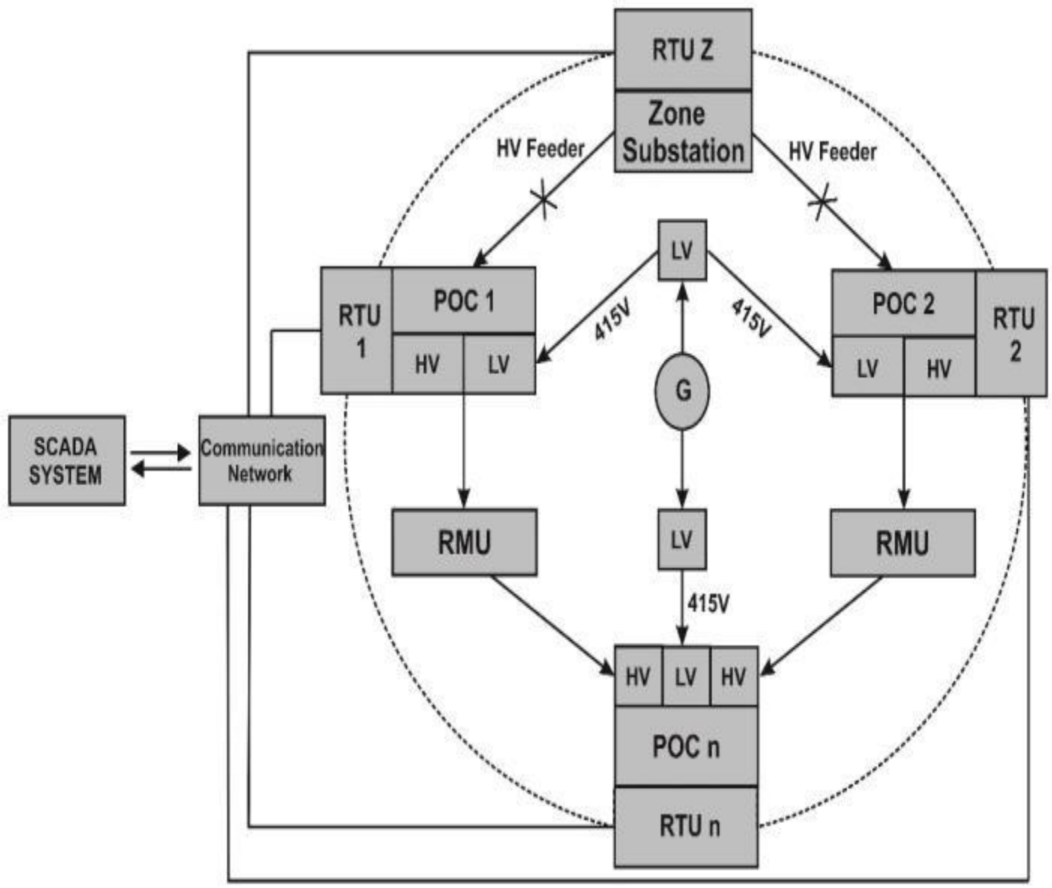


Figure 3.19 Scenario Two: WWTP Power Generation = Maximum Demand Load

3.9.3 Scenario Three WWTP Power Generation > Maximum Demand Load

Figure 3.20 represents third scenario, which requires reverse power generation via WWTP POCs. The relevant feeders at power company`s zone sub-station will open. WWTP generator interlocks with ATS of POCs while the HV feeders are already tripped. Surplus power is fed back to the power company`s grid by enabling the RPRs. A generator inhibit request signal is sent as an acknowledgement to the POCs and power company`s zone substation, which then reinstates the POC1 and POC2 breakers. Surplus LV supply from WWTP generators is directed to high frequency a step-up transformer that further feeds the HVs of POC1 and POC2 enabling reverse power. The generator inhibits signal via the smart RTU panels, reinstates the tripped breakers of HV feeders at POCs after the LV interlocks have been established. This allows reverse power generation at higher voltage and frequency levels to minimise line losses and over-heating of POCs HV busbars.

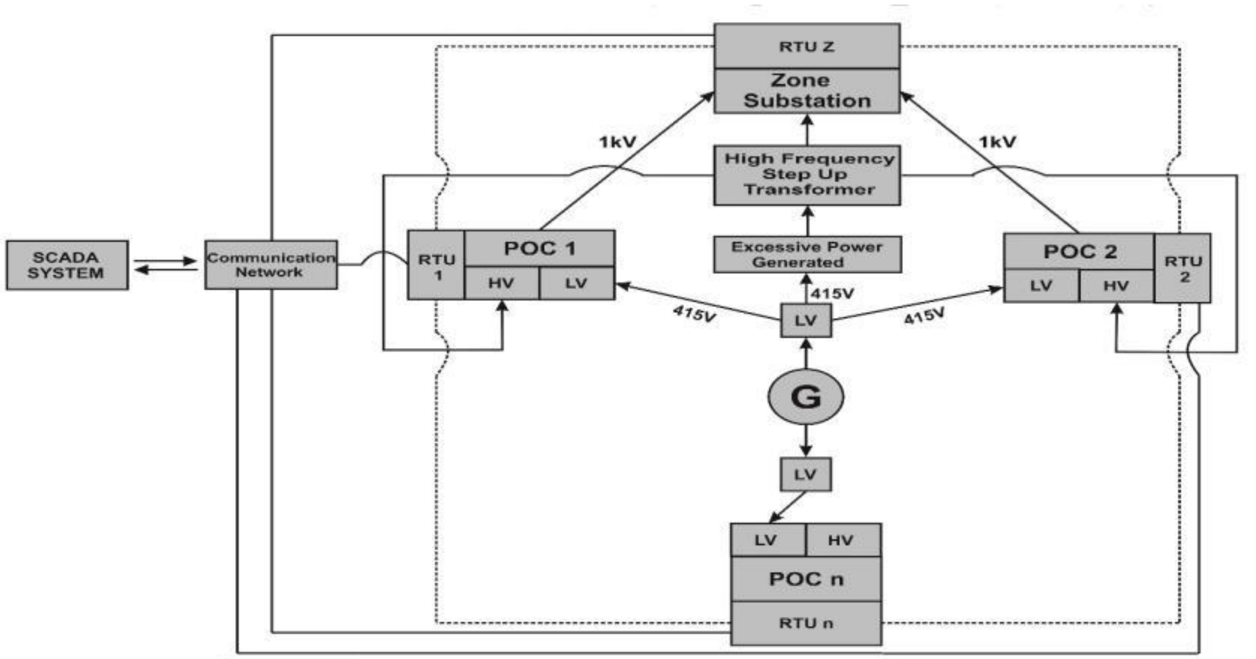


Figure 3.20 Scenario Three: WWTP Power Generation > Maximum Demand Load

3.10 RESULTS AND DISCUSSION

3.10.1 Power Network at MW-WTP

Stakeholders of existing and old WWTPs face strong challenges on issues related to power consumption, GHG emissions, operations and maintenance. Necessary follow-ups are, therefore, mandatory to verify the expected performance of the systems through modifications done in the existing infrastructure. The asset managers at MW-WTP wanted to implement an effective, automated and failsafe way of enabling electricity cogeneration through on-site generators. The modelled smart RTU philosophy was then implemented at MW-WTP POCs and power company`s zone substation. Simulated results, after this economical upgrade to the existing infrastructure, are shown in Figure 3.21.

3.10.2 Smart Metering Results

An estimate of the MW-WTP power generated with respect to its average actual maximum demand load is studied to map out proper protection relay coordination at the POCs. If metering signals are not available, then CTs of appropriate ratios are mounted on the phases and then calibrated on the analogue module of the PLC. These telemetric analogue signals are then communicated to an HMI. Figure 3.20 simulation results of the MW-WTP demand load for various wastewater treatment levels vs power generation. As compared to the results in Figure

3.21 data are more accurate, precise, discreet, efficiently obtained and communicated via the smart RTUs. These metering signals provide a proper monitoring platform to effectively develop an interlocking and intertripping philosophy of the MW-WTP HV/LV supplies.

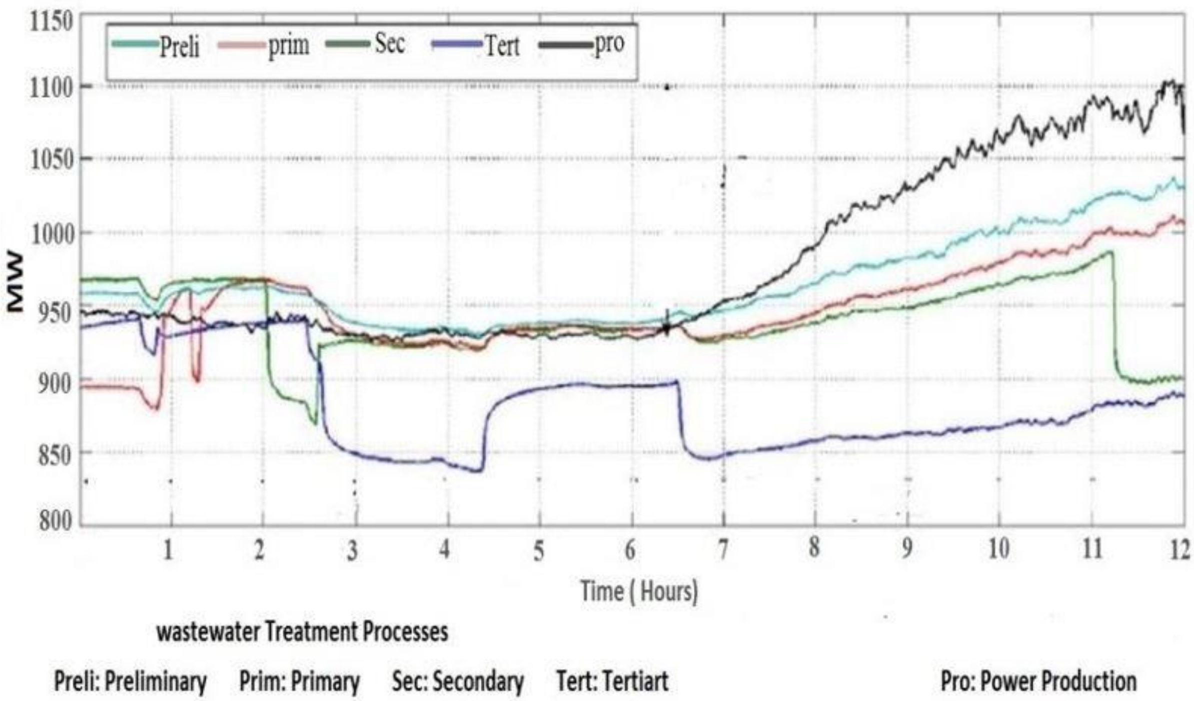


Figure 3.21 Telemetric Power Monitoring at MW-WTP

3.10. 3 Availability of WWTP Telemetric Status Signals

The proposed design is served by telemetric signals redundancy that effectively conveys the status of energy demand and supply before any operation. They can be made available through DC auxiliaries and interposing relays in the POC switchgear or simple upgradations where system lacks availability of status signals. The smart RTUs provide a platform for all these I/Os to be accumulated for SCADA.

Simulation for over-current relay trip signals being generated under various scenarios of electricity cogeneration at MW-WTP is shown in Figure 3.22. The spike reflects correspondence relay action against over-current activities in the smart RTU. Results show an effective management of faults. The protection relays trips instantly, isolating the power network from the defected part effectively and instantaneously when current exceeds its set threshold value.

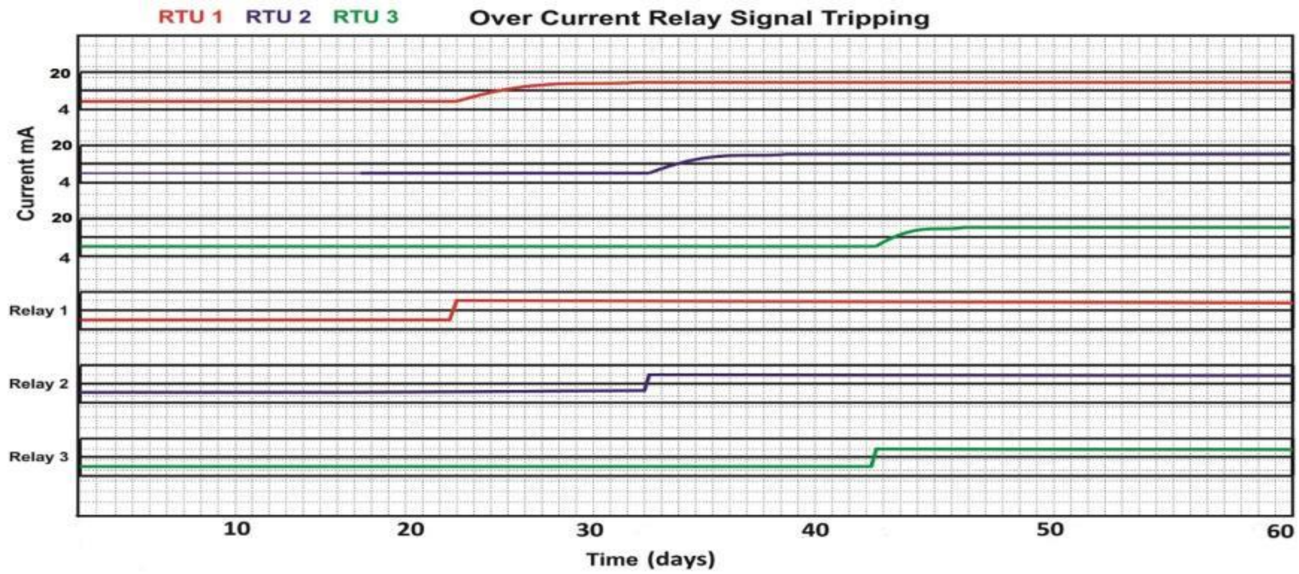


Figure 3.22 Smart RTU Relay Action against Over-Current

3.10.4 RPR

Simulation results Figure 3.23 at show directional power relays action the MW-WTP with smart RTUs under various scenarios of electricity cogeneration during the spring season. When power generated at the MW- WTP equals the demand, power relay1 trips to disconnect POCs from zone substation. At noon when biogas production increases due to increase in temperature, the RPR2 will trip for reverse power generation. During evenings, when power generated < the demand load, RPR3 trips to direct electrical power from zone sub-station to overcome the deficiency. These active relays can trip automatically and simultaneously with each step via the smart RTUs. POC intertripping and HV/LV interlocking provides effective controls and safety during the cogeneration process.

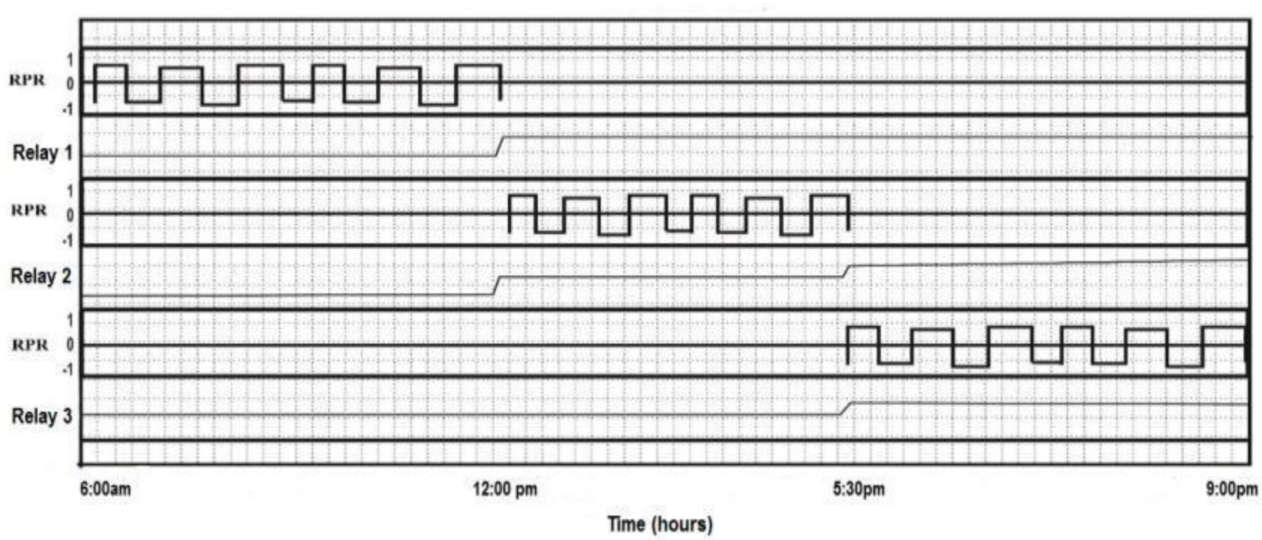


Figure 3.23 RPR Action via Smart RTU

3.10.5 Protection and Reduction in Intertripping Downtime

Differential protection relay for HV 22 kV busbar at the MW-WTP POCs needs to be activated when heavy inrush or false differential current causes CT saturation under faults. Generated and calibrated analogue signals from the CTs are mapped to the corresponding smart RTU of the POC to activate a series of actions against these faults. Simulation Figure 3.24 shows the current saturation and corresponding relay trip action at the MW-WTP. When a fault occurs or the CT reaches its saturation limits, protection relay will trip the correspondence feeder and POC CB automatically via the smart RTU for protection.

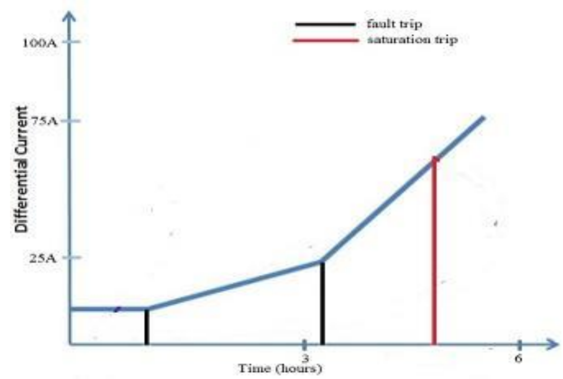


Figure 3.24 Differential Current Protection Relay Action

Figure 3.25 results indicate that the busbar connected with MW-WTP has reduced intertripping downtime by approximately 20% at POCs with increasing current magnitudes using the smart RTU philosophy. It is achieved by provisioning FOCs to patch and communicate the telemetric signals between the smart RTUs of their respective substation.

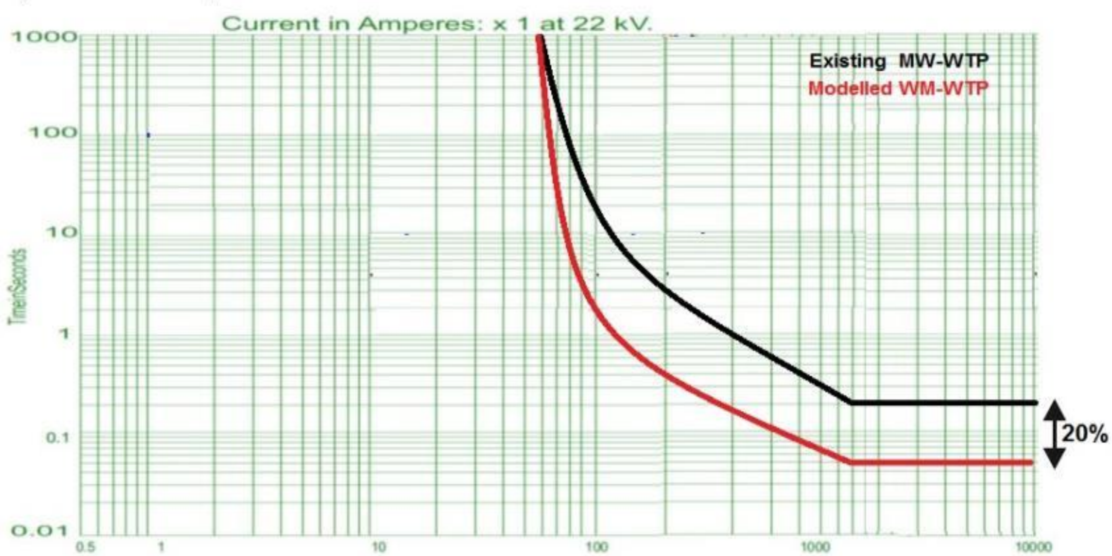


Figure 3.25 Differential Current Protection Curves for MW-WTP

3.10.6 WWTP Power Generated Versus Reverse Power Generation

Figure 3.26 shows simulated results for MW-WTP generated power exported via POC1 and POC2 to the power company's zone substation. The smart RTUs at MW-WTP demonstrated optimised PMS by successfully switching power supplies at POCs. Reverse power decreases with increased power consumption and vice versa.

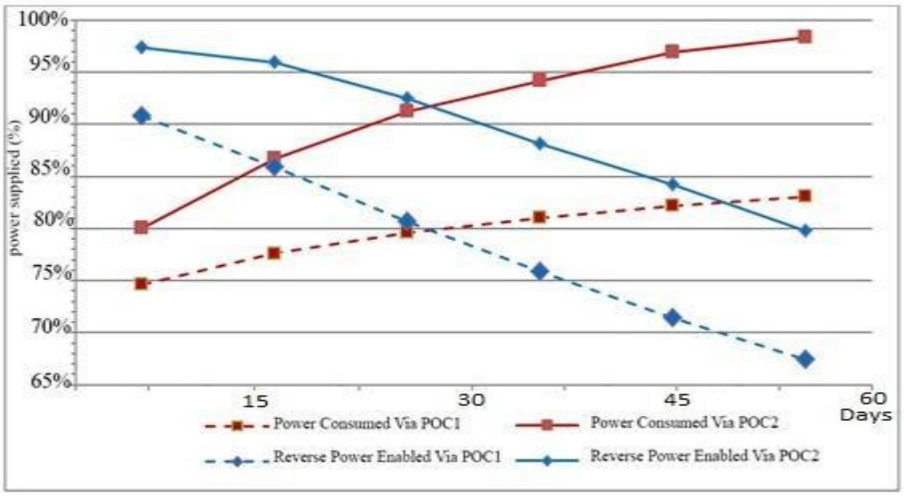


Figure 3.26 Reverse Power Generation Evaluation Curves for MW-WTP

3.10.7 Modelled RTU

The modelled smart RTU resolved issues associated with old and existing infrastructure of MW-WTP by presenting a flexible solution to enable electricity cogeneration with efficient results. Figure 3.27 results indicate that efficiency increased approximately 25% of MW-WTP with modelled RTUs in terms of electricity cogeneration, by effectively controlling and managing the scenarios and faults.

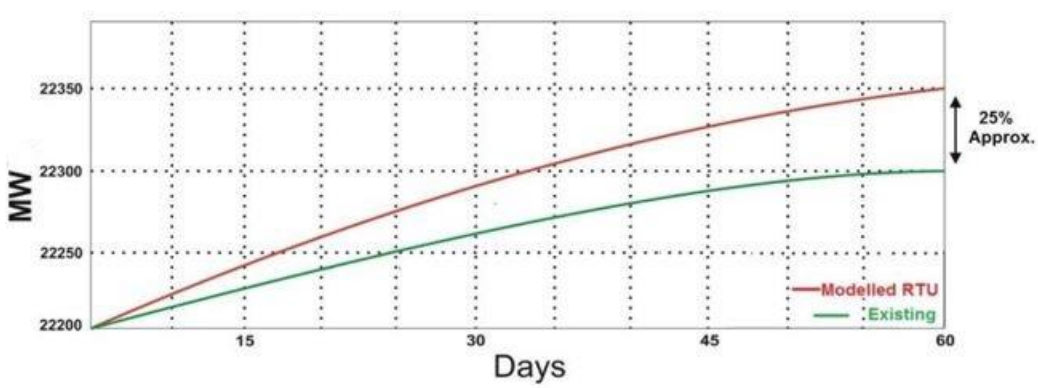


Figure 3.27 MW-WTP Modelled RTU Efficiency

3.11 IMPACTS

3.11.1 Energy Efficiency

Simulation results Figure 3.28 demonstrate optimised performance with significantly enhanced energy production by implementing the smart RTUs at MW-WTP. This efficient PMS consequently reduces load on the grids. It can also be observed that energy demand is usually less than the MW-WTP generation during summers by optimally utilising the on-site energy resources.

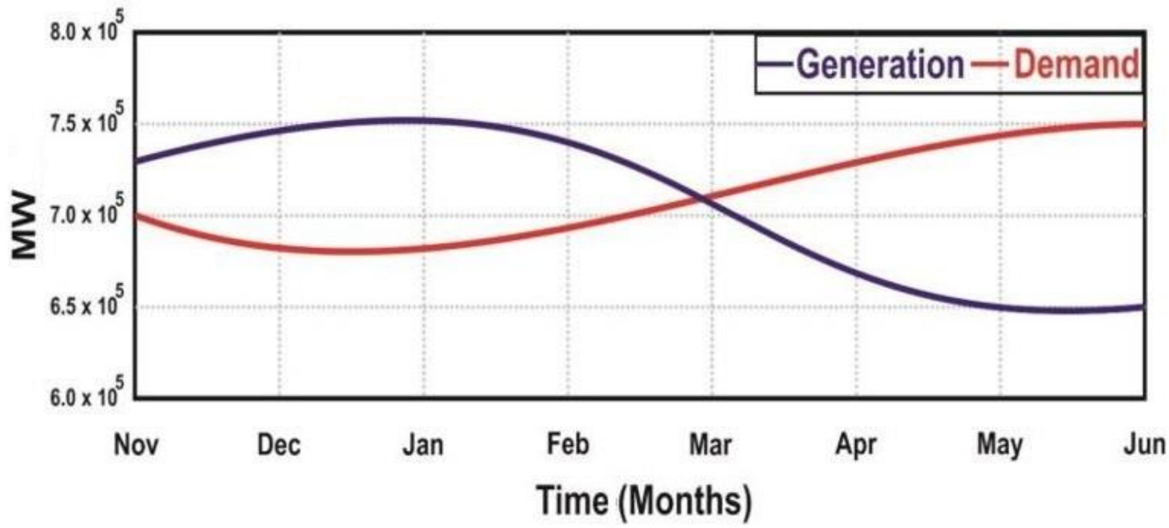


Fig 3.28 MW-WTP Energy Production and Demand Curves

3.11.2 Renewable Energy

Wastewater is a renewable resource. The biogas produced through anaerobic digestion can be best utilised and managed for electricity cogeneration by implementing the smart RTU philosophy. Water treatment gives some other by-products, which helps the recycling processes. The proposed research provides a perfect platform to effectively control, monitor and best utilise all of those renewable energy processes.

3.11.3 Environmental Impact

Wastewater treatment reduces waterborne diseases and keeps the ocean clean. The proposed research helps reduce GHG emissions and bad odour around the WWTP vicinity. It was noted at MW-WTP during the course of this research that by controlling and utilising the biogas produced prevented approximately 87000 tonnes of CO_2 to enter into the atmosphere. SAS using smart RTUs also reduces heat emissions. Moreover, treated sludge is used as a soil-improving substance for agriculture and treated water can be used in many ways. Simulations at MW-WTP Figure 3.29 show reduction of CO_2 emissions, reducing environmental footprint.

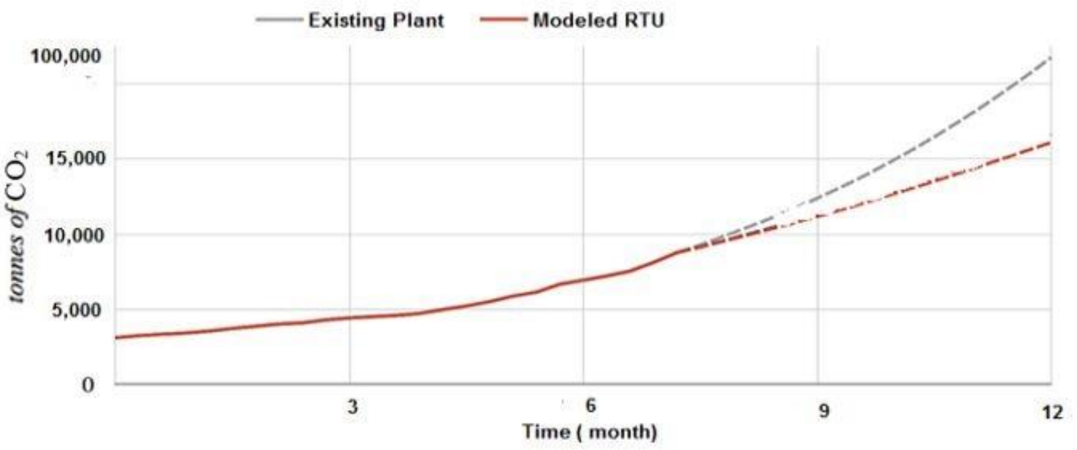


Figure 3.29 SAS and Smart RTUs Reduces GHG Emissions at MW-WTP

3.11.4 OH&S

Automation of all interlocking, intertripping, switching and fault scenarios of MW-WTP has minimised the HV operator`s interaction with equipment, increasing OH&S standards. It provides a “one stop” for WWTP operators to determine faults and make corrective actions accordingly as per the plant`s design philosophy and O&M procedures. Reduced intertripping downtime has also improved safety of the power network during electricity cogeneration.

3.11.5 Easy to Implement on Existing and Old Infrastructure

Proposed modelled RTUs can easily be implemented on existing or old infrastructure at MW-WTP through minor modifications and minimum investment. They can be installed at various POCs, where smart metering and electricity cogeneration needs to be implemented, are easy to wire, maintain, and provides a stand-alone and safe point of control. Effective PMS and SAS can be achieved by implementing the smart RTUs at any WWTP or site where renewable resource is available.

3.11.6 Financial Impact

Financial savings are achieved in three ways. Reduction in power bills, man-hours required to operate and maintain WWTPs and by increasing the life of substations without replacing the existing switchgears in the POCs or commissioning new substations to manage the demand load. The research provides optimum utilisation of biogas and waste energy. Simulation result in

Figure 3.30 show financial savings at the MW-WTP. Considering maximum demand load and energy production at the MW-WTP with failsafe and redundant power supply – PMS is more efficient using the modelled RTUs and serves an average saving of 0.65 million AUD over six months.

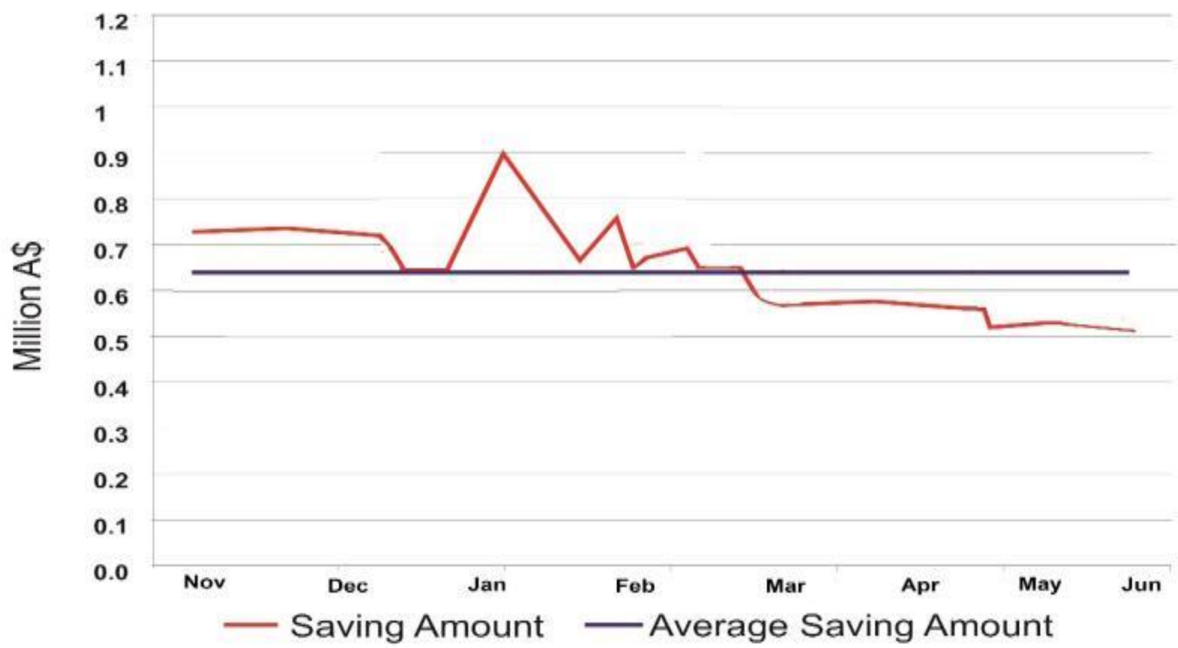


Figure 3.30 Average Energy Saving using Smart RTUs

3.12 CONCLUSION

This research shows the potential of anaerobic digestion for WWTP biogas production and has addressed the energy intensive demand and made electricity cogeneration economically viable. Implementing smart RTUs and improving the mapping philosophy of telemetric signals functionality have considerably enhanced the safety of existing WWTPs equipment during cogeneration. This has effectively added the required communication between the zone and distribution substations, which the old/existing infrastructure lacked. Not only HV/LV redundancy was achieved, but also different layers of OSI protection were added to WWTP through an automated intertripping and interlocking mechanism, ensuring a failsafe and reliable multidirectional power flow with minimum losses. Sections of WWTP requiring maintenance or upgrade works can be isolated without affecting power supplies to other segments of the plant. OH&S standards are improved by minimising HV operator`s interaction equipment. Financial savings by implementing the smart RTUs on existing infrastructure without any expensive upgrades to the switchgear and the grids are massive. With the world moving towards renewable resources, it is important to implement such plans on sites that produce waste energy.

CHAPTER 4:

MODELLING SMART RTU TO ACHIEVE TELEMETRIC COMMUNICATION FOR ELECTRICITY COGENERATION AT WWTP

4.1 INTRODUCTION

The operator control and monitoring of this wide-scale system utilises a complex network of intelligent electronic devices (IEDs) that are interconnected with each other through network components and communication channels bearing a swift response [135]. The IEC61850 standards along with Ethernet-based communication system support this using SAS for secure data transmission, protection, reliable operation and maintenance. This thesis focuses on setting up an effective communication protocol and network to transfer various telemetric signals from IEDs between power equipment of WWTP sub-station and power company's zone substation, to achieve a redundant and failsafe communication system for electricity cogeneration on existing infrastructure without any major or expensive upgrades. The research focuses on modelling cogeneration of electricity on existing and old infrastructure of WWTPs using smart RTUs. This research was conducted on a multi-layered architecture for enhanced protection, control and monitoring of data. Ring topology is established between the WWTP substations and power company`s zone substation, using smart RTUs, for an effective communication system. It would facilitate the existing or old WWTP systems by permitting various sections of power and communication networks to remain operational and be able to reconnect automatically under various scenarios of electricity cogeneration, failures, fault trips, power outages and shutdowns [136]. Figure 4.1 shows typical arrangement for electricity cogeneration at WWTP in ring topology. Biogas is produced and then utilised to excite on-site generators with controlled multidirectional power flow between the distribution and zone substations.

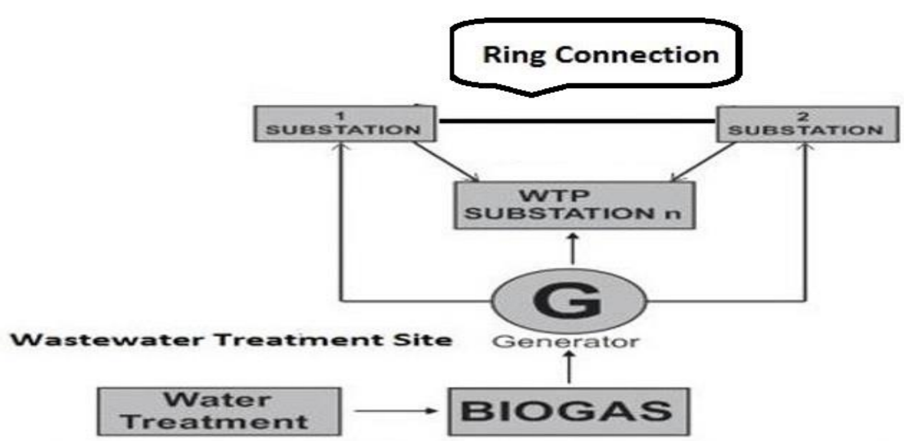


Figure 4.1 Biogas Production and Two-Way Power Flow at WWTP

4.2 ADVANCED BIOGAS PRODUCTION METHOD

Anaerobic digestion is a series of biological processes where the degradation of organic content takes place in the absence of oxygen to produce biogas and biofertiliser. Methanogen bacteria produced biogas (methane) through anaerobic respiration. It is further divided into two groups, which is Hydrogen and Acetic Acid utiliser [137]. This generated biogas acts as a fuel for the production of electrical energy. Figure 4.2 explains the advantages of using anaerobic respiration process as compared to aerobic respiration in which methane gas is produced for power generation.

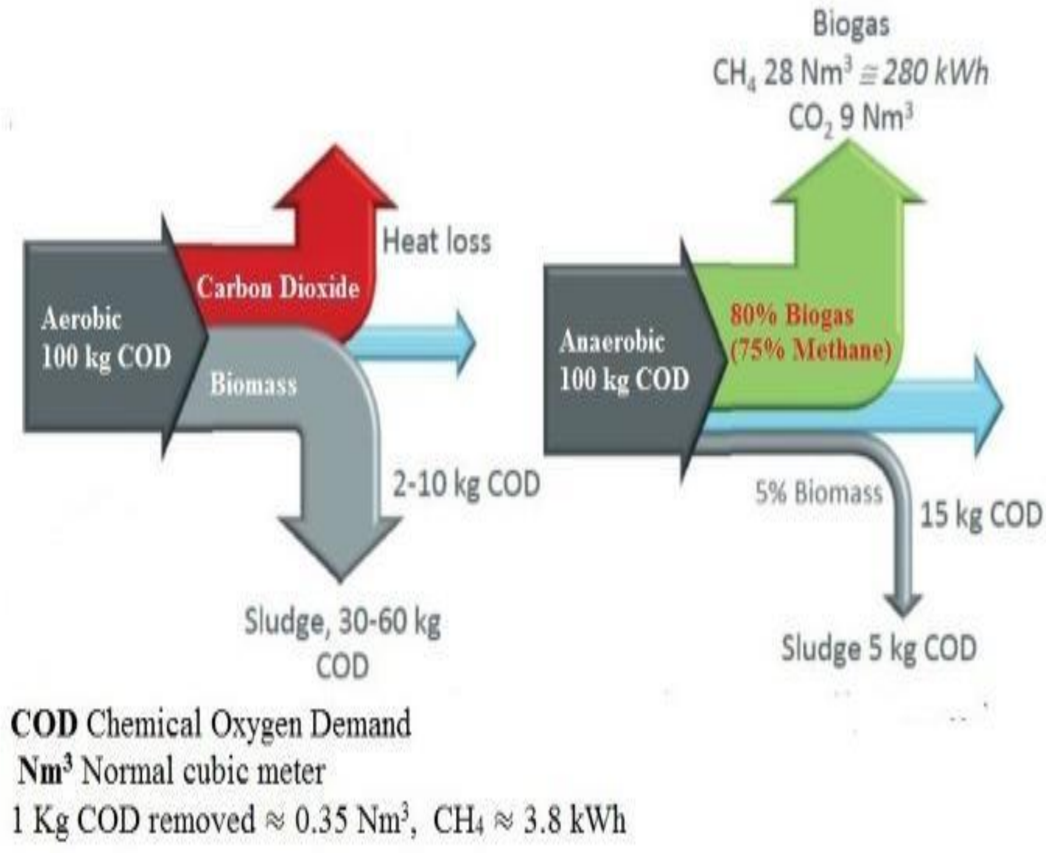


Figure 4.2 Advanced biogas production method

The figure shows that anaerobic digestion method is more acceptable for bio-waste treatment. Organic contents of sewage perform the energy recuperation process from anaerobic digestion of sludge, and the resultant biogas produced is consequently utilised when connected with a power unit.

Figure 4.3 explains the aerobic and anaerobic digestion process. Anaerobic digestion involves a series of biological processes where degradation of organic contents (Methanogen) takes place in the absence of oxygen to produce biogas and biofertilisers [137].

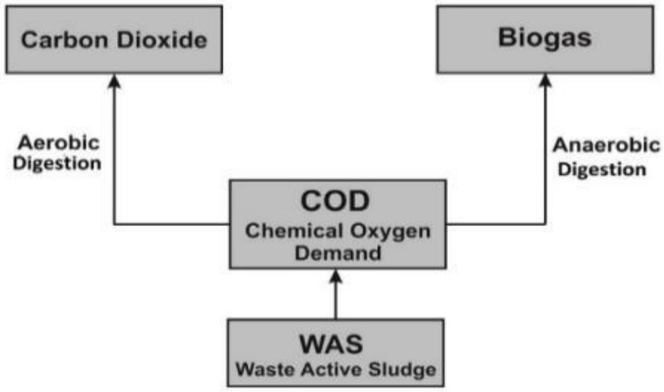


Figure 4.3 Biogas Productions at WWTPs

4.3 ELELETRICITY CO-GENERATION

The process of power generation with waste heat usage is known as combined heat and power (CHP) process. Anaerobic digestion in the biosolids digester section produces maximum amount of methane gas through CHP process. The sequential treatment flowchart is shown in Figure 4.5. Flammable gases are burnt to produce sufficient amount of steam. This steam is further utilised to excite the on-site WWTP generators for electricity generation.

CHP process is performed in an internal combustion turbine while the heat generated during the process is used for increasing the temperature of anaerobic digesters, especially during winters. Hence, a robust communication system is required for the WWTP substations equipment that interconnects them and the power company`s zone sub-station for proper relay coordination, control, monitoring and protection to achieve electricity cogeneration and overall efficiency [138]. Figure 4.4 shows basic percentage comparison of conventional and combined heat and power process which indicates that CHP process is 26% more efficient than the conventional system.

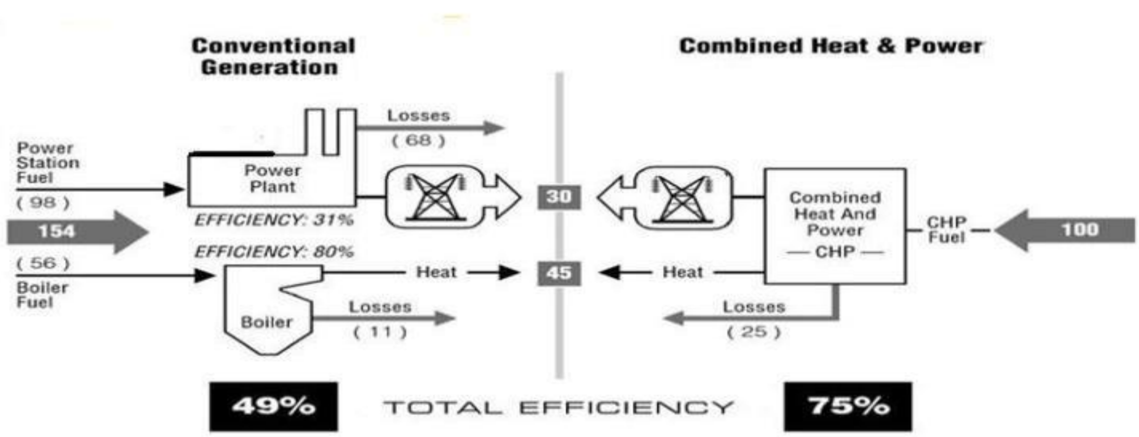


Figure 4.4 Percentage of Separate and CHP System

Figure 4.5 indicates power generation process from biogas produced through anaerobic digestion process.

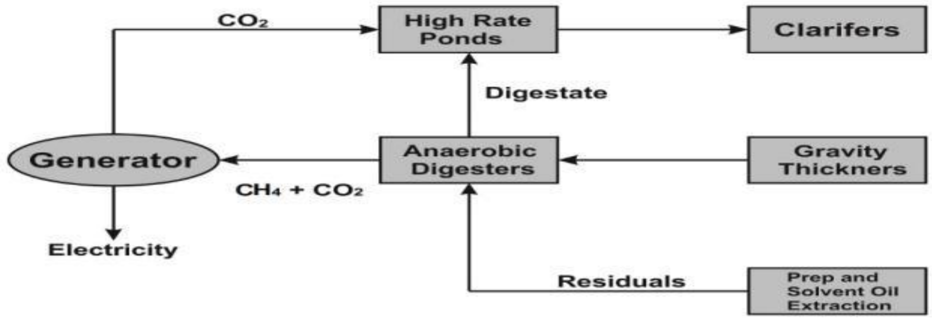


Figure 4.5 Biogas Production and Power Generation at WWTP

4.4 PROBLEM STATEMENT

4.4.1 Inability to Manage Variations in Biogas and Power Generation in Existing and Old WWTPs

Figure 4.6 shows relative biogas yields at 35 ^{0}C temperatures for anaerobic digestion process at MW-WTP. The yield increases with the increase in temperature and then stabilises after reaching its peak value [143]. Hence WWTP electricity generation also varies leading to three different scenarios electricity cogeneration.

This calls for a robust and failsafe communication network for the control and monitoring of WWTP infrastructure so that the status, fault and telemetric signals, along with other important information about the state of WWTP power network, can be efficiently and swiftly shared across all the relevant substations.

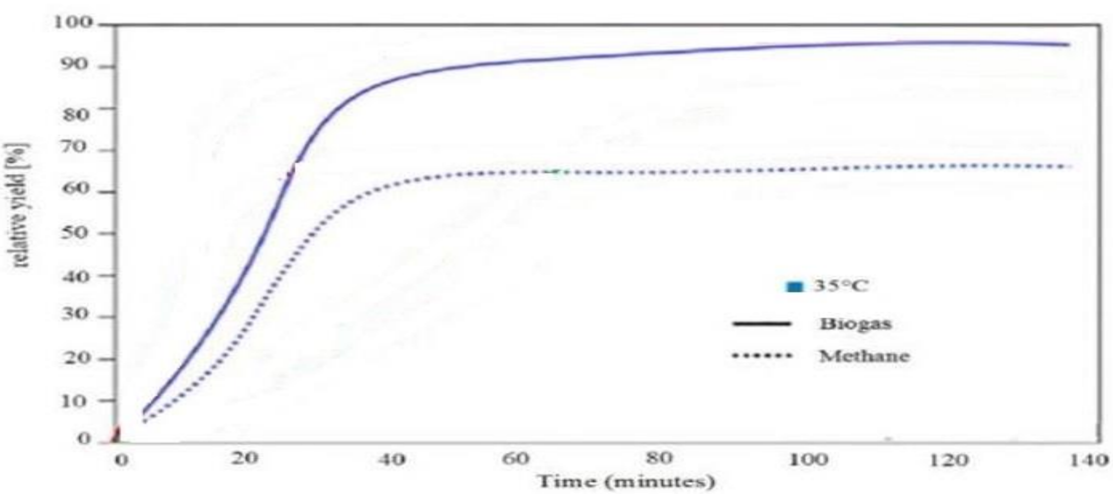


Figure 4.6 Relative yields at 35 ^{0}C of biogas and methane at MW-WTP

4.4.2 Existing WWTP Substations do not have a Failsafe and Redundant Communication System:

Most of the existing WWTP substations do not offer a failsafe and redundant system for communication network and power supplies. The backup protections and communication systems offered by traditional infrastructure have coordination issues with respect to selectivity and sensitivity of protection relays and switchgear auxiliaries. This increases the fault occurrence probability during the two-way power flow making the arrangement unsafe and infeasible for electricity cogeneration. The operation requires an efficient and automated monitoring and controlling interface that enables continuous coordination [144]. Therefore, a philosophy must be developed considering LCTA principles for the optimum usage of the WWTP biogas production that can manage this complicated process. There exists a communication network between MW-WTP distribution substations, termed as “Point of Contact” (POC1, POC2, POC3, POCn) and the power company`s zone substation. If communication fails between POC2 and POC3 due to a fault, the breakdown causes coordination issues within the MW-WTP equipment, resulting in unnecessary power outages and shutdowns, making the arrangement unsuitable for electricity cogeneration, which requires continuous coordination and monitoring. Figures 4.7 and 4.8 show a communication system without any layers of protection for acknowledgements to manage the MW-WTP electricity cogeneration process.

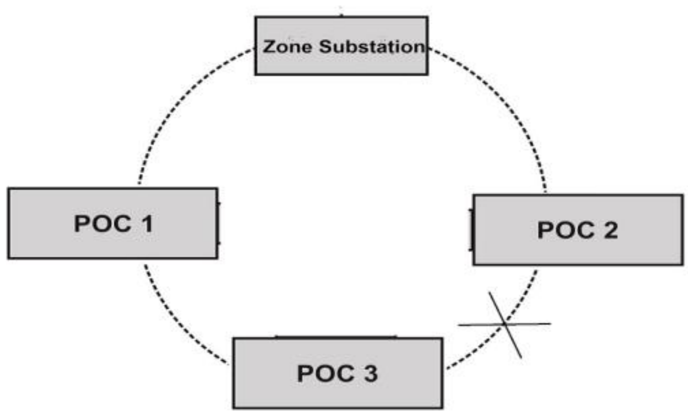


Figure 4.7 Fault Scenario on Existing MW-WTP Communication System

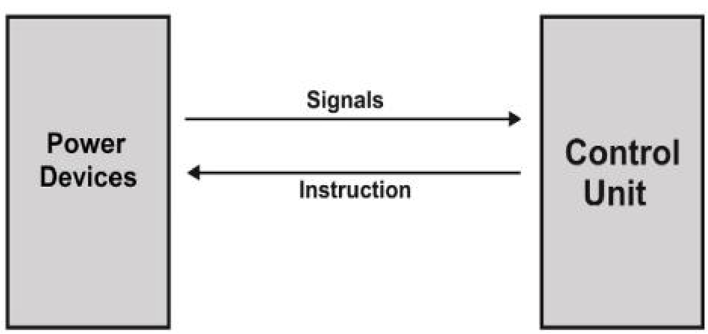


Figure 4.8 Transmission without Acknowledgements

4.4.3 Power Management System (PMS) – Operational Issues

Existing WWTP substations comprise of complex secondary designs to monitor and communicate metering signals, protection relay trips and other switchgear monitoring data. The reliance on relays performing protective and important tasks, such as local backup for the entire sub-station and the interconnected transmission lines, is too much. This causes operational and maintenance issues. Moreover, there is no proper system to receive WWTP equipment status acknowledgements throughout the network, which is very important for adding a layer of protection during the electricity cogeneration process to reduce manual and physical operator tasks and interaction with the WWTP HV equipment for switching purposes [145]. Thus, operations are unable to perform tasks within the required time due to network failure, contributing to unwanted power outages and shutdowns. Simulation shows in Figure 4.9 unwanted shutdowns at MW-WTP due to lack of communication and PMS.

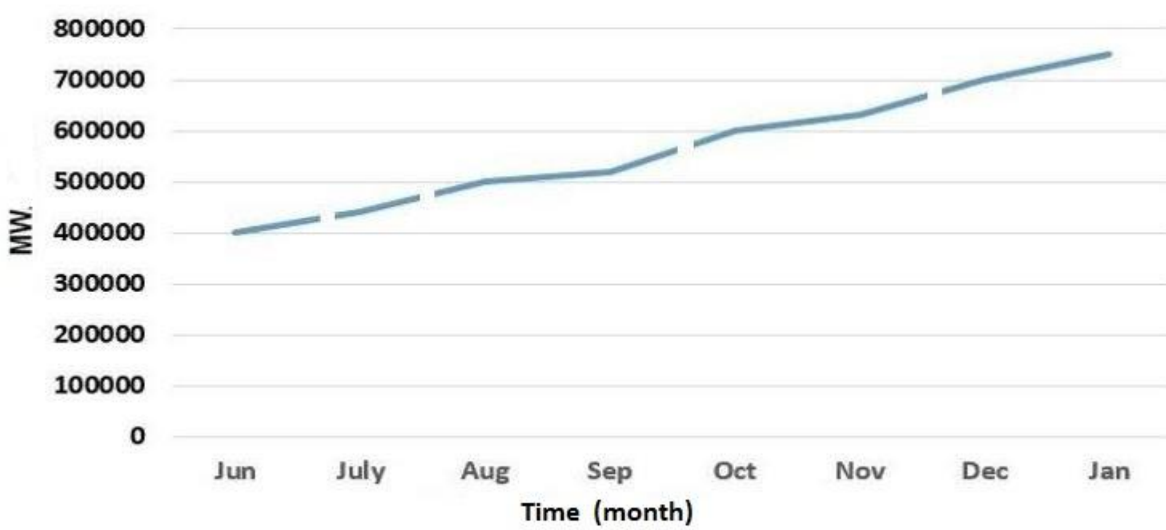


Figure 4.9 MW-WTP Shutdowns due to Faults

4.4.4 Telemetric Signals and SCADA Compatibility Issues

Required status signals for control and monitoring of WWTPs, with a proper communication system, is unavailable for electricity cogeneration in the existing infrastructure. The telemetric sequential philosophy needs to be designed, mapped and made available at the WWTP substations for an efficient PMS. Moreover, failsafe and redundant systems to give efficient continuous automated results are unavailable due to the inability of the existing system to synchronise with SCADA or any other HMI.

4.4.5 Auxiliary Supply Battery Charger Failure

When a fault occurs in battery chargers, the auxiliary switches, contacts and installed modems in existing WWTP substations are unable to function and the messages cannot be transferred across the power network. To avoid risks, the two-way power flow process is discontinued till the DC supply resumes. Continuous supply to the sub-station switchgear auxiliaries is also affected [146]. The Simulation shown in Figure 4.10 recording of the auxiliary DC voltage supply during an automatic re-close switching attempt at MW-WTP POC1. In this case, the CB fails to close due to failure of DC supply, which receives supply from the battery when the close circuit is energised.

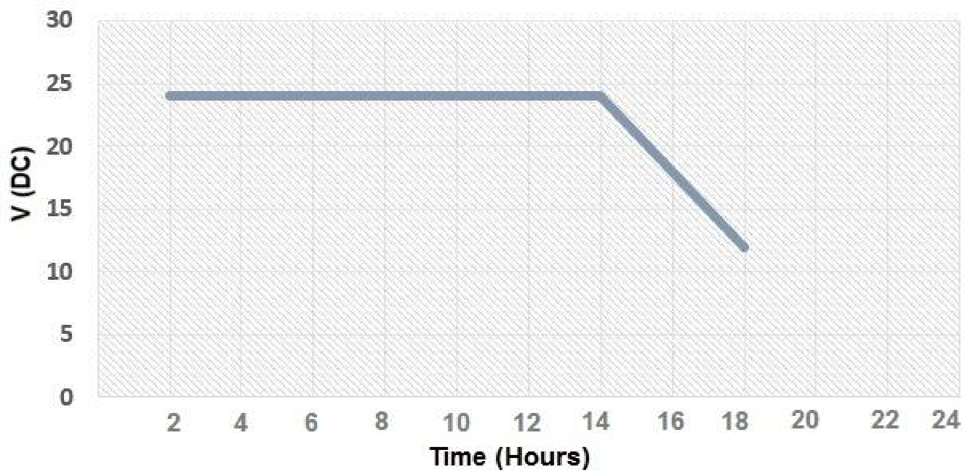


Figure 4.10 Record of DC Supply Failure at MW-WTP POC1

4.4.6 WWTP Protection Systems and Intertripping Downtime

Fault detection devices perform their operations with CBs, relays and contactors. Existing and old WWTPs have manual CBs and relay controlling system that has an inefficient operational time creating hazards for equipment protection and operation [147]. Figure 4.11 shows simulation of MW-WTP existing over-current relay operational timing at POC1.

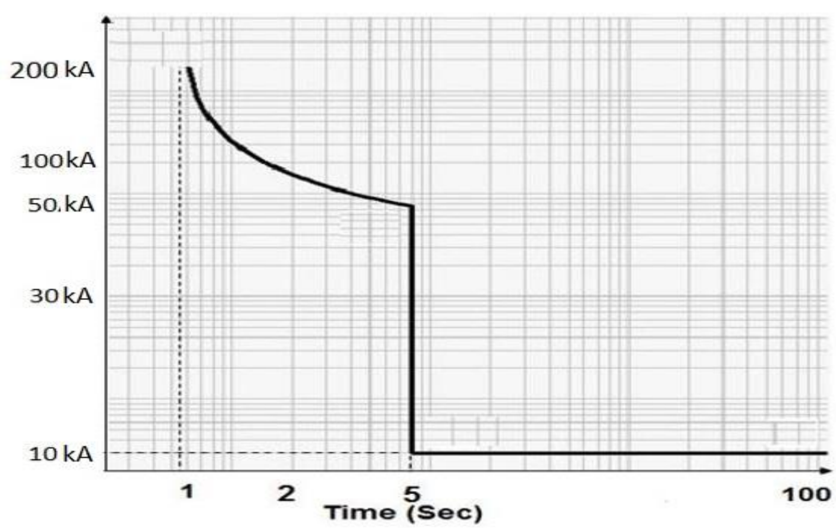


Figure 4.11 Over-Current Relay Operational Time for MW-WTP POC1

4.4.7 OH&S, Environmental Issues

When WWTP substations, in a predefined time interval from any power network equipment, receive ‘no response’, all the connections are terminated and the CB of the respective POC opens to prevent any power flow. This is done to avoid any blind operation or task being carried out automatically, or by WWTP operators, impacting OH&S standards. Eliminating the probability of fault occurrence that can damage the WWTP equipment and infrastructure is important for electricity cogeneration. This can be achieved by providing a redundant communication system. Figure 4.12 shows GHG and carbon emissions during MW-WTP power generation. WWTPs can contribute to global warming and can leave a bad environmental footprint without a robust system to utilise on-site biogas and heat.

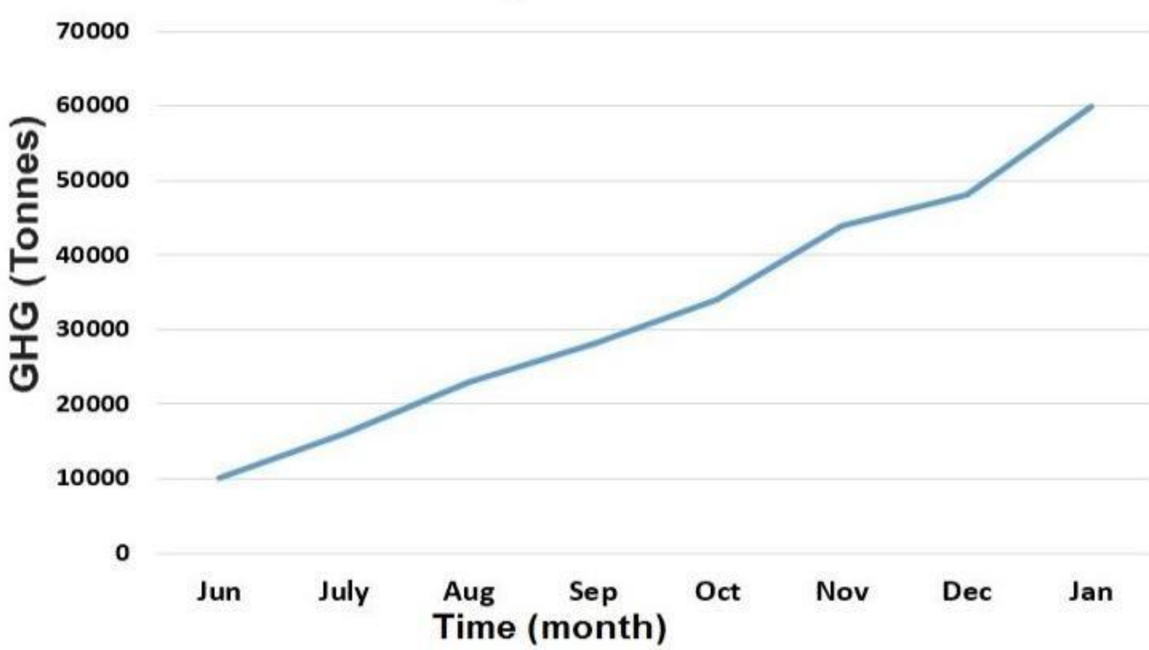


Figure 4.12 GHG Emission

4.5 PROPOSED PHILOSOPHY AND METHODOLOGY

4.5.1 Network Protocol and Standards

Node to node communication between the WWTP substations is driven by IEC61850 standard that defines a standardised format for sub-station configuration language (SCL). It includes various functions for SCADA, Intelligent Electronic Devices (IED) and for the network control technology. Distributed Network Protocol (DNP3) is a register-based protocol that stores data intended to be communicated in a register location of IEDs. Systems complying with these standards are most suited to provide protection and control for WWTP electricity cogeneration. IEDs connected to WWTP substations and power network exchange data where they are given equal priorities. The source and destination IEDs can efficiently communicate with each other under this system by specifying and allocating functionalities to indicate events occurring in the substations such as Generic Sub-station Event (GSE), which can replace the traditionally deployed hard-wired auxiliary and secondary circuits in the existing WWTP substations. GSE messages are also structured in a standardised format, which can be communicated and acknowledged by the IEDs and any given HMI. This set up also minimises the network traffic during faults. The IEEE1588 standard facilitates the usage of the Precision Time Protocol (PTP) to fulfil the clock synchronisation requirements in packet-oriented networks [148]. Link aggregation control protocol (LACP) is implied for physical connection of the network nodes. The DNP3 protocol has compatibility with IEC62351-5 and is widely recognised as a communication standard for utilities and WWTPs.

4.5.2 Connectivity and Standards

Modern Ethernet networks can effectively integrate and carry out the operations required in SAS with telemetric mapping of a WWTP. Ethernet networks sends all the data between WWTP and power company`s zone substations through fast HIPER-ring topology setup. A backup power supply is also made available for every node. Network paths going through low transmission speed are assigned a higher path cost. The Hirschmann Ethernet switches are installed in each smart RTU at substations that deliver the bandwidth required for data traffic. Higher network priority is assigned through quality of service (QOS) designation. Fibre optic communication system (FOCS) is designed to communicate via smart RTUs, which have the ability to patch and integrate protection, control, and monitoring devices. IEEEC37.238 utilises FOCS with IEC61850 [149].

4.5.3 High Frequency Transformers

Higher frequency transformers use ferrite toroidal cores. Their frequencies range between 10 kHz to 100MHz. A higher frequency is maintained to reduce losses, size and weight of the transformer. The technology upgraded to a solid-state transformer is replacing the traditional 50/60 Hz power transformer by means of high frequency isolated AC/AC solid state conversion techniques. Power generation, transmission, and distribution are the three main parts of the modern power system, in which the power transformers play a critical role. The power transformers enable the high efficiency and long-distance power transmission by boosting the voltage to a higher one in the generation side. Figure 4.13 shows the reverse power factor has increased during the WWTP cogeneration process using step-up transformers.

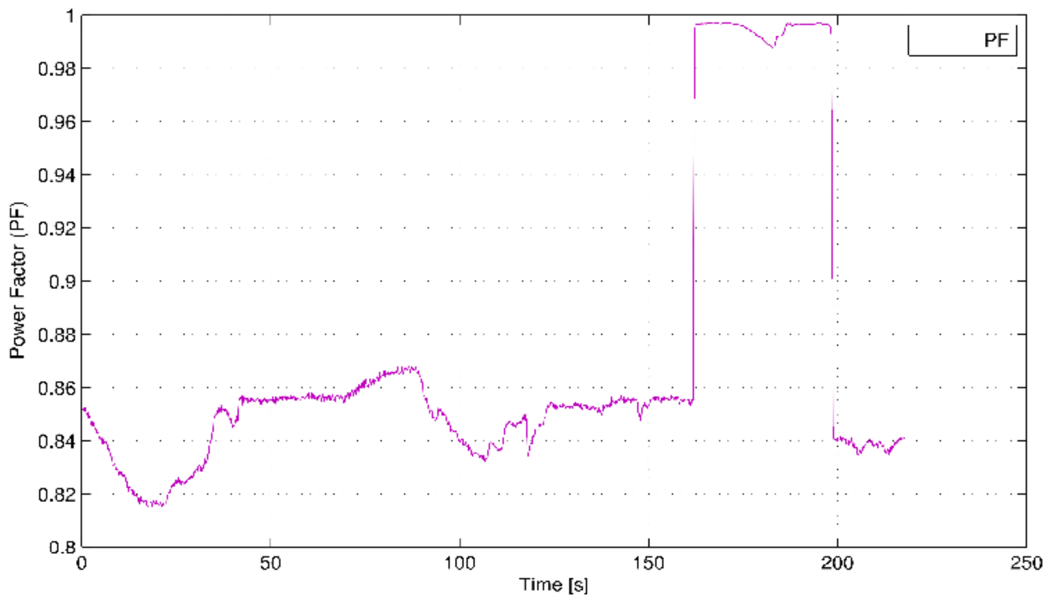


Figure 4.13 Power Factor for Cogeneration process at WWTP

4.5.4 Modbus Serial Communication with Smart RTU

Modbus is an open, serial RS-232 protocol derived from master-slave architecture. It is widely used due to its user-friendly and reliable features. It is considered as an application layer for messaging protocol that provides master-slave communication between devices connected through buses and networks. This protocol can be efficiently applied on an existing WWTP infrastructure for electricity cogeneration.

4.5.5 Structure of SAS

Figure 4.14 shows the structure of SAS in three levels of protection that are defined by the IEC61850 standards as mandatory. Smart RTU philosophy can be successfully implemented in the existing WWTP infrastructure using these protocols [150]. These protocols form the basis of the design philosophy and the layout of the SAS. The proposed smart RTU in this research, provides that link between the field devices, the communication interface and the HMI. The three basic levels in a power distribution system to form an integrated SAS are:

1. **Station Level:** A shielded control room, which receives data from various bay levels for necessary data exchange through any network protocol.
2. **Bay Level:** Located near the switchgear, it provides protection, control, and monitoring of IEDs installed at WWTPs. It also facilitates exchange of relevant information between bay and station levels.
3. **Process Level:** It provides an interface between power devices and the bay level. It involves the switchyard section of Sub-station such as CT and VT. The smart RTU transfers

telemetric signals and time critical messages, such as CB status and trip controls, between the process and the bay levels swiftly.

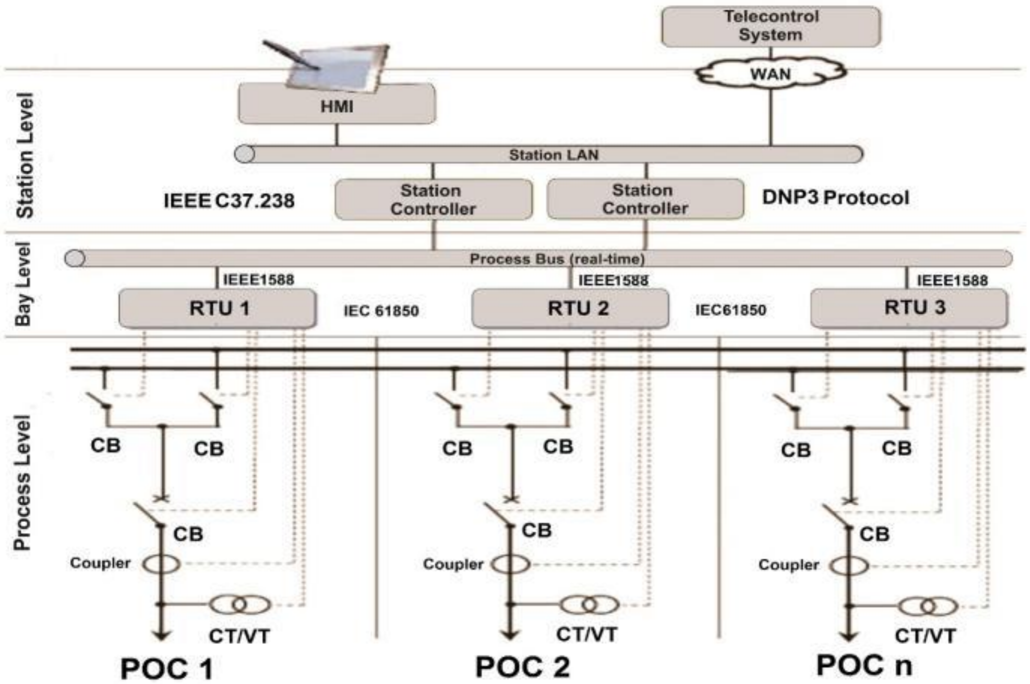


Figure 4.14 SAS Architecture

Connectivity between the zone sub-station and the WWTP distribution substations in the form of ring topology is made through smart RTUs on the power network to form a redundant and failsafe communication network. Open System Interconnection (OSI) is mandatory for the swift flow and mapping of telemetric signals across the network. It requires a tool to monitor and evaluate the state of the entire WWTP. This can be achieved by having a centralised HMI or SCADA system.

4.5.6 Embedded Ethernet-based Communication Technology

Embedded ethernet technology is used in SAS as an efficient mode of communication. A smart, failsafe and redundant network communication system requires proper synchronisation of IEDs with data transmission protocols to make it secure and reliable. For proper mapping of this telemetric data, the WWTP designers must perform manual and logical coordination and configuration of IEDs to determine the flow and direction of power system variables like index numbers and metering data. The provision in object models of IEC61850 enable IEDs to present their data using identical structures that directly correspond to their relative power system functions. IEEEC37.238, on the other hand, defines mapping of these signals and is considered for nodes with one or more Ethernet ports [150]. Figure 4.15 shows WWTP embedded system with corresponding IEC standards.

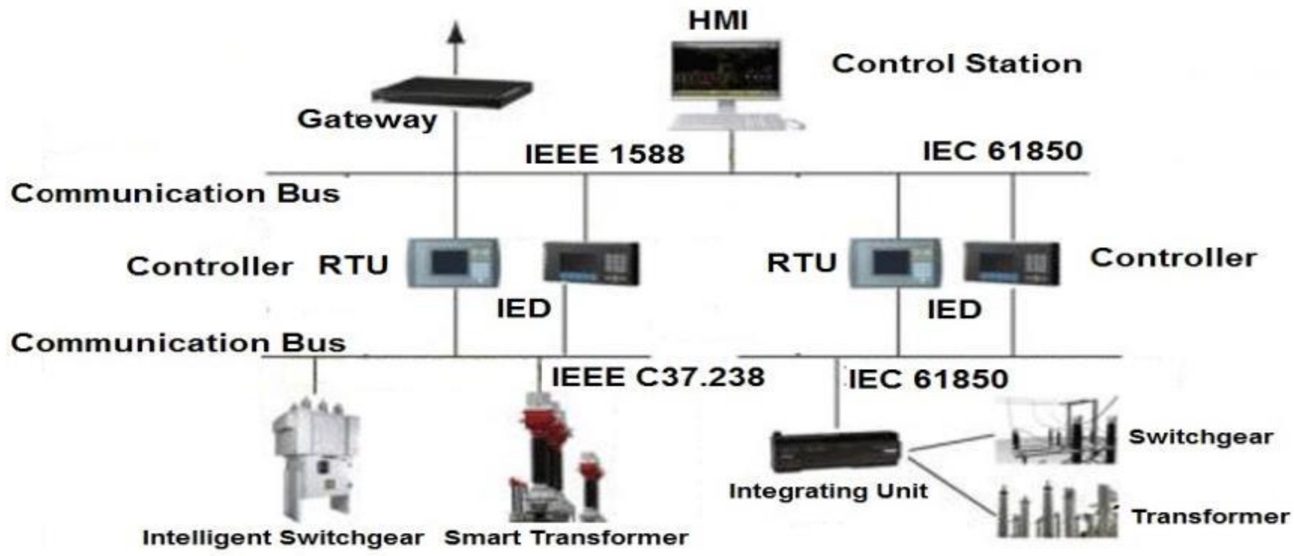


Figure 4.15 Embedded SAS with IEDs

4.5.7 Power Management System (PMS)

Control, automation and management of a WWTP are sensitive and crucial tasks that require constant supervision. With advanced sewage treatment strategies getting progressively common, communication networks need to be able to respond swiftly with robust control mechanisms and secure designs. SAS and redundant failsafe communication provide proper PMS for effective multidirectional power flow systems. Power expressions are modelled with proposed philosophy for load control management in different POC busbars for protection. Equation (4.1) represents utilisation of demand load on each busbar at POC [151].

Load Control Management

$$L_d = \sum_{i=1}^{l} \frac{w_i}{2n} \left(\frac{IV_iI - IV_iI^r}{\Delta V^d}\right)^{2n}$$

$$PI_{MVA} = \sum_{i=1}^{nl} \frac{w_{li}}{2n} \left(\frac{S_l}{L_d}\right)^{2n} \tag{4.1}$$

Where;

IV_iI = voltage magnitude at bus i

r = relative load in bus

l = number of buses in a system

w_i = weighting factors set arbitrary for each bus

ΔV_i^{lim} = limit of load demand in each bus

S_l = power flow of line

L_d= maximum load can flow in line

nl = number of lines

W_{li} = weighting factors of each line

Figure 4.16 shows load management system between power generation and distribution site.

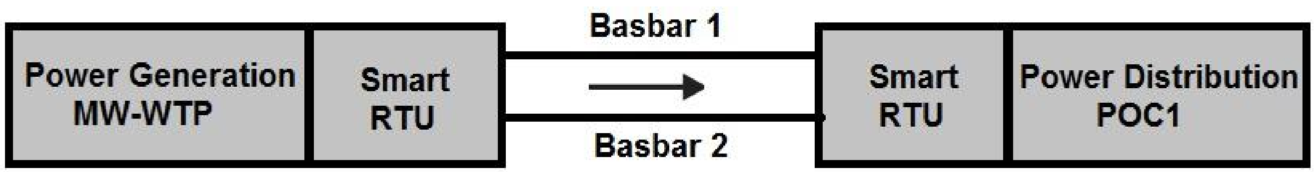


Figure 4.16 Load Management System

4.5.8 FOC Patching in Ring and Mesh Topology

A redundant and failsafe network setup is essential to ensure constant resource availability and control to address single point connection failures. Existing WWTPs are based on legacy system, which either have a stand-alone deployment or traditionally utilise a star topology Ethernet network for telemetric communication. Valuable data from field devices have high loss probability when WWTP POCs encounter a fault. Ring topology introduces flexible performance by rebuilding the network and data route immediately via an alternate path under such conditions. The smart RTUs provide patching and testing point for these FOCs at a WWTP.

4.5.9 FOC and Reliability Flexibility

FOCs facilitate in attaining the required electrical isolation in order to reduce electrical hazards under fault conditions [151]. Hirschmann switches continuously perform the reachability test through a series of internet control message protocol (ICMP) echo requests that are further sent to connected networks for monitoring instant response time and connectivity.

WWTPs must have broad network coverage for equipment placed at distant sites and substations. FOCs are the most suitable choice while extending to long distance point-to-point connections. The FOCs channel strengthens electromagnetic interface and control, which provides secure and reliable communication in harsh weather conditions. This advanced networking setup demands adoption of a network with wide bandwidth that will make it possible for the SCADA system to command execution of a remote status from a centralised control centre at a WWTP. The noise free system and rapid data transfer are key feature for SAS [151, 152]. Hence, transmission via FOC enhances integrity and reliability of data by increasing the level and speed of communication at WWTPs or any site where renewable energy is available. Figure 4.17 shows FOCs communication network with SCADA system.

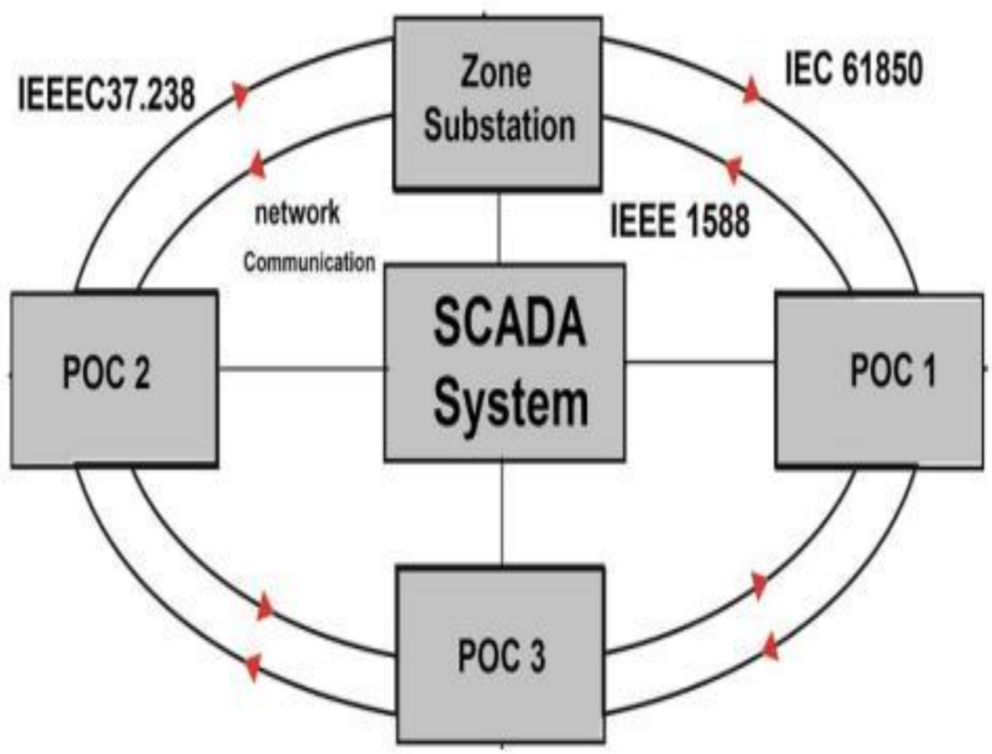


Figure 4.17 FOCS Ring and Mesh Communication Network

Existing WWTP power infrastructure lacks the desired communication capacity to minimise its complicated secondary circuits like metering signals, protective relaying and control gear monitoring for a flexible infrastructure. Smart RTUs allow easy functional implementation that provides each vendor with an opportunity to use his/her own design to achieve required functionality.

It also allows for data to pass through communication bus and makes performance evaluation of sub-units feasible without affecting the substation's usual operations. This flexibility is achieved through implementation of network ring topology via smart RTUs. They are easy to manage and provide a one-stop for operations and fault detection. The modular nature of smart RTUs provides flexibility to integrate with any future upgrades or technology.

4.6 PROPOSED SMART RTU INTERFACE

The SCADA needs to assemble data from various network components in order to ensure the availability of entire WWTP information at a centralised location for an effective and common use. The smart RTUs are normally utilised as part of SCADA system to reinforce correspondence between the substations and control room [153].

The proposed philosophy aims to set up a suitable configuration and connectivity based on cost effectiveness, adequate ingress protection, reliable implementation, efficient performance, and the ability to manage and control all WWTP power failure and electricity cogeneration scenarios.

The proposed design utilises remote and on-site controls for monitoring metering data, protection trips, status, supervision and fault indications of the substations and the WWTP generators. This network extension can seamlessly integrate with existing WWTP infrastructure.

An intertripping and interlocking mapping philosophy is developed with required telemetric signals made available to the proposed smart RTU`s interface at a potential-free contact to optically isolate different control voltage levels.

Figure 4.18 represents the proposed smart RTU interface. Depending on their central function and mapping philosophy, these telemetric signals are directed accordingly using PLCs, network protocols, modems, patch panels and FOCs. The design monitors the status of electrical flow, protection trips, and faults.

The wiring of smart RTUs with their respective substations is based on the mapping, interlocking and intertripping philosophy of WWTP. These signals are mapped onto an HMI or SCADA for proper monitoring and control. The potential-free contacts in the smart RTU are energised by an external redundant source.

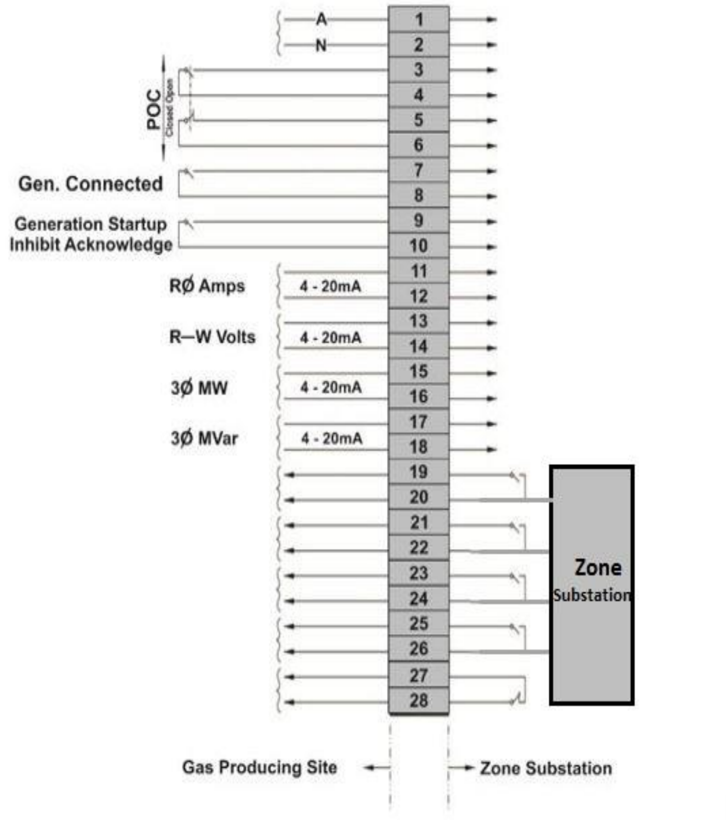


Figure 4.18 Smart RTU Interface for WWTP Electricity Cogeneration

4.6.1 Implementation of the Network Philosophy

The proposed smart RTU philosophy has been realised at MW-WTP. It has a massive sewage and industrial waste treatment facility that produces huge amount of biogas. Existing power infrastructure, through smart RTUs at MW-WTPs POCs and power company`s zone substation, resulted in achieving electricity cogeneration, power supply and communication redundancy with optimum usage of biogas by CHP process. The zone sub-stations directly connected to POCs via the smart RTUs that provide an interface to transfer data from relays and internal storage. To guarantee availability of MW-WTP status, ring topologies are implemented including intelligent network managed switches like Hirschmann switches [154]. The smart RTUs interface has the ability to process telemetric signals from the POC-PLC, interposing relays, switchgear auxiliaries and communication bus to IEDs and HMIs. Information accumulates in POC-PLC and is then sent to SCADA via the smart RTUs. The installation considers reduced cabling by segregating the centralised control and monitoring of the updated SAS. The proposed network philosophy, therefore, presents a flexible solution as opposed to conventional schemes in existing WWTP substations.

4.6.2 Network Arrangement at MW-WTP

Figure 4.19 presents proposed network arrangement for the smart RTUs to achieve redundant and failsafe communication at WWTPs. Communication design is divided into two sections, power company`s zone sub-station and MW-WTP POCs. The physical network nodes are interconnected via LACP to make accumulated bandwidth of each trunk in the network, accessible for transmission of information. When communication failure occurs, the remaining connections gain control of the on-going data transmission thereby ensuring redundancy. There is also an automated load distribution mechanism between the trunks. The DNP is used for enabling communication mode between SCADA systems and smart RTUs. This robust and intelligent protocol also facilitates reliable interoperability between the system nodes [153, 154]. SHDSL NTU managed Hirschmann switch provides IEC61850 standards redundancy protocol. SHDSL isolation transformers are used for fast communication in gigabytes and can be configured with various ports. It eliminates the use of multiple routers, saves time and cost. TEP-TSU provides reliable and flexible external network interface for the structures of telecommunication cabling systems. REMOTE HQ module enables communication with the control-centre database and sends information from a database through the Internet. Transceivers work as a transmitter and receiver for the smart RTUs. Cat6 Ethernet provides a swift communication system with 500 MHz frequency HMI interfaces via RJ45 connector. These provisions consider compatibility with future technologies and WWTP upgrades.

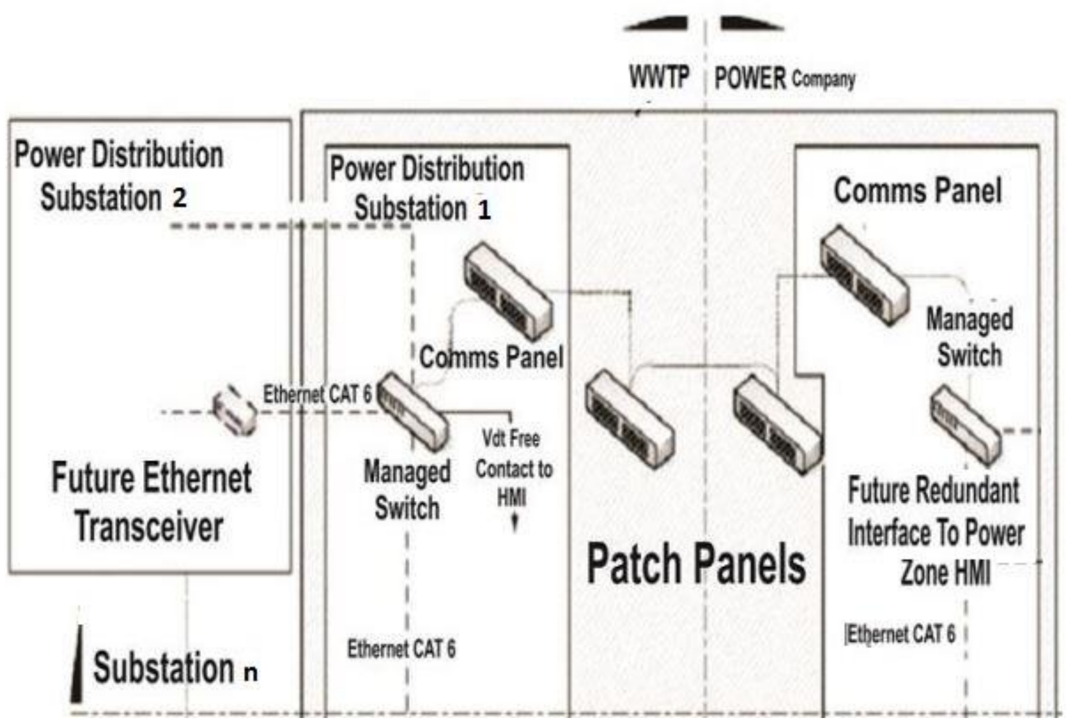


Figure 4.19 Network Switching using FOC Patch Panels at MW-WTP

4.6.3 HV Reticulation

The HV reticulation mechanism is applied to the Melbourne Water WTP. The smart RTU philosophy installed is comparatively easy to implement and reduces the need for complex secondary wiring in the distribution substation(s) for attaining interlocking and inter-tripping of the power supply equipment. The figure describes the power flow from the main feeder to the distribution substations POC1 and POC2. The treatment plant utilises self-generated power on first priority and the surplus power is passed through high frequency transformers to feed to the zone sub-station POC1 and POC2. The inter-tripping mechanism ensures that power can only be supplied through site generators when there is sufficient capability while the power coming from zone Sub-stations being shut down and vice versa.

The network provides a failsafe and redundant solution by implementing a ring topology. Power factor correction is necessary for on-site generated power to handle energy quality problems. Balancing the capacitive reactive power for voltage regulation and reducing the harmonics, which with improved telemetric signals communication, achieves this functionality.

The system optimally uses the produced biogas by exciting the eight on-site generators connected with the plant LV supplies and feeding the excess back into the power supply company`s zone substation. With the intertripping and interlocking philosophies provided, the surplus amount of electricity is fed back to the zone sub-station through high frequency transformers, which step up the excessive amps to 1 kV.

Intertripping signals are established between CBs of the POCs to trip during faults while interlocking is achieved between the zone sub-station and biogenerators thus providing two layers of protection.

4.6.4 Layout of Distribution Substations

Figure 4.20 represents the equipment layout of POC1 and POC2 with front elevation. It elaborates on the telemetric functions communicating via PLC and other relays that are responsible for efficient RTU panel operation. Two modes namely sink mode and source mode define the connectivity between the I/O coming from the smart panel and I/O of the PLC.

Hirschmann RSR-20 managed switch is specifically designed with consideration of industrial automation to show compliance with industry standards. The switch is capable of operating under severe surrounding conditions with reliable and long-lasting performance. Residual current device (RCD) provides the protection to deal with electrocution and power quality issues. These devices act as circuit breakers (CBs) enabling automatic circuit opening at the point of placement when the residual current, arising due to circuit failure, crosses a specific threshold. The POC2 has an additional component, a modem, to create networking between equipment.

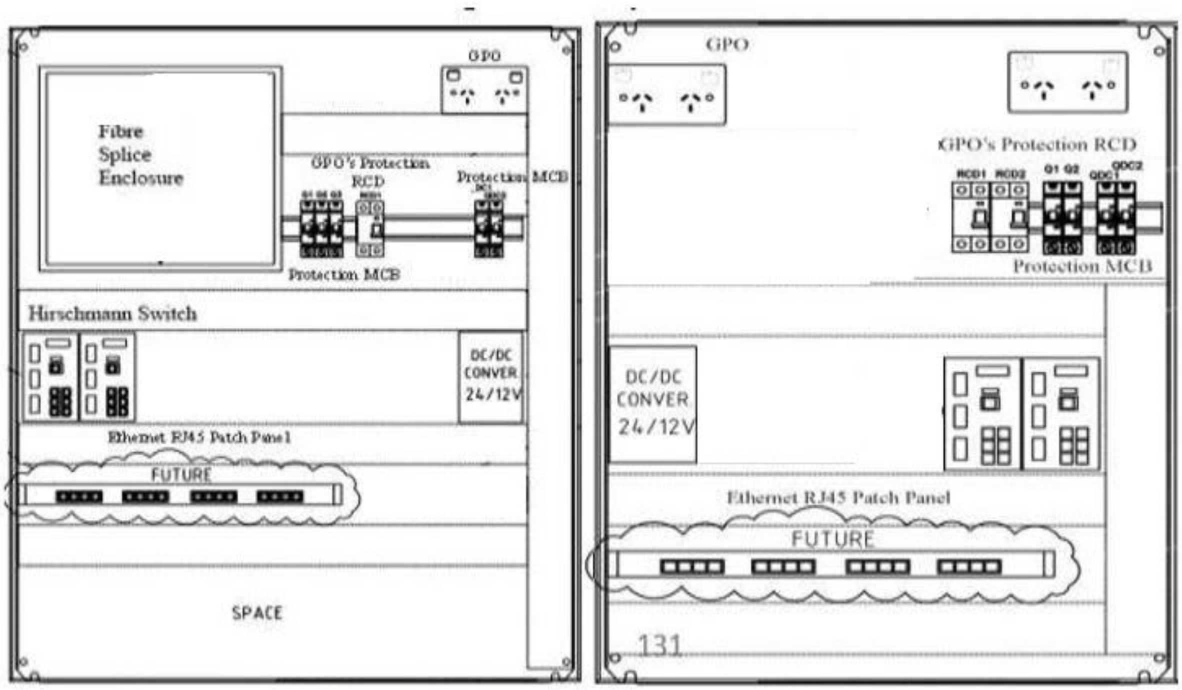


Figure 4.20 Layout for Substation

4.7 PROBLEM EVALUATION

4.7.1 Redundant and Failsafe System

Figure 4.21 shows proposed effective communication between different devices at the POCs and the zone substations. Smart RTUs are also interconnected with a communication network for reliable and effective control on power flow with SCADA system [155].

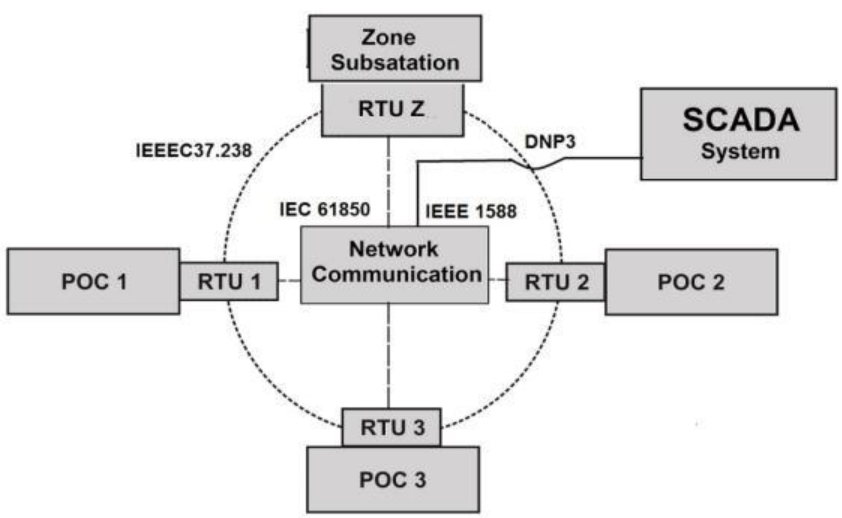


Figure 4.21 Redundant and Failsafe System

4.7.2 Loss of Communications

Different levels of anaerobic digestion produce varying amounts of biogas. Lower levels of anaerobic digestion lead to intra-communication loss between the MW-WTP POCs and the power company`s zone substation, triggering an assertion of 'loss of communication' output at the POCs. This telemetric output initiates a timer, which enables reverse power protection upon expiration. When communication fails, acknowledgments are not received, which imposes safety issues. Figure 4.22 shows fault scenario at POC2. An alternate path for communication, provided by the smart RTUs, makes the system failsafe and redundant. WWTP continues its operation without any shutdowns.

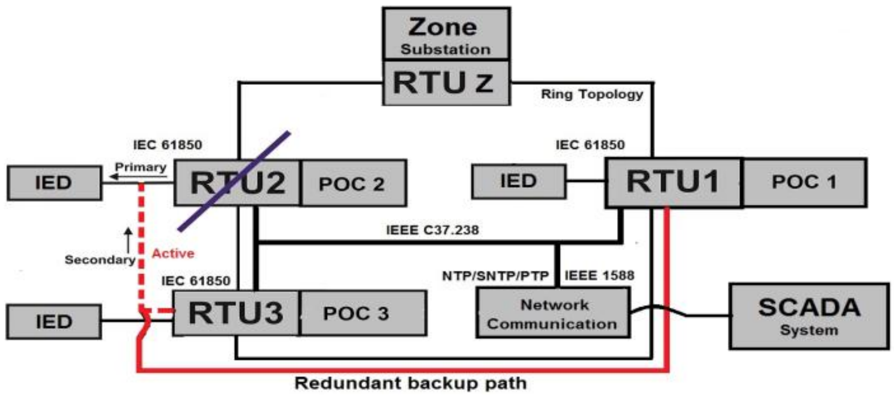


Figure 4.22 Fault Scenario Redundant Backup Path at MW-WTP

4.7.3 FOCs with Smart RTUs

Figure 4.23 shows ring topology network in which each node is connected to the adjacent node to form logical rings via smart RTUs. The network is easy to install and very flexible as new nodes can be added at any point in the ring.

Data packets travel in the circumference of the ring within the latency requirement of the network protocol. Cable redundancy must be built in the ring network so that it is protected against any node failures and cable leakages at WWTP [154, 155].

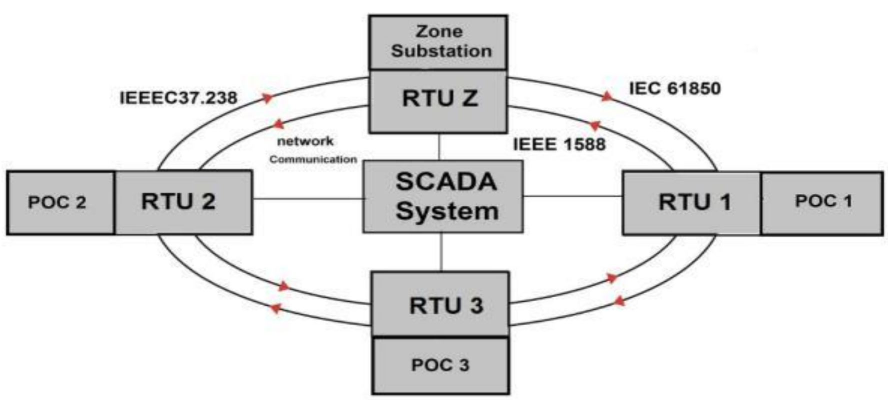


Figure 4.23 FOC RTUs Connectivity and SCADA System

4.7.4 Advanced Network Communication

DNP3 employs SCADA to control and monitor the efficiency of IEDs through smart RTUs. IEC61850 provides full compatibility and interchangeability features between the IEDs, regardless of their manufacturer. It allows the existing conventional protocols, like Modbus and DNP3, to synchronise with the IEDs and HMI. Ethernet-based switches have provisions for fibre and copper interconnections. Power network equipment is able to send and receive commands simultaneously. Figure 4.24 shows communication and relay coordination system using smart RTUs**.** Every telemetric status signal is followed by an acknowledgment before any command instructions. Smart RTUs maintain connectivity of the relevant action against it. Messages received are instantly sent as acknowledgements to the transceivers for reliable coordination.

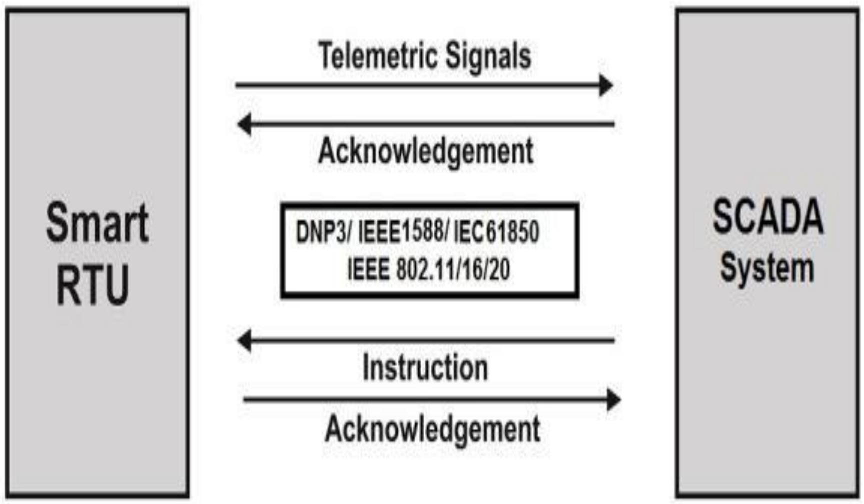


Figure 4.24 Communication with Acknowledgement

4.7.5 Signal Transfer and Intertripping Downtime

Intertripping communication in power network substations with status acknowledgements using IEC61850 protocol, is extremely reliable for coordination between different equipment and IEDs. IEC61850 compatibility with FOCs and other network protocols decreases intertripping downtime between substations, reducing risk factor and shutdowns and enabling automated WWTP electricity cogeneration process.

4.7.6 Advanced Monitoring Systems (AMS)

WWTPs have sophisticated electrical installations. Additional functions and systems can be added using smart RTUs, simplifying the whole architecture with enhanced application. Figure 4.25 shows communication between IEDs and SCADA via smart RTUs. This enables proper and continuous coordination between power supplies and substations that is required during various scenarios of electricity cogeneration and faults. This provides an AMS platform to support WWTP electricity cogeneration [156].

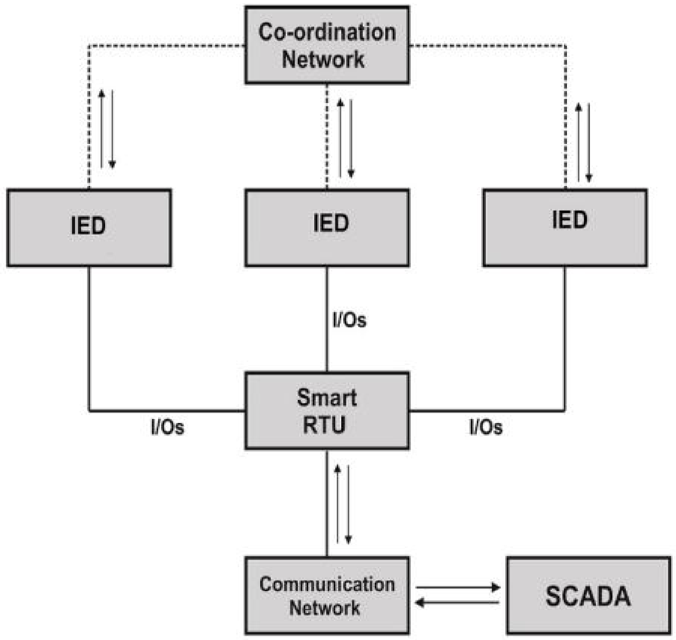


Figure 4.25 Constant Two-Way IED Coordination System with RTU

4.7.7 Smart Sensing Devices

The structure of SAS in three levels of protection that are defined by the IEC 61850 standards require support from smart sensing devices that are associated with the various electrical equipment in the power network of the WWTPs. These devices are used to sense faults, ambient conditions and other required parameters to monitor, control and evaluate the performance of the system. The proposed smart RTU in this research, provides that link and interface between the field smart sensing devices, the communication modules and the HMI in the control room.

Open System Interconnection (OSI) is required for the swift flow and mapping of the telemetric signals coming from these smart sensing devices across the network. These I/O are monitored and evaluated to determine the scenarios and the control philosophy of the WWTP. This can be achieved by inter connected network of smart sensing devices.

4.7.8 Hybrid Communication System

A smart, failsafe and redundant network communication system will provide the necessary protocols defined by the relevant IEC and IEEE standards to provide a logical philosophy for the smart RTU, smart sensing devices and the sub-station auxiliaries to connect with each other. The smart RTUs provides a hybrid communication system to the sub-station where same set of telemetric signals can be transferred across other sub-stations at WWTP using FOC and wireless routers. These hybrid communication systems form various layers of protection and redundancy for the swift transfer of the generated signals.

4.7.9 Intelligent Smart and Net Metering

The current transformers mounted on the busbars of the sub-station can generate analogue signals that can be calibrated on the smart RTU interface for monitoring and evaluation of the power parameters. These parameters are then transferred across various stations and control points for the relevant action. The hybrid communication system offered in the smart RTUs can be used to transfer and map these metering signals on any given platform. MW-WTP is now moving to evaluate their plant state on web and mobile apps for their asset managers. This will provide prompt response against any fault condition or shut down, thereby increasing WWTP productivity and safety.

4.8 RESULTS AND DISCUSSIONS

4.8.1 MODBUS Communication

Figure 4.26 simulation shows PLC connection with smart RTU and data exchange with other devices at MW-WTP using Modbus protocol. It shows redundant communication with FOC system's active and backup links enabling failsafe electricity cogeneration process.

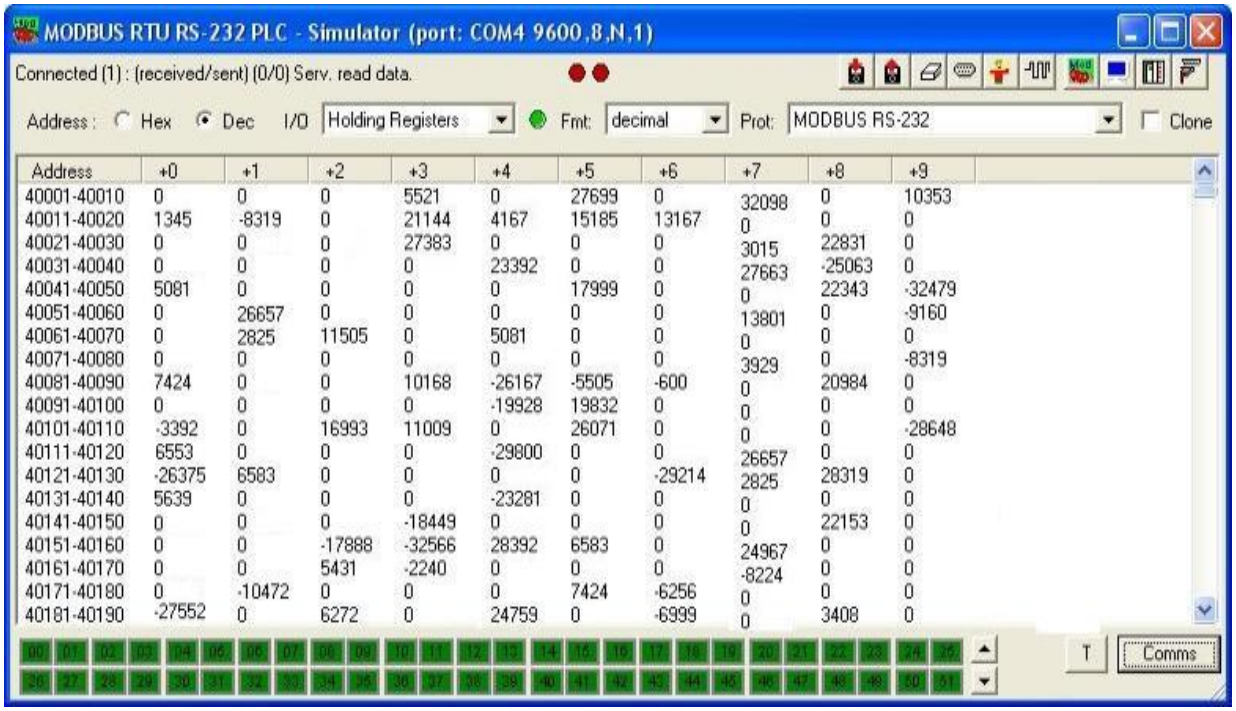


Figure 4.26 Smart RTUs with MODBUS

4.8.2 Latency for Telemetry Request and Response

Figure 4.27 shows latency comparisons of telemetric requests and their responses to evaluate the communication effectiveness with the proposed RTU interface and network arrangement at MW-WTP. The DNP protocol normally establishes communication with 1200, 2400, 4800, 9600, and 19200-baud rates. The analogue and status signals achieve better latency rates as compared to commonly used baud rates. The latency impact drastically reduces as the baud rate increases. The effect of latency on communication depends on baud rate, mode of communication and telemetric scheme. The smart RTU supports these communication protocols with an independent master SCADA system that enables automated WWTP electricity cogeneration process between the distribution and the zone sub-station.

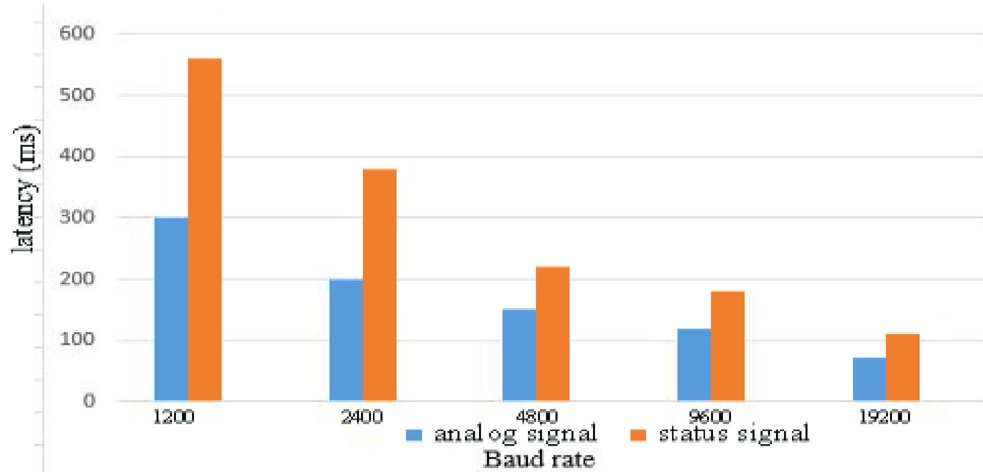


Figure 4.27 Latency for Telemetry Request and Response

4.8.3 Smart RTU Network Reliability with SCADA

Simulation of connectivity Figure 4.28 results at MW-WTP show reliable communication of the POCs with main servers of control room. Information sent back to the servers is received as acknowledgement status. Telemetric signals are provided a potential-free contact so that they could be easily synced to any given HMI. MW-WTP operator can now observe, monitor and control the electricity cogeneration process without physically present at the substations. It serves to reduce operator's tasks and his/her interaction with the power equipment.

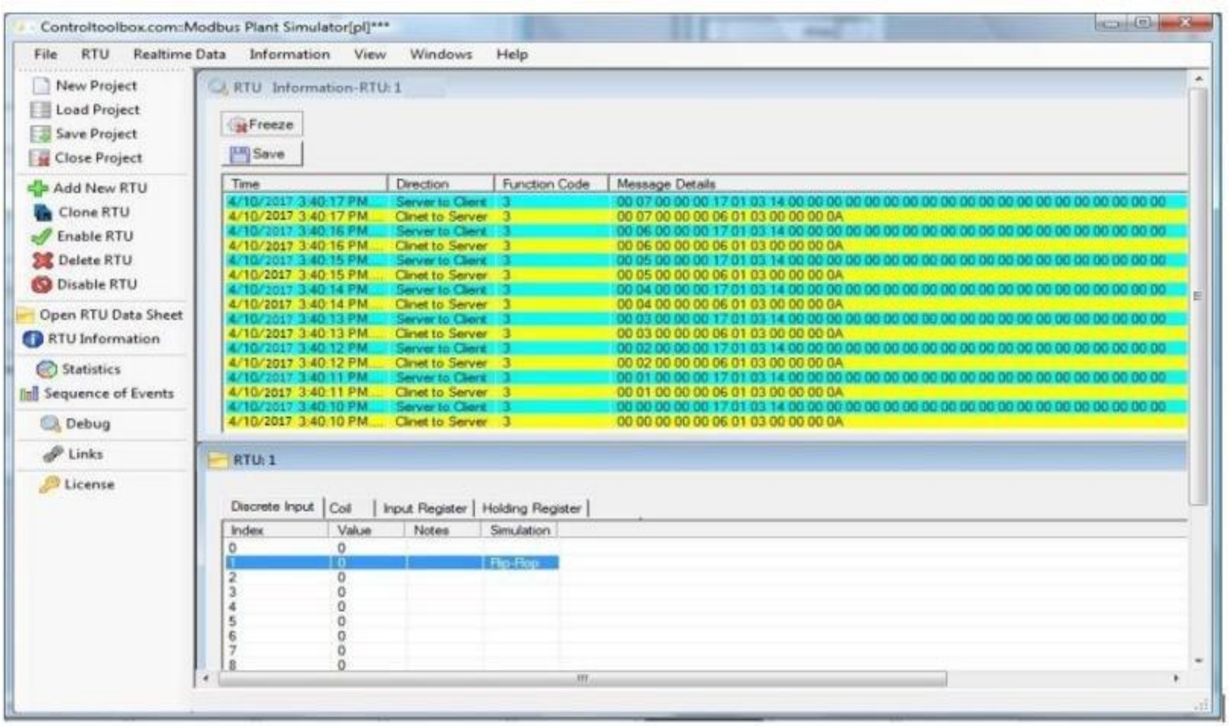


Figure 4.28 RTU Connectivity with Main SCADA Servers

4.8.4 PMS

Advanced POC1 busbar load management system was simulated at the MW-WTP and the results are shown in Figure 4.29. Results show reliable, safe and optimised electricity cogeneration with proposed communication, control and monitoring system.

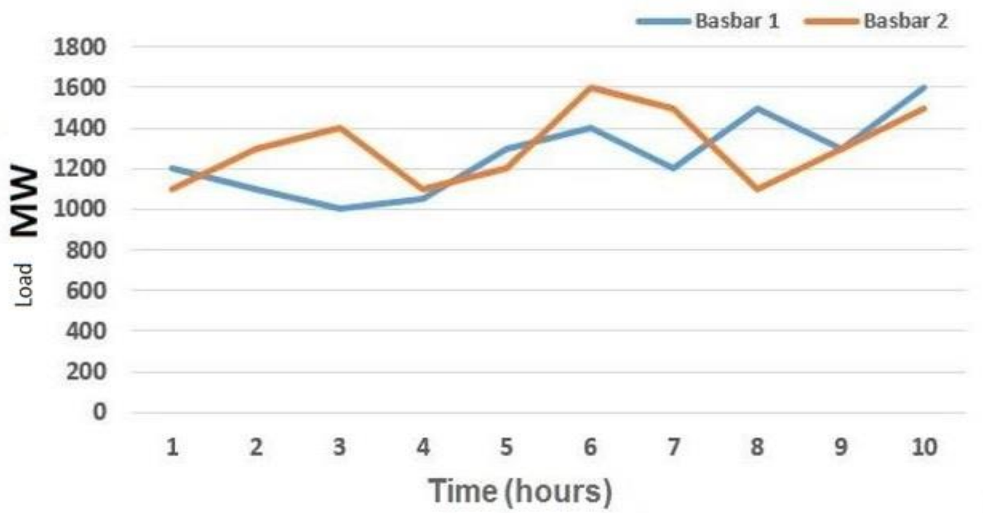


Figure 4.29 Busbar Load Management System

4.8.5 Backup Auxiliary Supply

Simulation Figure 4.30 shows backup of auxiliary DC control power supply for redundancy via smart RTUs at the MW-WTP. The backup supply becomes active when auxiliary supply collapses spontaneously due to battery charger failure, enabling redundancy for protection devices to support electricity cogeneration.

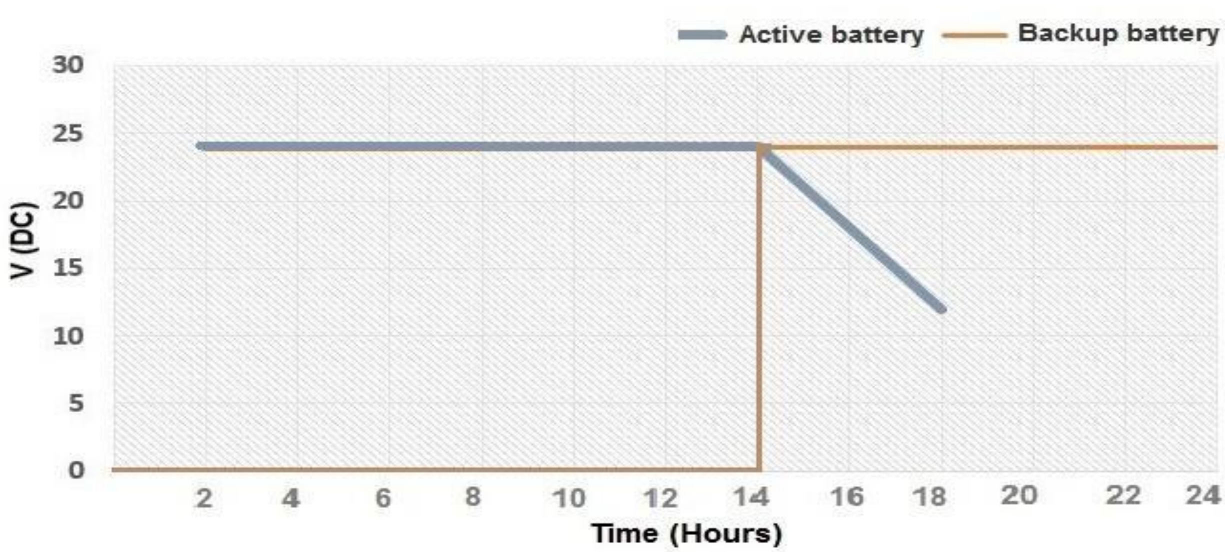


Figure 4.30 24VDC Auxiliary Backup Power Supply

4.8.6 AMS for MW-WTP

Simulations of monitoring and connectivity Figure 4.31 shows curves obtained over short interval of time at the MW-WTP. It shows on status of power demand and production, DC power supply and biogas. Results indicate continuous coordination and monitoring of MW-WTP that is required to achieve an automated and controlled electricity cogeneration process.

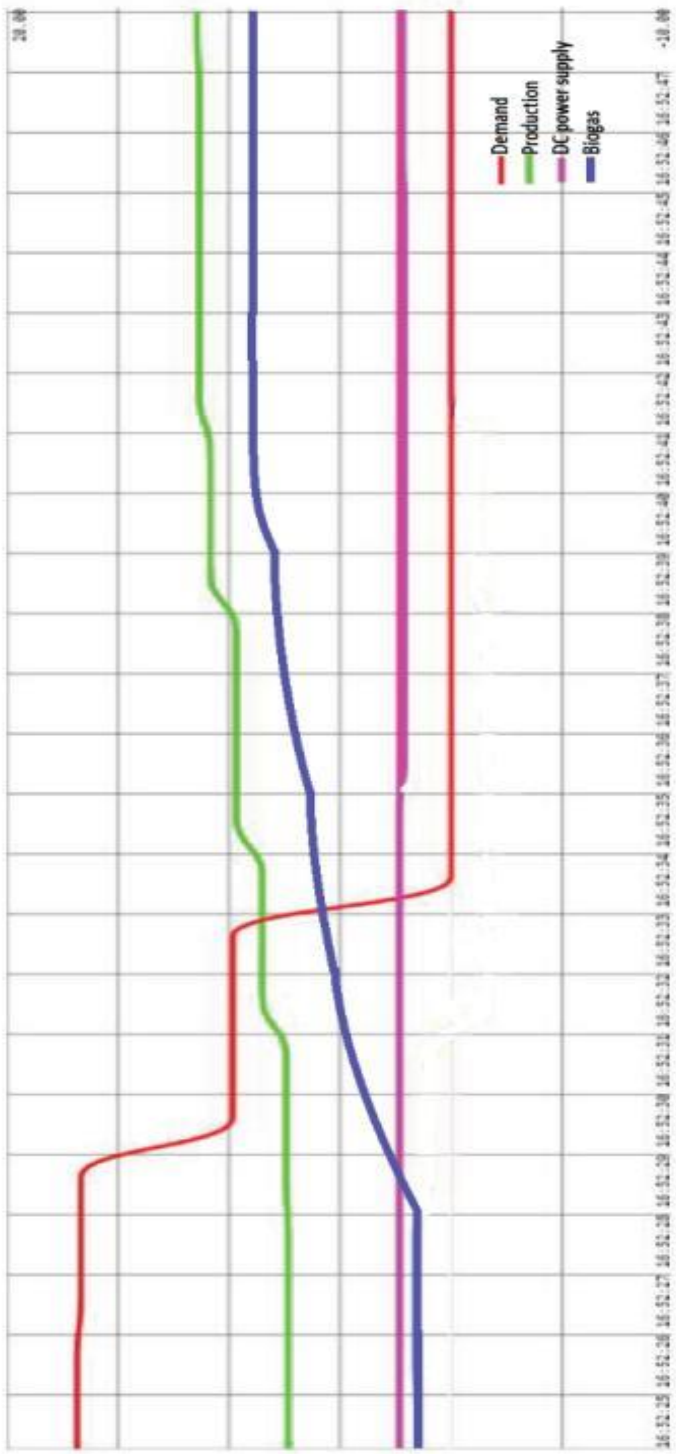


Figure 4.31 Smart RTUs Monitoring Results

Figure 4.32 shows three scenarios of MW-WTP electricity cogeneration due to varying amounts of produced biogas with respect to power demand. They indicate a redundant power supply and communication system with the proposed smart RTU and communication system philosophy.

A) Scenario One: MW-WTP Power Generation < Maximum Demand Load
The MW-WTP generators provide power to POCs with already set priorities. The smart RTUs enable a trip signal for top priority POC2, its relevant feeders at the zone sub-station and the shortfall is imported via POC1.

B) Scenario Two: MW-WTP Power Generation = Maximum Demand Load
Power from the zone sub-station is not required. Interlocking mechanisms of all the power supplies are activated via smart RTUs by providing an effective communication and coordination system.

C) Scenario Three: MW-WTP Power Generation > Maximum Demand Load
The surplus power is fed back to the zone sub-station by enabling reverse power relays via the smart RTUs. The surplus supply is subjected to increased potential and frequency using high frequency step-up transformers to minimise losses.

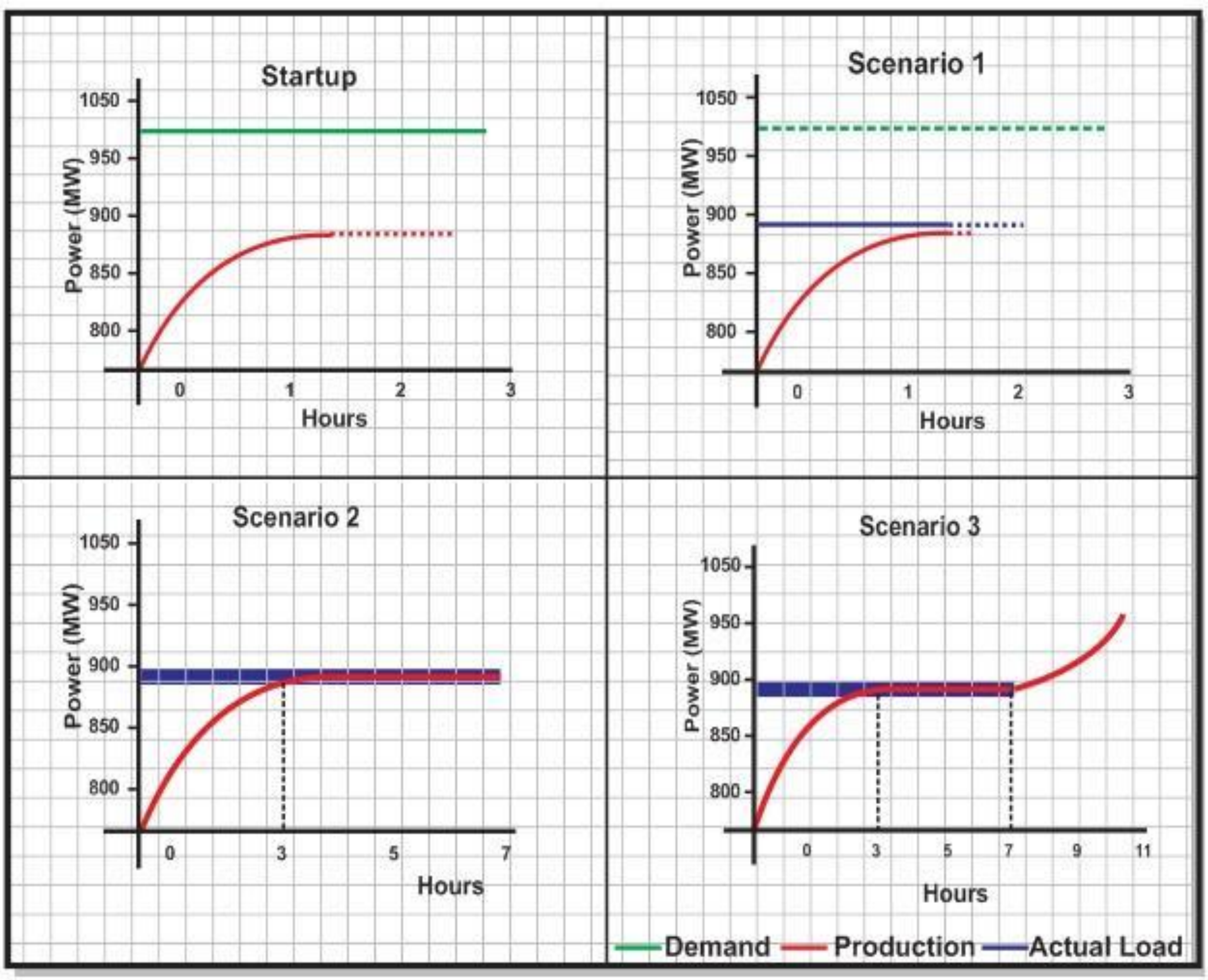


Figure 4.32 MW-WTP Power Demand vs Generation Scenarios

4.8.7 Sustainable MW-WTP

The modelled smart RTU presents solution for effective and sustainable energy management for WWTPs by providing a long-term solution for its demand load. The continuous and efficient monitoring and communication system enables MW-WTP to optimally utilise the energy resources on-site. Figure 4.33 shows that the MW-WTP increased power generation efficiency with smart RTUs and proposed communication systems. It is achieved by providing an effective control and monitoring system on all electricity cogeneration and fault scenarios.

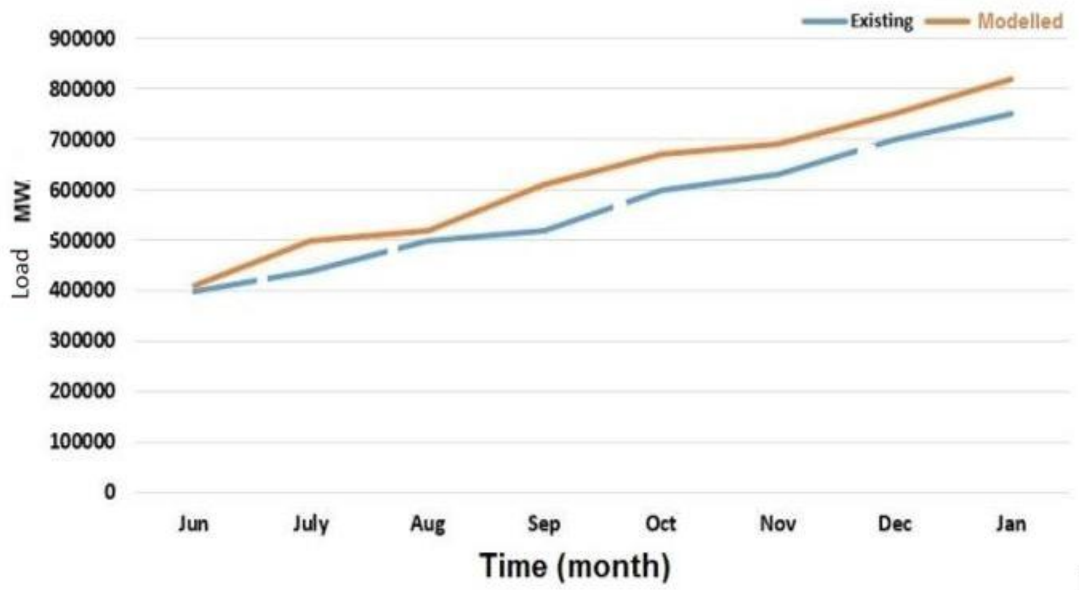


Figure 4.33 MW-WTP Power Generation – Existing vs Modelled

4.9 IMPACTS

4.9.1 Asset management

Wastewater is produced around the clock, especially in urban areas and hence, reduction in WAS during water treatment must be a continuous process. The proposed redundant, failsafe and reliable solution ensures non-stop operations at WWTPs. Excessive energy produced through on-site biogas production can now be fed to the power company. The asset managers can monitor the state of WWTPs, scheduled maintenance and capital works without any shutdowns.

4.9.2 SAS and OH&S

Telemetric measurement, control, and remote operations using smart RTUs enhance OH&S standards of WWTPs. Operators interaction with the equipment, specifically HV, has been minimised through SAS. Figure 4.34 shows significant reduction in over-current relay operational downtime at MW-WTP with the use of FOCs and advanced network protocols with smart RTUs, increasing the safety of substations.

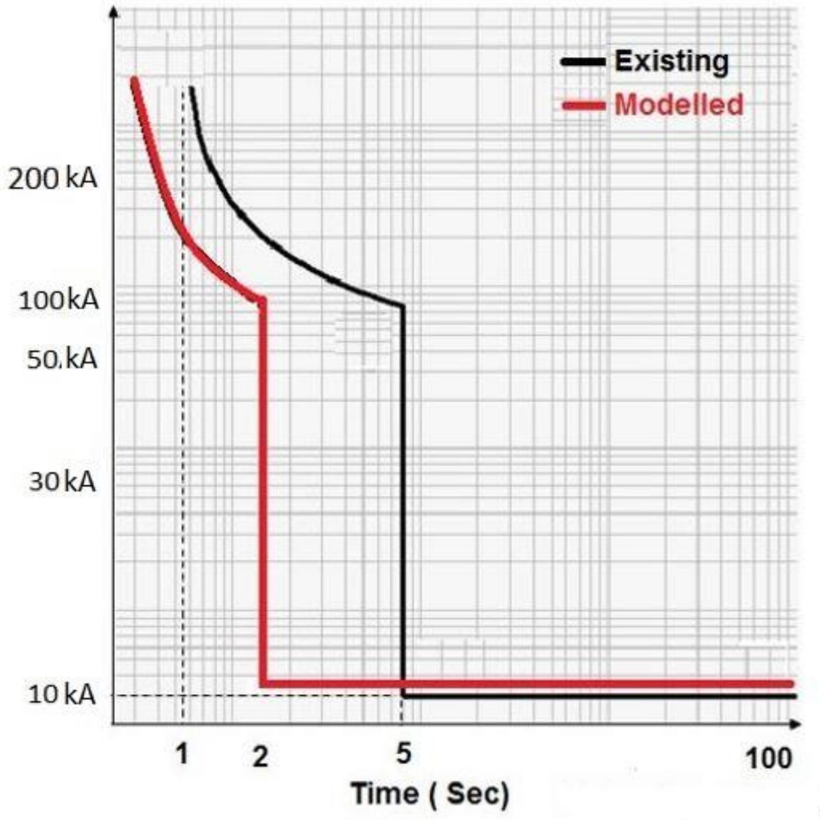


Figure 4.34 Over-Current Relay Downtime with Smart RTUs

4.9.3 Environmental Impact

Continuous automated wastewater treatment process keeps the sanitation of the cities intact and also ensures cleaner oceans. Self-generated green energy reduces GHG and the CHP system ensures that the heat produced in the process is being utilised, thereby reducing WWTPs environmental footprint. Treated sludge is used in agricultures. Figure 4.35 shows a reduction of 87,000 tonnes (approx.) in GHG and carbon emissions by implementing the smart RTUs philosophy.

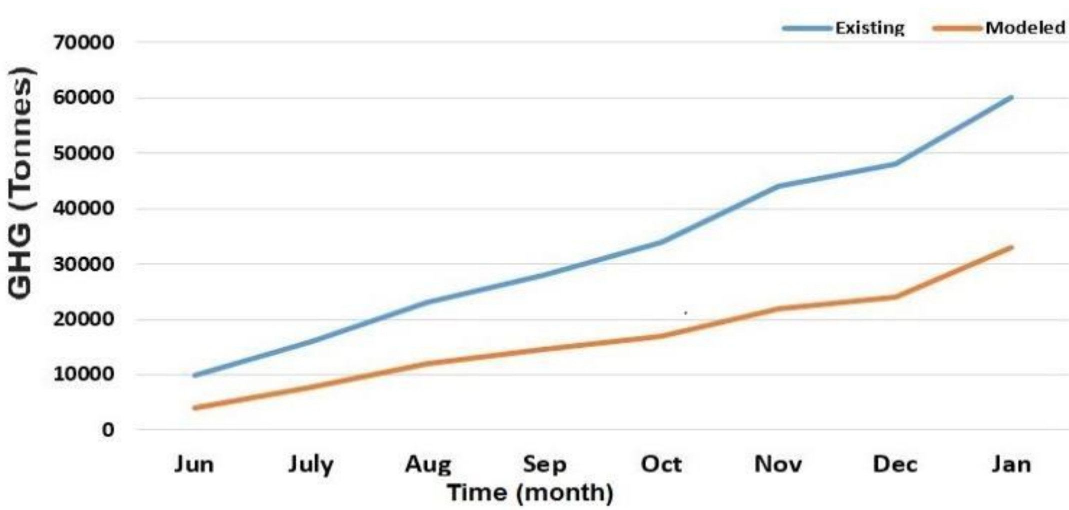


Figure 4.35 GHG Emission Rate

4.9.4 Economic Impact

The green electricity is generated through optimum usage of biogas. The enhanced automated performance reduces cost of operations and maintenance as compared to conventional electricity supply from the power distribution company. Figure 4.36 shows average savings in AUD, by implementing smart RTUs with SCADA and redundant communication for efficient PMS.

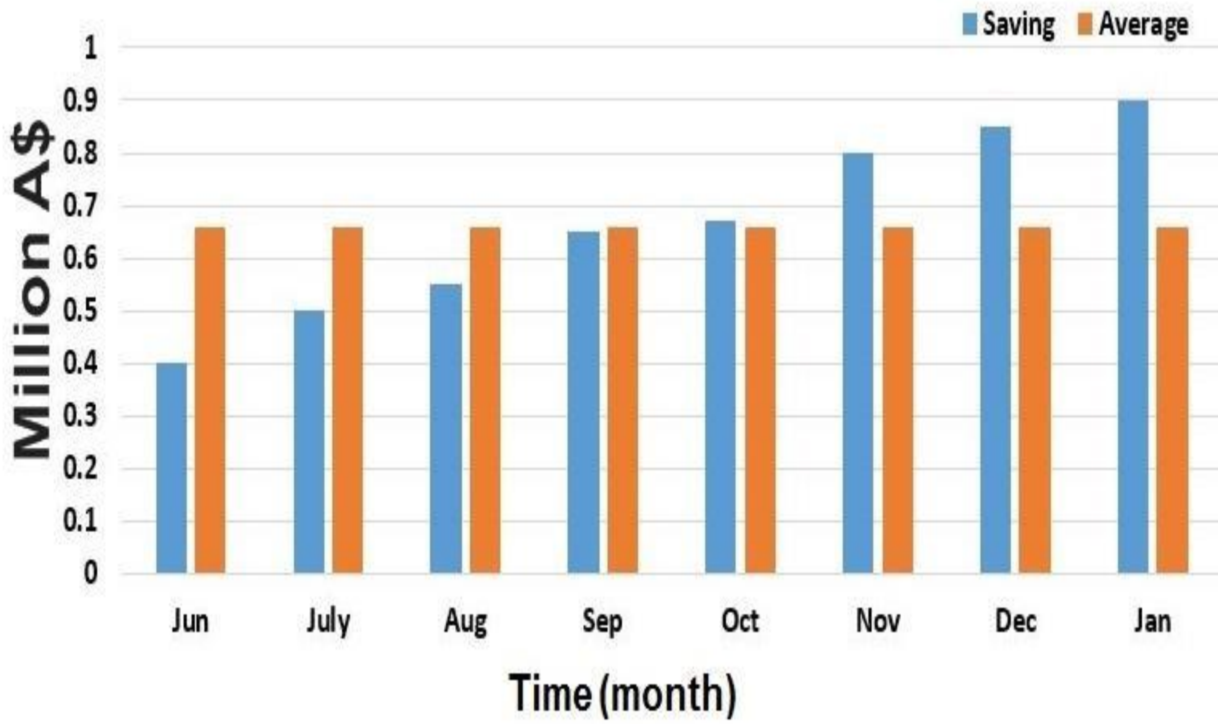


Figure 4.36 Financial Impact at MW-WTP

4.10 CONCLUSION

This research concludes that the existing power infrastructure at WWTPs requires an advanced and reliable communication network which transmits telemetric signals from distant nodes to a control centre and vice versa in a timely and efficient manner. Network modification and upgradation is required to meet relevant IEC/IEEE WWTPs electricity cogeneration standards. The proposed smart RTUs implemented at MW-WTP POCs provide a perfect platform to achieve an isolated point that can be replicated in existing infrastructures without any major upgrades and investments to the switchgears or substations. WWTP operators can easily manage, control, and communicate intertripping and interlocking functions on-site from a centralised location. The shutdown, maintenance and power outages times are almost eliminated.

CHAPTER 5:

MODELLING SMART RTU FOR SMART GRID AT EXISTING WWTP

5.1 INTRODUCTION

Wastewater treatment is an energy intensive process that puts huge load on power company`s grid and can also have detrimental impacts on the environment. This calls for wastewater to be utilised as renewable energy resource through smart grids Combine heat and power (CHP) process provides sustainable means for power generation at WWTPs thus fulfilling their energy demands. There is also a need to utilise the existing WWTP infrastructure to minimise the cost and time impact. Sub-station automation systems (SAS) are deployed using smart RTU philosophy to achieve failsafe and redundant monitoring, control and communication functions for existing or old WWTPs. Relay coordination with smart RTUs offer a reliable remote control and monitoring system for distributed power generation that provides an effective power management solution with multidirectional flow. Smart grid prevents greenhouse gases (GHG) and carbon emissions to enter into the atmosphere, hence reducing the environmental footprint and enables (co and tri) generation of green electricity with improved occupational health and safety (OH&S) standards. Table 5.1 shows comparison of modern and traditional grids with their application [157].

Table 5.1 A Comparison between Traditional and Smart Grid Station

Traditional Grids	**Smart Grids**
Electric machinery	Advanced digital machinery
One-way communication	Two-way communication
Centralised power generation	Distributed power generation
A small number of sensors	Full grid sensors layout
Lack of control	Robust control technology
Less energy efficiency	Higher energy efficiency
Difficult to integrate renewable energy	Easy to integrate renewable energy
Manual monitoring	Automatic monitoring
Failure and power outages	Adaptive and Intelligent
Few user option	More user options

This efficiency is achieved by using “smart RTUs with relay coordination” philosophy at WWTPs. Smart RTUs are electrical panels that integrate generated telemetric Inputs/Outputs (I/Os), advanced SCADA and their monitoring compliance requirements with wide range of communication protocols. Figure 5.1 shows typical arrangement in ring topology between WWTP and zone sub-station to achieve power supply redundancy. This arrangement can be easily utilised to achieve the required objectives using LCTA principles as minimum amount of cabling, sensors and electrical panels are required. The research, therefore, discusses setting up smart grid stations for advanced energy management and enhanced power production using renewable energy.

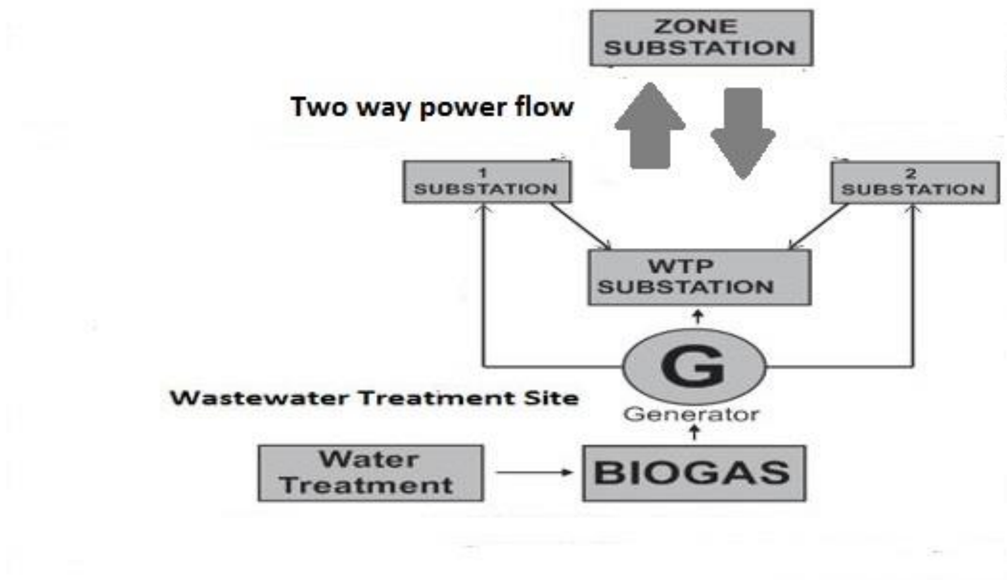


Figure 5.1 Power Flow in Ring Topology at WWTP

5.2 ADVANCED METHODS FOR BIOGAS PRODUCTION

Waste Active Sludge (WAS) is formed during the wastewater treatment process, which is converted into Chemical O_2 Demand (COD) and biogas with the help of anaerobic digestion [158]. Figure 5.2 Shows biogas production at WWTPs.

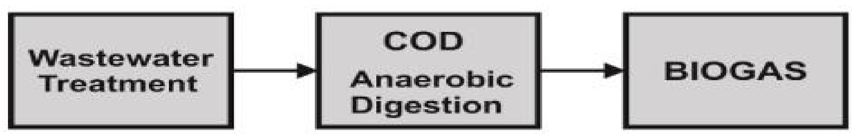


Figure 5.2 Biogas Production Process

5.3 ELECTRICITY GENERATION

The biogas produced is captured and utilised for on-site electricity generation through an internal combustion turbine while the heat generated during the process is used for heating the anaerobic digesters especially during winters [159]. Power generation utilising biogas is modelled from power production method [160].

$$m_{biogas} = COD_r \times Y$$

$$MW = m_{biogas} \times y \times S \times \rho_{CH4} \times LHV_{biogas} \times 1.165 \times 10^{-5} \times \eta_{el} \quad (5.1)$$

Where;

m_{biogas} = mass flow rate of biogas ($m^{3/}h$)
COD_r = biodegradable function of COD
Y = biogas flow rate m^3/h
y = biogas yield (m^3/kg)
S = methane fraction
ρ_{CH4} = density of methane ($tons/m^3$)

LHV_{biogas} = lower heating value of biogas (MJ/kg)
η_{el} = efficiency in percentage.
Equation (5.1) states that power cogeneration systems depend on the production of biogas. It requires proper coordination, monitoring and controlling of WWTP equipment. Variation in production of biogas leads to three different scenarios of electricity cogeneration.
Anaerobic digestion produces biogas through CHP process. The sequential water treatment flow process is shown in Figure 5.3. Flammable gases produced are burnt to produce steam. This steam is further utilised to excite on-site generators for electricity generation.

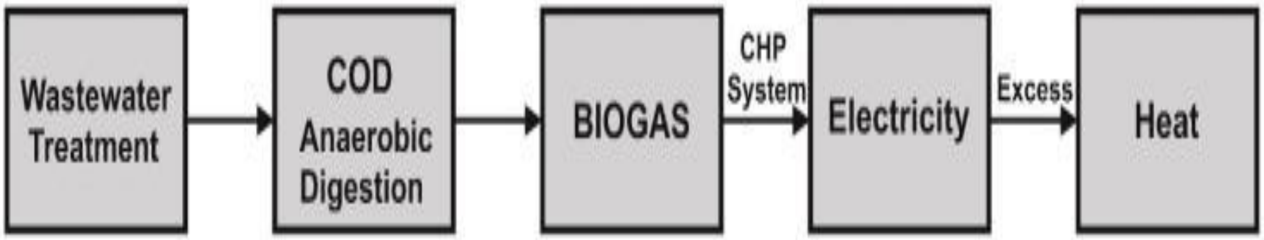


Figure 5.3 Power Generation in WWTP

5.4 PROBLEM STATEMENTS

5.4.1 Variation in Biogas Production and Power Generation at MW-WTP

Figure 5.4 indicates that relative biogas yield at 45 ^{0}C is maximum when temperature is high at different time intervals and the production of electricity is different because of varying yield of biogas as discussed in section 4.6.1 and 3.5.1. [161].

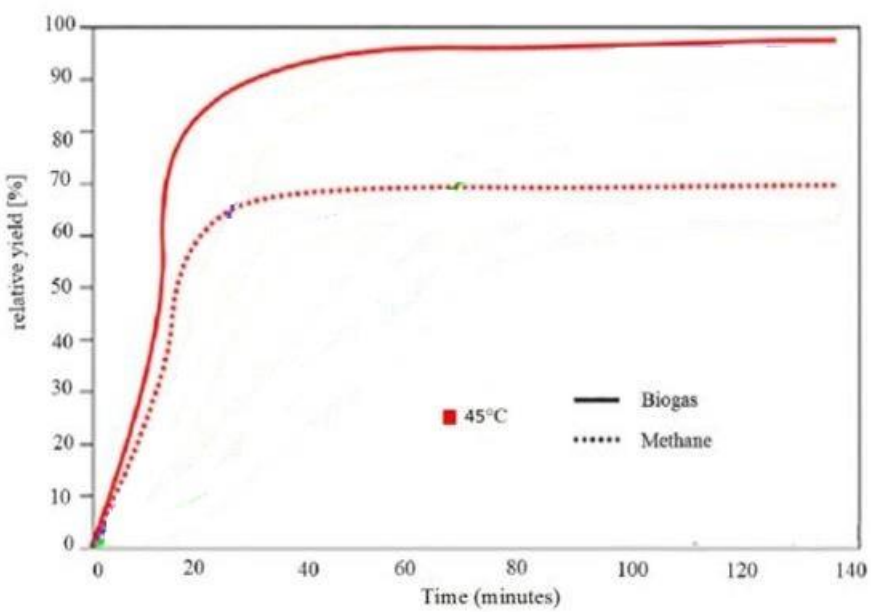


Figure 5.4 MWWTP Relative Yields of Biogas w.r.t Temperature

5.4.2 Existing Sub-station Coordination System

The backup protections and communication systems in most of the existing WWTP substations has coordination issues, which increases the occurrence of fault probability [162]. Figure 5.5 shows existing communication system between the MW-WTP (POC1, POC2, and POC3) and zone substations. Any faults between the POCs will shut down the whole system causing unnecessary shutdowns. MW-WTP existing system is not failsafe and redundant for electricity trigeneration.

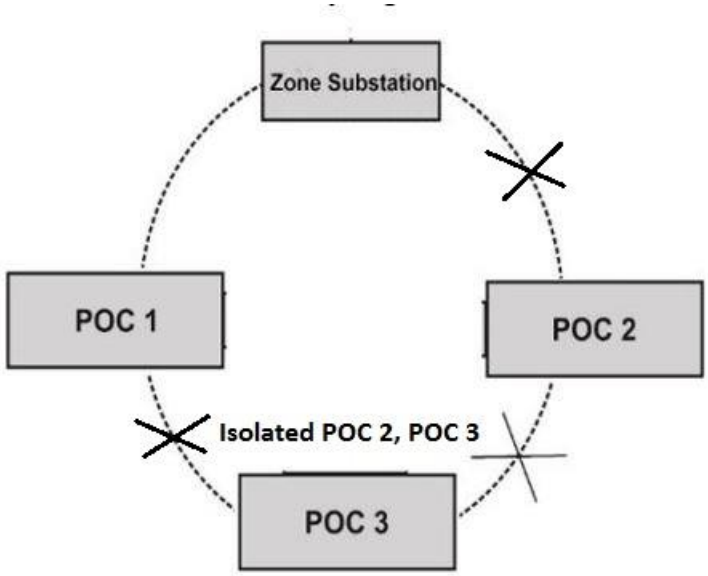


Figure 5.5 Fault Scenario at Existing MW-WTP Communication System

5.4.3 Operational Relay Coordination System

Existing WWTP substations have complex secondary designs and wiring for metering signals, protection relays and control gear monitoring circuits. The protection depends only on conventional relay systems, which do not provide the required Open System Interconnection (OSI) layers of protection for electricity trigeneration, as defined by the IEC61580 standards. Protective relaying is the only form of local backup for the entire sub-station and the inter-connected transmission lines.

5.4.4 CHP Efficiency and Trigeneration

Existing WWTPs, that utilise biogas for electricity generation, are unable to manage the excessive heat produced during the process [164]. When temperatures are high, the excessive thermal energy needs to be utilised in an efficient way to achieve trigeneration. Simulation collective heat losses on a hot summer day shown in Figure 5.6 at the MW-WTP.

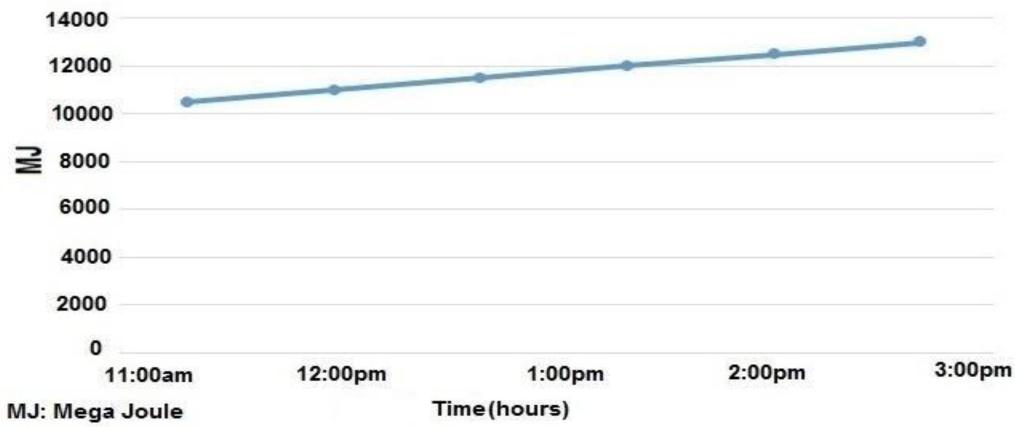


Figure 5.6 Heat Losses at MW-WTP

5.4.5 Health, Safety and Environmental Issues

Most of the existing infrastructures have manual HV switching, interlocking and intertripping that increases risk for the plant operators [165]. The gas and heat produced in the water treatment process must be prevented to enter the atmosphere. The load on grids must be reduced to lower the impact of fossil fuels. Wastewater is a renewable energy resource that needs to be utilised to minimise the environmental footprint. Simulation shows carbon emissions of greenhouse gases (GHG) in Figure 5.7 at the existing MW-WTP that could have been used and prevented to enter the atmosphere by developing a smart grid.

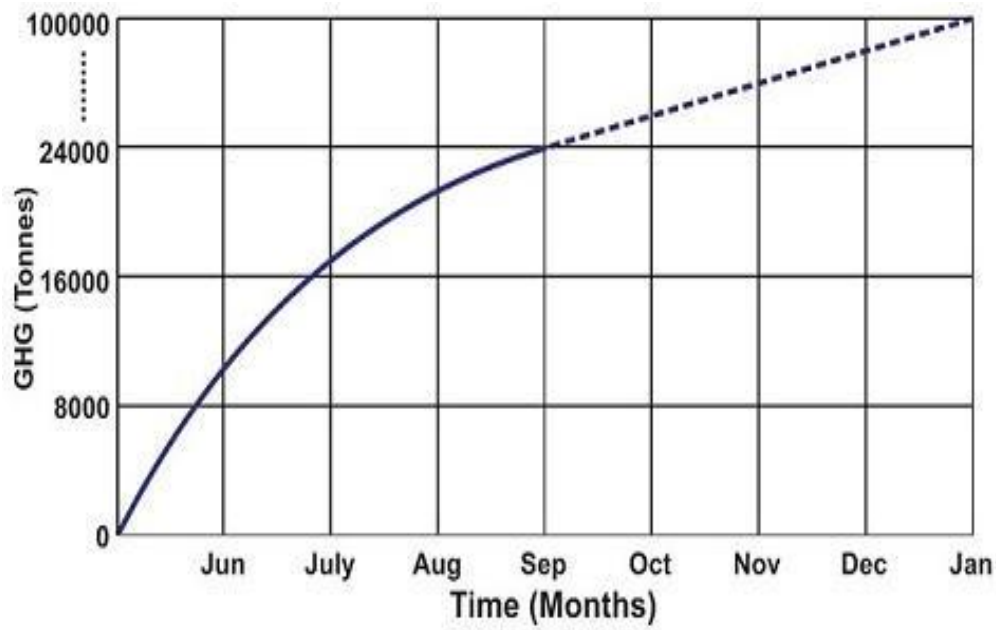


Figure 5.7 GHG Emissions MW-WTP

5.5 PROPOSED PHILOSOPHY

5.5.1 Sub-station Protocols for Smart Grid

IEC61850 with Distributed Network Protocol (DNP3) provides a standard operation to achieve reliable and fast communication for smart grids. It defines a standardised language for sub-station automation systems (SAS) called the Sub-station configuration language (SCL), which includes various functions for SCADA and the network control technology. It is compatible with existing and old substations and also has telemetric mapping capacity with a number of protocols including Manufacturing Message Specification (MMS) and Generic Object-Oriented sub-station Event (GOOSE) [166].

They provide high-speed networks communication with fast response time required for efficient protective relaying operations during the WWTP electricity trigeneration process. IEEEC37.238 utilises fibre optics communication system (FOCS). IEC61850 also has wide compatibility with other network standards like IEEE802.11/16 WiMAX, 3G/4G cellular, IEEE 802.15 ZigBee and IEEE 802.20 Mobile-Fi.

5.5.2 IEEE1588 Time Synchronisation

IEEE1588 is a precision time synchronisation (PTS) standard that delivers data within its defined timeframe. Precise timekeeping data are important for substations reliability [167]. These timestamps achieve accuracy of up to nanosecond levels, enabling the control of sequential events in multidirectional power systems. PTS includes Network Time Protocol (NTP), SNTP (Simple Network Time Protocol) and PTP (Precision Time Protocol).

5.5.3 Smart Intelligent Electronics Devices (IEDs)

Proposed smart RTUs, along with IEDs, sensing devices (SDs) and communication devices are used for developing smart grids. IEDs have higher efficiency rate, faster communication and response, effective power management and coordination as compared to conventional power devices. Hence SDs and IEDs can replace the conventional device systems [168]. These devices have robust results with IEC61850 and can easily be implemented on existing or old substations. They can handle multiple processes and acknowledgements at the same time in a proper coordinated way.

5.5.4 SAS

Electricity generation, transmission and distribution can be controlled and monitor by SAS. Figure 5.8 shows represents SAS structure and the levels of protection provided.

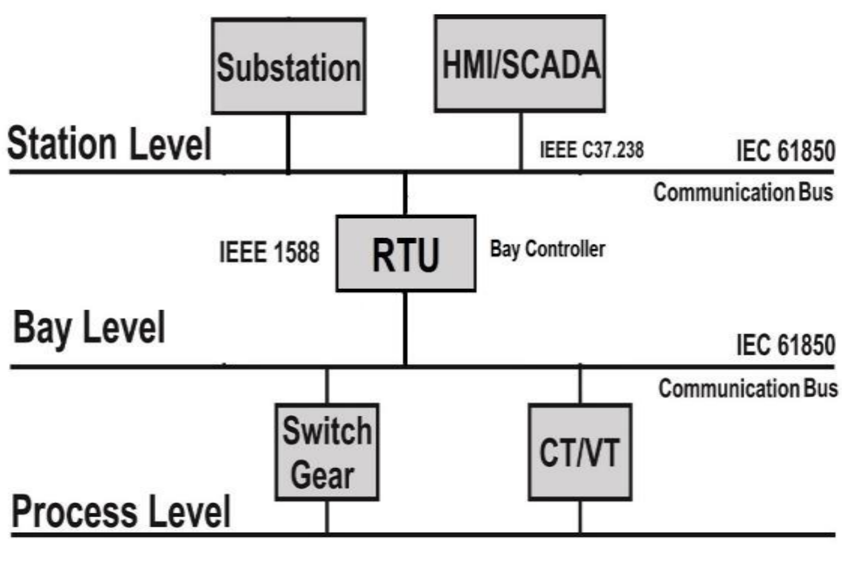


Figure 5.8 Sub-station Automation Structure

Figure 5.9 shows basic architecture for smart gird with protective relay coordination and standards implementation at each level of protection.

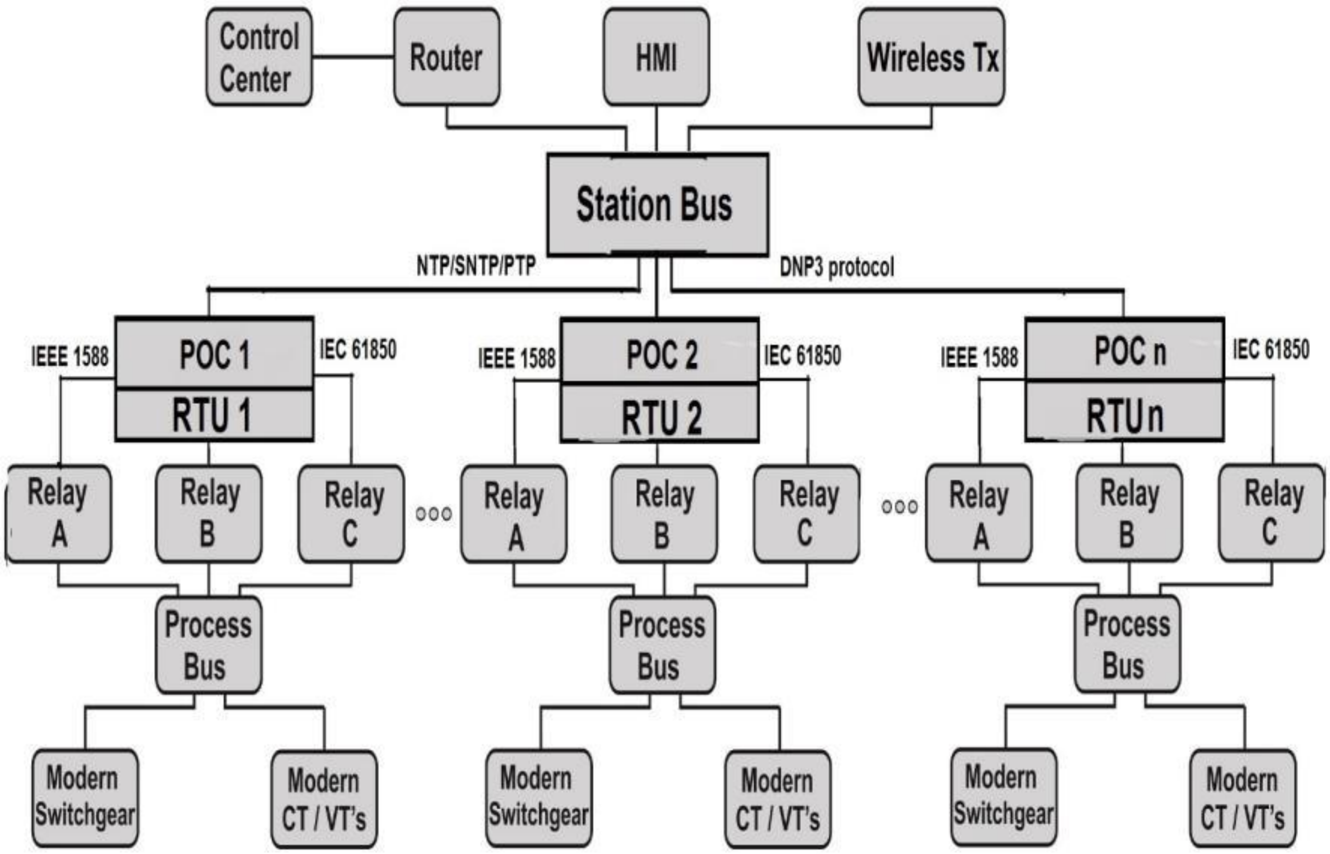


Figure 5.9 SAS with IEC61850

5.5.5 Mathematical Model for Relay Operational Time

Protective relaying [167] is modelled to calculate different action response time. Equation (5.2) states that a single relay can perform multi-timed control sensitive tasks for electricity trigeneration.

$$\text{Fast action response time} = TMS \times 0.10/[(I_f/I_s)^{0.02} - 1] \tag{5.2}$$

Where;

TMS = Time Multiplier Setting for relay coordination

I_s = pickup current for relay

I_f = fault current

Operating time characteristic for modelled relay for reverse power flow at WWTPs in prescribed operational time is given by equation (5.3) [169].

$$T_{ops} = 0.14/[\ I^{0.02} - 1]^8 \tag{5.3}$$

Where;
T_{ops} = relay protection fixed operational timing
I = set value of current for relay
Equation (5.6) and (5.7) state that relay operational time become more time synchronised with smart RTUs.

5.6 METHODOLOGY

5.6.1 Proposed Smart RTU Interface

Smart RTUs are utilised as a part of SCADA system that needs to assemble data from various generation systems at WWTP to ensure availability of entire information at a centralised location for common use. The proposed smart RTU design aims to set up suitable configurations and connectivity based on cost effectiveness, reliable implementation, and performance [170]. The philosophy utilises remote and on-site controls for monitoring metering data, protection trips, equipment status, supervision and fault indications. This network extension would seamlessly integrate with the existing WWTP substations. An intertripping and interlocking mechanism is developed with required telemetric Inputs/Outputs (I/Os) made available to the proposed smart RTU at a potential-free contact to optically isolate different control voltage levels. Figure 5.10 represents the proposed smart RTU interface with telemetric I/Os generated at zone sub-station and WWTP distribution substations (POC1, POC2, POCn).
The telemetric signals are continuously monitoring the status of electrical flow, protection trips and faults. The wiring and integration of smart RTUs is based on the design, interlocking and intertripping philosophy

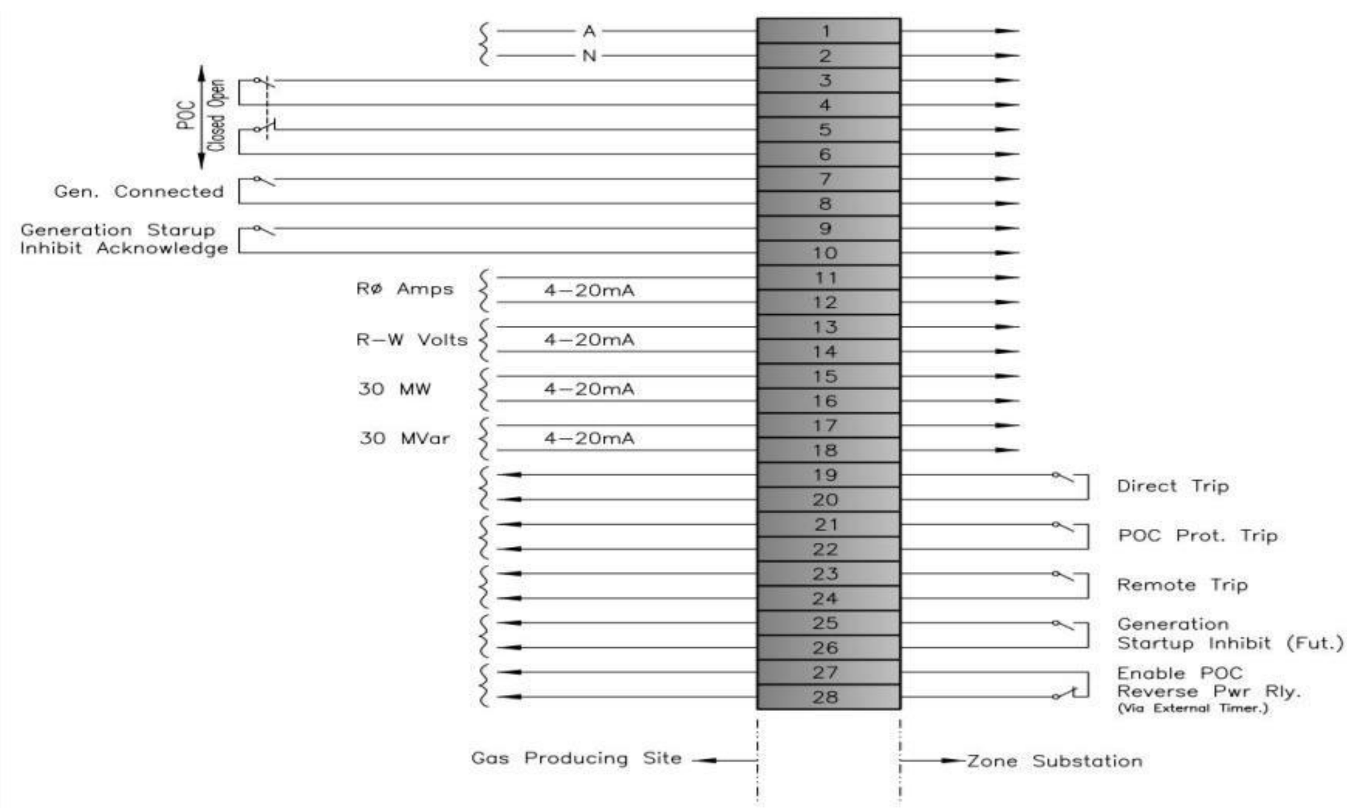


Figure 5.10 Proposed Smart RTU interface with Telemetric I/Os

of the existing WWTP network substations. These I/Os are mapped via PLC and then onto human machine interface (HMI) for proper monitoring and control. The potential-free contacts are mounted in the smart RTU, which are energised by an external redundant source. Communication redundancy is also a key design component of the smart RTUs.

Table 5.2 RTU Telemetric I/O summary at WWTP

Input point	**Function**	**Device**	**I/O type**
1-2	Power supply	UPS	24VDC supply
3-4	POC open	Auxiliary NC	Digital Input
5-6	POC close	Auxiliary NO	
7-8	Gen connection	Generator	Digital Output
9-10	Gen Acknowledgement	Relay	
11-12	Rϕ Amps	CT	Analog Input
13-14	R- Volts		
15-16	3ϕMW		
17-18	3ϕMVARs		

Table 5.3 RTU Telemetric I/O summary at power company`s zone substation

19-20	Direct trip	Zone sub-station Control Room	Digital Input
21-22	POC Prot. Trip	Protection Relays	Digital Output
23-24	Remote trip	Control Relays	
25-26	Gen start-up Inhibit (fut.)	WWTP Generator	
27-28	Enable POC reverse power	Relay External Timer	

5.6.2 SCADA for Smart Grids at WWTPs

Figure 5.11 shows architecture of SCADA implementation at WWTP substations (POC1, POC2, POCn) and the power company's zone substation. Smart RTUs are interconnected with each other, relays and IEDs in closed loop ring topology, which monitor the entire system in real time. Telemetric communication transmits and receives via a dual network system FOCs and wireless networks telemetric communication simultaneously that makes it more reliable, failsafe and redundant.

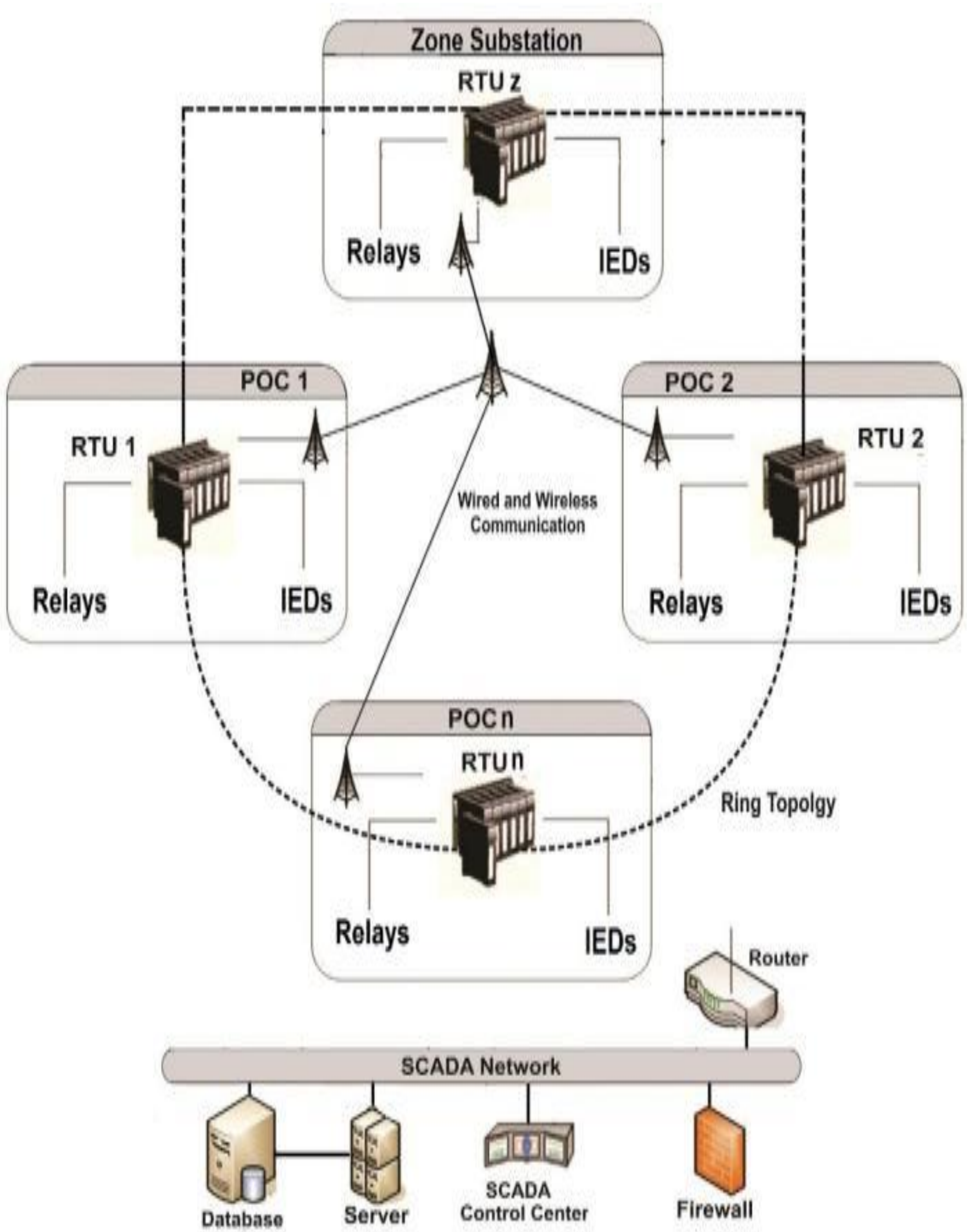


Figure 5.11 Smart RTUs with SCADA in Ring Topology

5.7 EVALUATION

5.7.1 Advanced Network System with Acknowledgement

DNP3 employs SCADA to control and monitor the efficiency of IEDs through smart RTUs [51]. The IEC61850 provides full compatibility and interchangeability features between IEDs, regardless of their manufacturer. It allows coordination with existing conventional protocols, including Modbus. Figure 5.12 shows advanced network communication system for reliability, where telemetric signals generate necessary acknowledgements and the appropriate functions against them, providing an extra safety level to the system, complying with IEC61850.

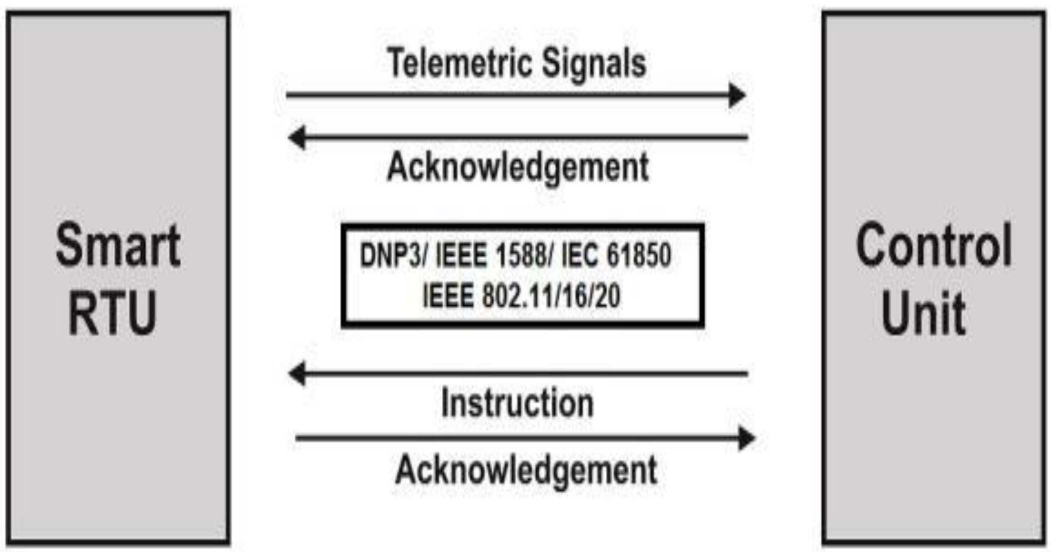


Figure 5.12 Advanced Networking System

5.7.2 Embedded Communication System for Smart Grid

Embedded Ethernet technology is efficiently used in SAS. Intelligent network communication system requires merging of IEDs with data transmission to make it secure and reliable. It has advanced features for protection and timing. The provision in object models of IEC61850 enables all IEDs to represent their data using identical structures that corresponds to their relative power system functions [171]. Installed IEDs assemble synchronised sampled data from one or more integrating units for sequential alignment and processing. Figure 5.13 shows embedded communication network architecture for smart grids. HMI or SCADA interfaces are implemented at the “Station Level.” Protection functions at the “Bay Level” while the entire relay coordination at the “Process Level”.

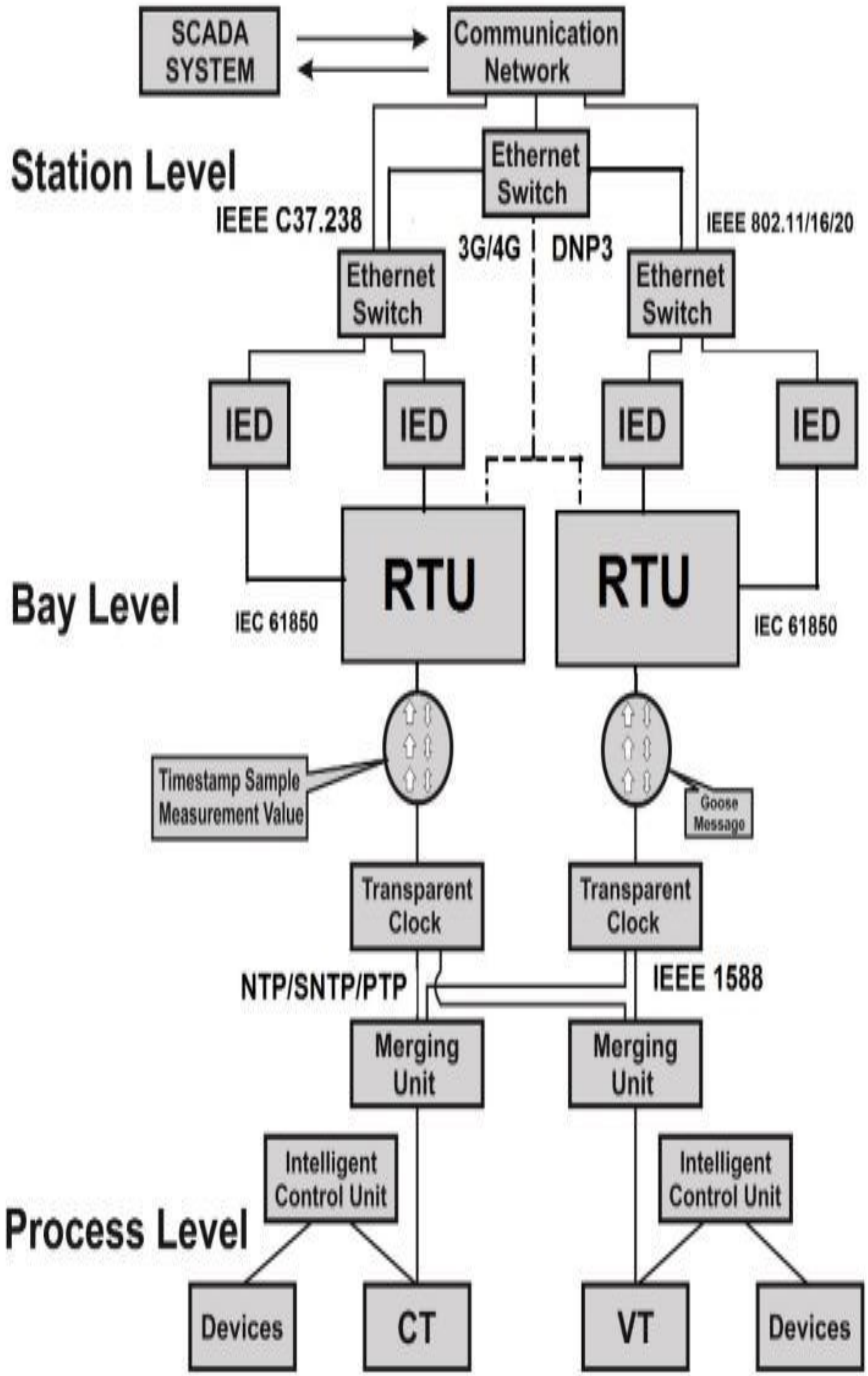


Figure 5.13 Embedded Communication System using Smart RTUs

5.7.3 FOCs

WWTPs must be equipped with reliable broad network coverage for distant sites. The FOCs channel strengthens electromagnetic interface and compatibility of telemetric signals for secure and reliable communication in harsh weather conditions, increasing the data integrity. Figure 5.14 shows FOCs in ring and mash topology for a failsafe and redundant system.

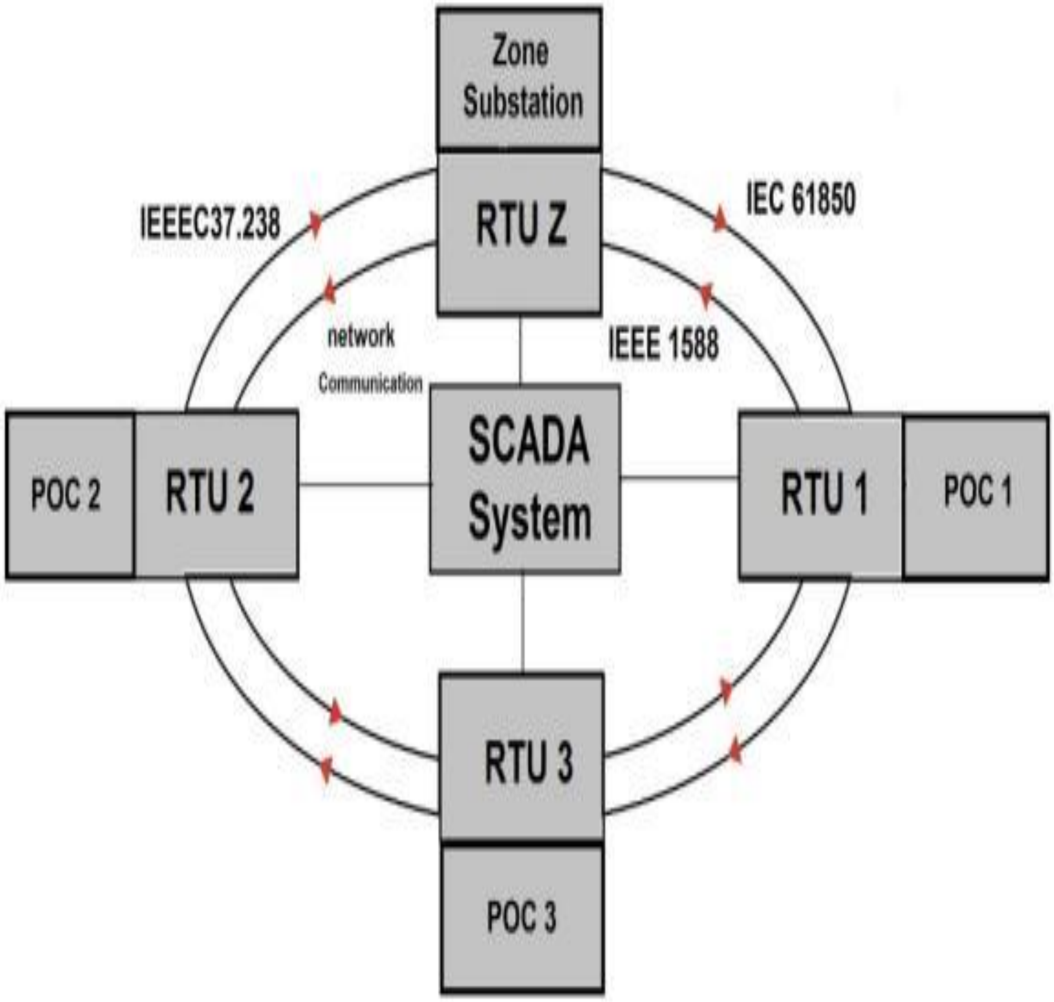


Figure 5.14 FOCs in Ring Topology at WWTPs

5.7.4 Efficient Wired and Wireless Communication System

Efficient communication between substations and devices is one of the main objectives for smart grids to achieve WWTP electricity trigeneration. Ring and mesh topologies are compatible with SCADA and FOCs while wireless communication IEEE 802.11 standards provide efficient data transmission [172]. Wireless sensors can be used for transmitting data to IEDs and SCADA via the smart RTUs. Figure 5.15 shows wireless communication with smart RTUs for smart grids at a WWTP.

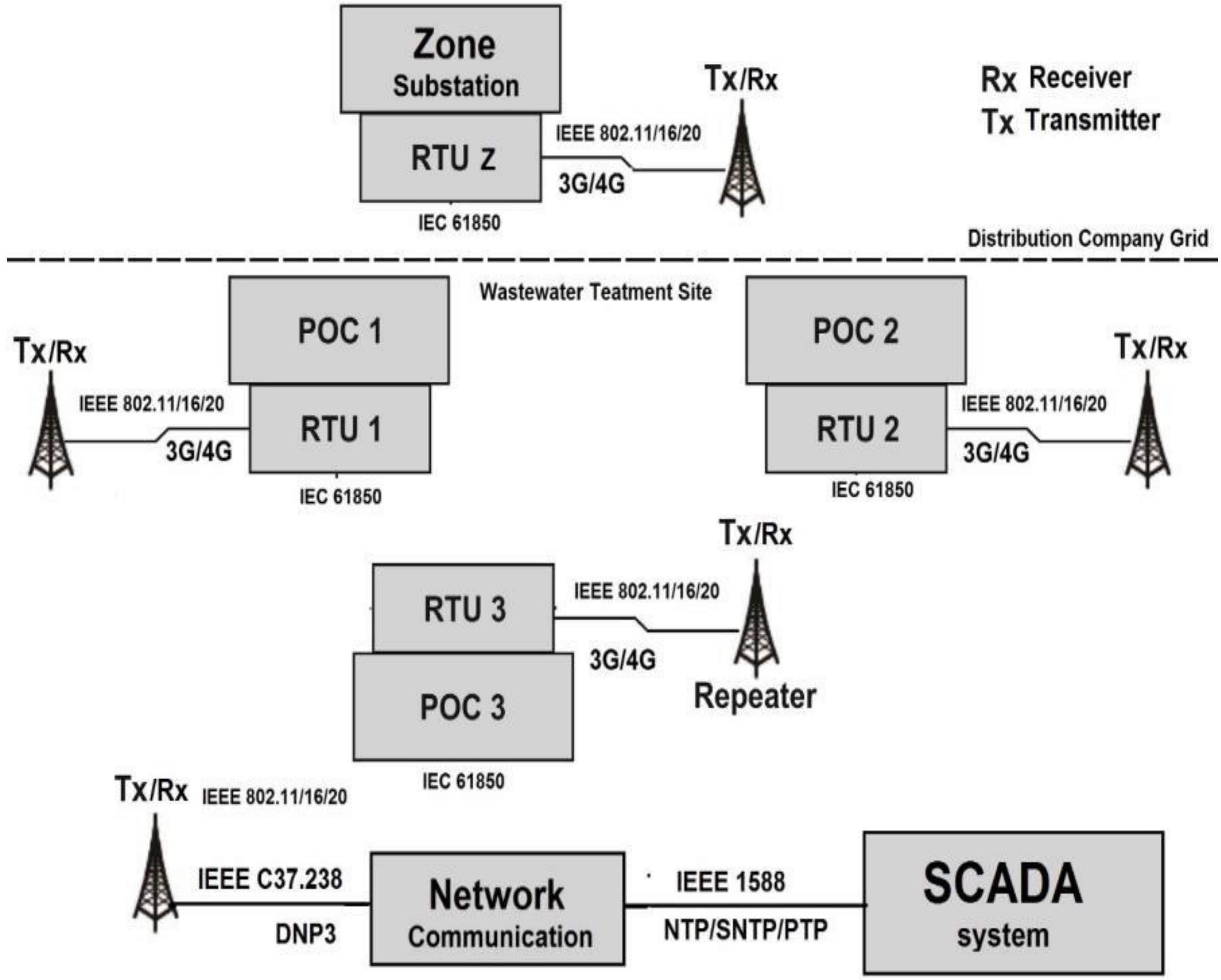


Figure 5.15 Wireless Communication with Smart RTUs at WWTP

5.7.5 Advanced Monitoring System (AMS) and IEEE1588

AMS with SCADA system enhances daily quality of service and reliability. AMS deployment provides a continuous monitoring and metering solution by enabling multidirectional communication. This system can gather information on voltage, current and power of substations. It has three main objects namely measurements, control device communications and data processing that enhances safety and provides redundancy.

IEEE1588 can work with existing ordinary clocks that connect Ethernet switches to coordinate synchronised sequential data time keeping for communication. Figure 5.16 block diagram shows IEEE1588 communication network system for a WWTP. Smart RTUs in ring topology with time synchronised control system enable trigeneration.

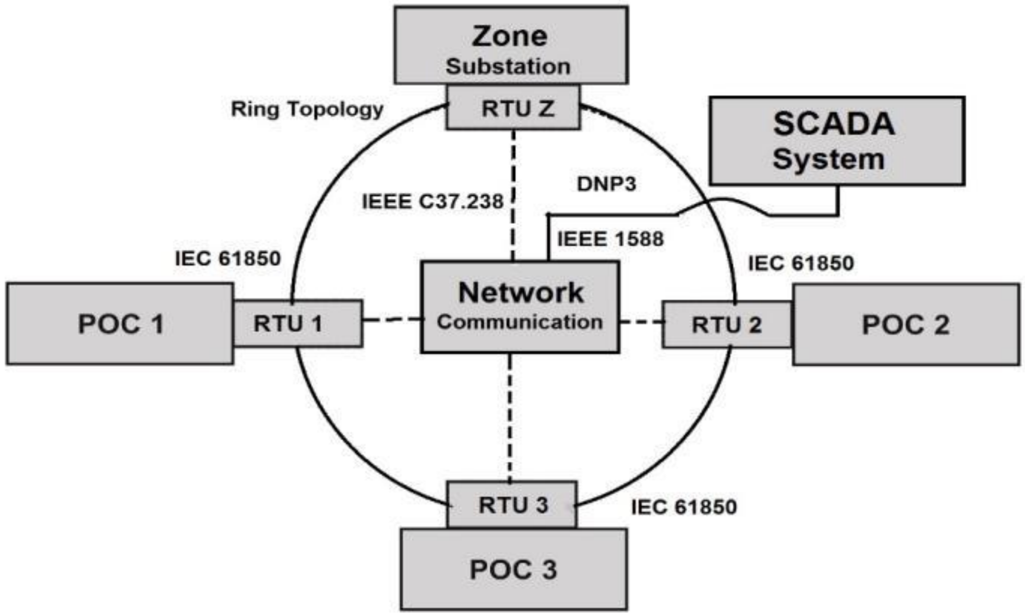


Figure 5.16 Smart RTUs in Ring Topology with IEEE 1588 and DNP3 Standards

5.7.6 Smart Sensing Devices (SD)

Smart SD improves reliability and control by increasing efficiency and safety of WWTPs for power generation. They have the ability to communicate telemetric signals through an advanced network via the smart RTU, which is connected with SCADA for smart grid. Figure 5.17 shows the block diagram of SD interface with smart RTUs for AMS at WWTPs.

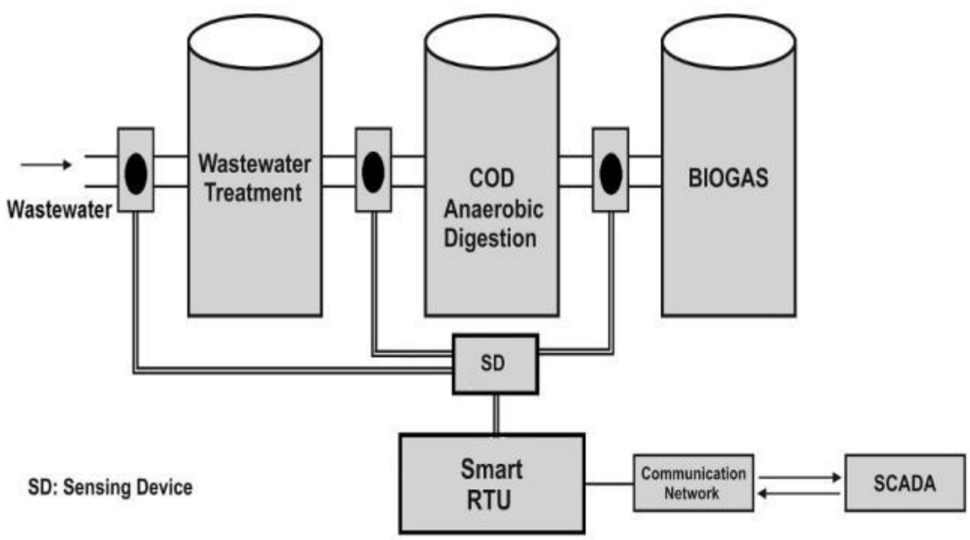


Figure 5.17 SDs with Smart RTUs

5.7.7 Smart Protection System

Equipment and auxiliary supply failure, over-current protection and all the scenarios for multidirectional power flow must be implemented in smart grids with integrated AMS to provide an efficient power management system (PMS) at WWTPs. Smart RTUs and relays are able to collect metering and system status information and store data records for power system operations. This dual coordination system enables trigeneration at WWTPs. This enables them to coordinate with each other at distant sites and locations at WWTP through an interconnected communication network. Figure 5.18 shows relay coordination for protection systems with smart RTUs for efficient protection system.

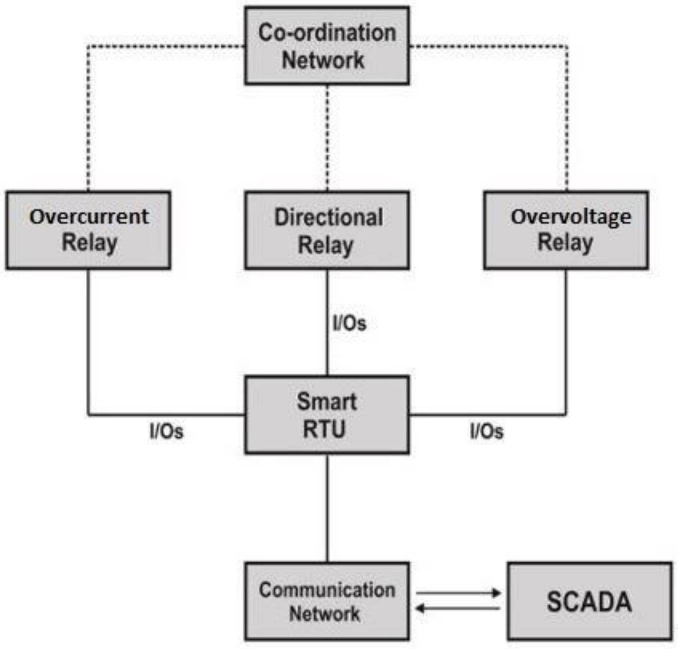


Figure 5.18 Relay System with Smart RTUs

5.7.8 Efficient Power Flow Management

The proposed methodology suggests sustainable WWTP electricity distribution that can be achieved through self-generation and can accommodate various scenarios of multidirectional power flow and faults. A redundant communication capacity is, therefore, required at WWTP substations with centralised PMS [173]. This will also address other aspects of SAS such as enhanced performance, advanced supervisory controls and reliability of power protection, which is done through seven OSI protection layers via smart RTUs.

5.7.9 Failsafe and Redundant System

Smart RTUs interconnected in double ring topology provide a backup path for failsafe and redundant communication to achieve WWTP electricity trigeneration. Figure 5.19 shows effective communication with backup links between MW-WTP POCs, zone sub-station and other devices. It also shows an alternate path for communication when fault occurs at POC2.

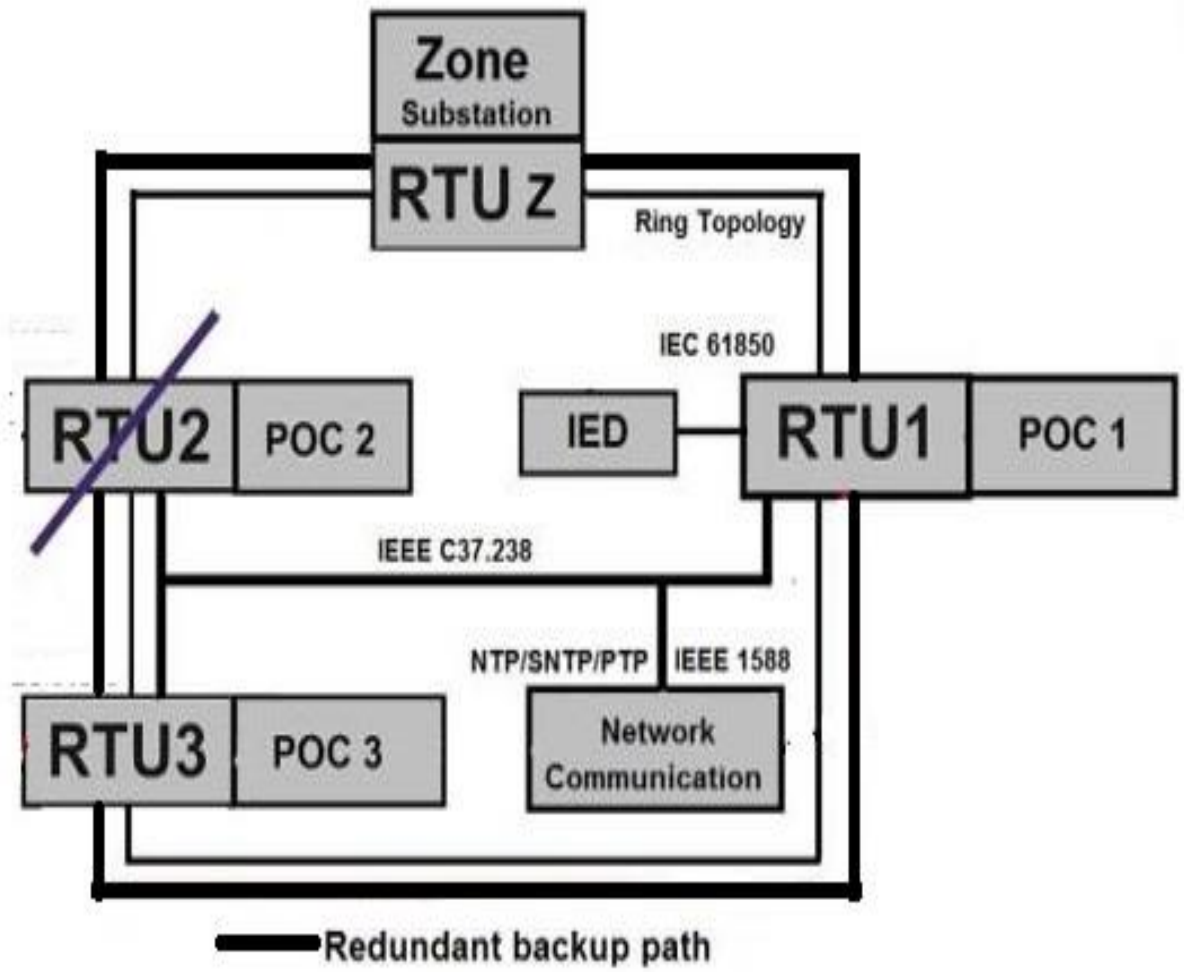


Figure 5.19 Redundant Communication Network

5.7.10 Trigeneration of Electricity

Smart grid with renewable energy resource, such as biogas at WWTP, gives high efficiency and flexibility. Heat emissions from electricity generators, especially in hot seasons, can be utilised for thermal power plant to achieve electricity trigeneration [174]. Figure 5.20 shows electricity trigeneration at WWTPs using surplus heat and CHP process. This also reduces environmental footprints.

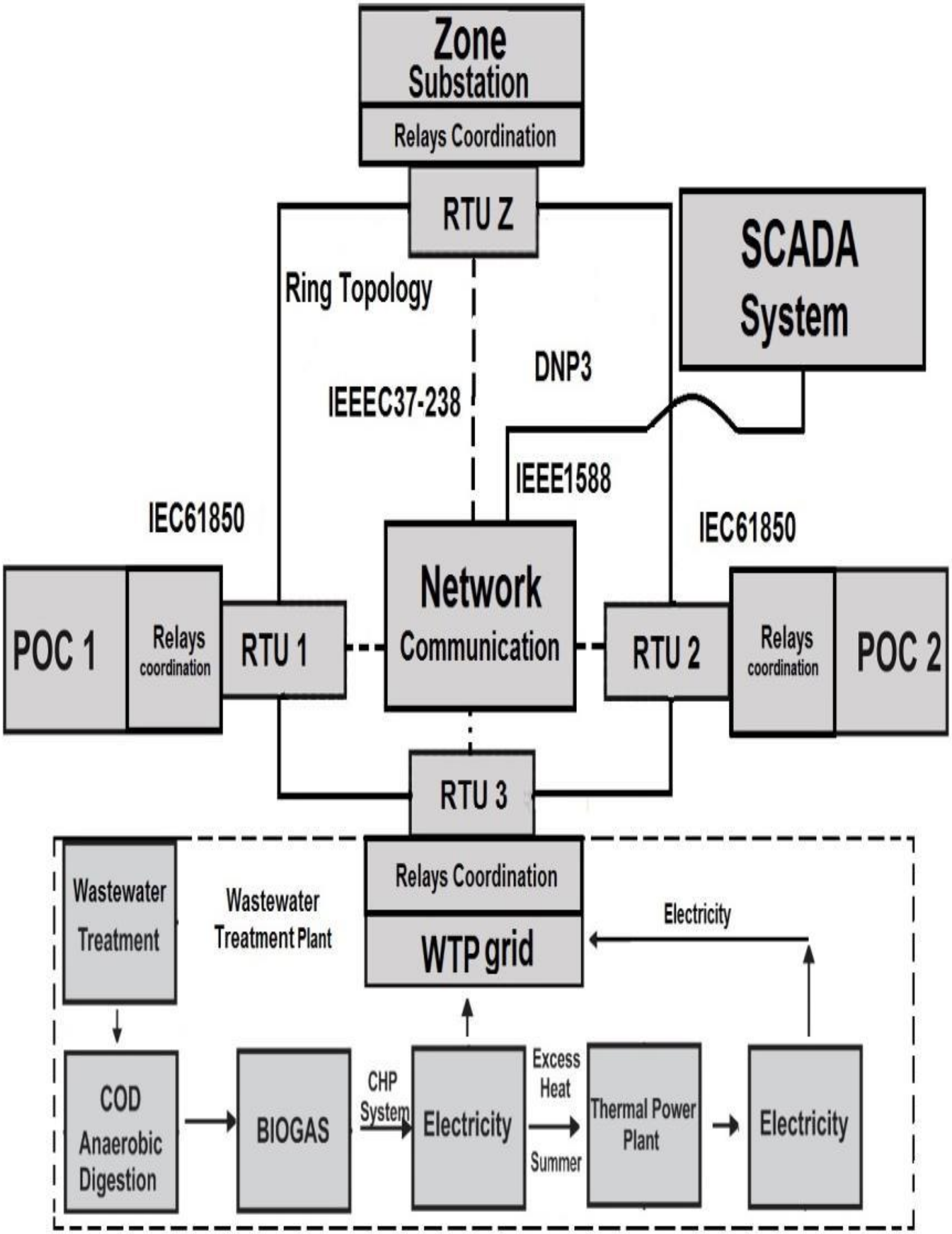


Figure 5.20 Distributed Electricity Trigeneration at WWTP

5.8 HARDWARE SYSTEM SPECIFICATION AND LAYOUTS

5.8.1 Biogas Production and Electricity Cogeneration Layouts

Figure 5.21 shows the basic architecture of MW-WTP biogas production and electricity cogeneration at WWTP. Power generation at POC1 and POC2 and their communication regarding inter trips with SCADA network system has been demonstrated. Each section is divided into blocks that are interconnected with FOC and CAT6 cables for efficient control on biogas production and electricity cogeneration.

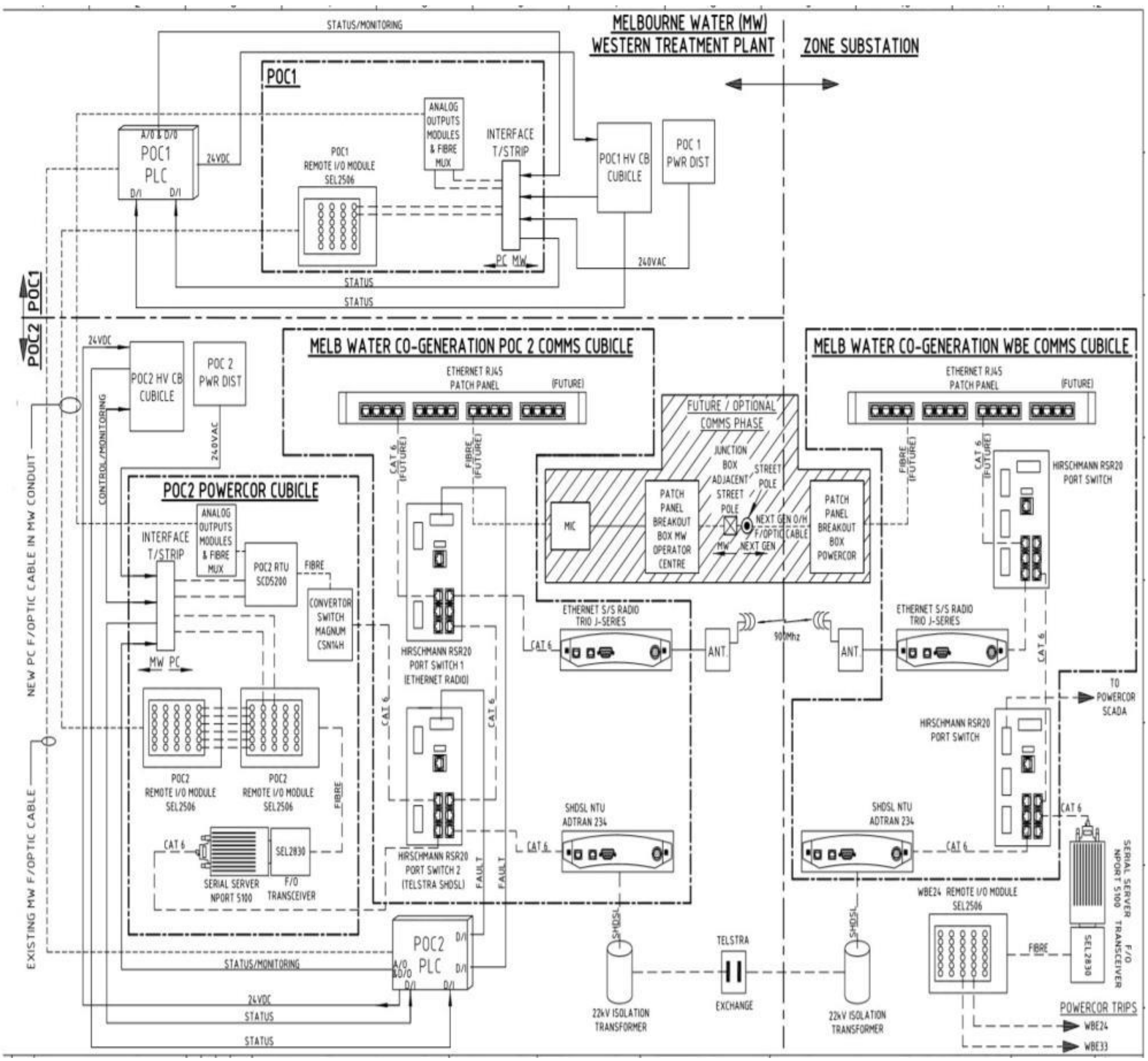


Figure 5.21 Biogas Generators Export Intertrip SCADA Network Arrangement

5.9 RESULTS AND DISCUSSION

Results are obtained and tested at MW-WTP Australia, which is the largest water treatment facility in the Southern Hemisphere. The tools used for simulations are ETAP, EDSA and MATLAB.

5.9.1 Smart SDs Telemetric Monitoring

Figures 5.22 and 5.23 show wastewater and sludge flow using SDs via the smart RTUs at digester ponds of MW-WTP. The results can be used to do demand-load flow analysis to effectively manage electricity trigeneration and help in forecasting the amount of biogas production required to effectively control different power generation fault scenarios.

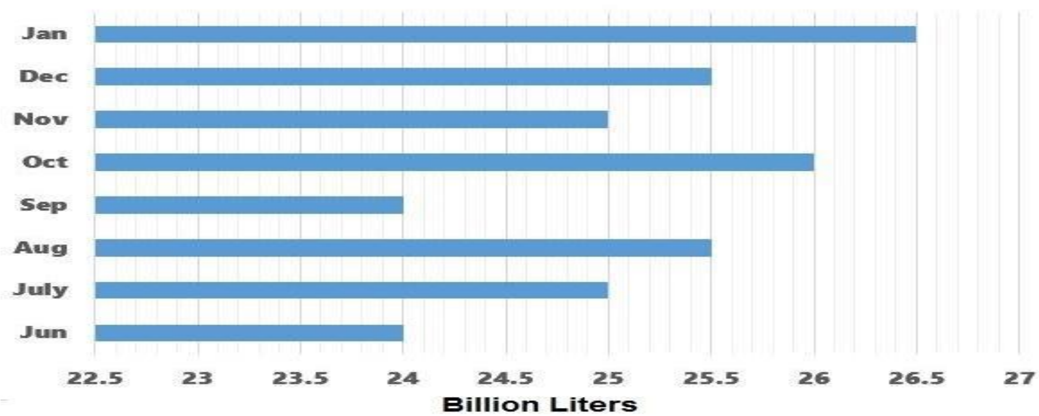


Figure 5.22 Wastewater Flow Monitoring SDs

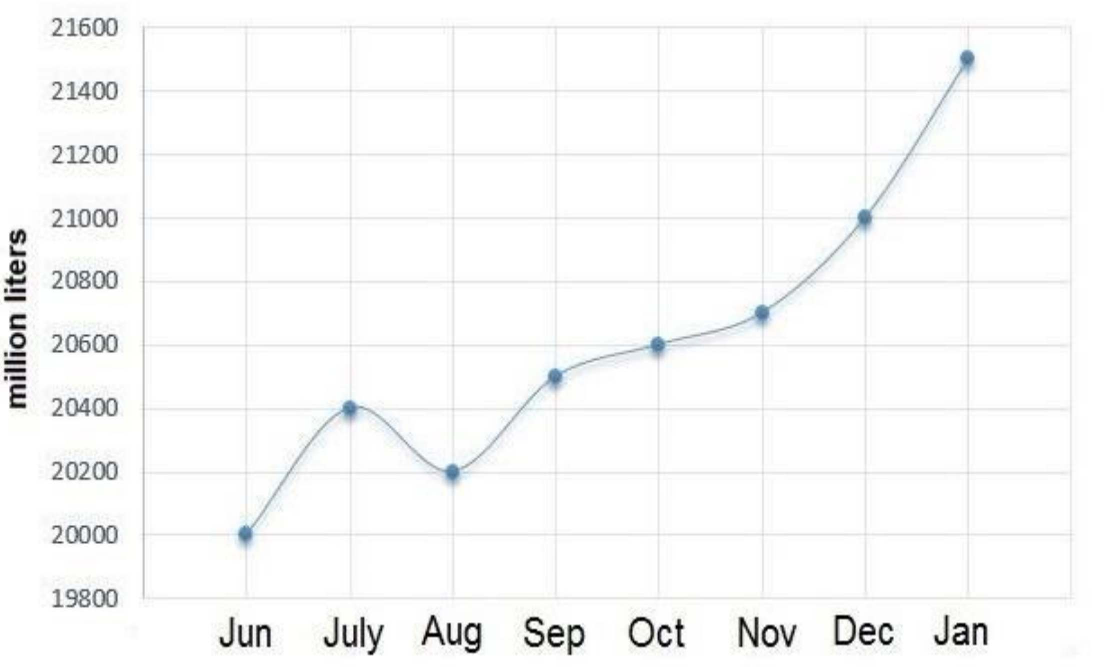


Figure 5.23 Sludge Production Monitoring using SDs

5.9.2 Electricity Trigeneration

Figure 5.24 simulation shows the results of the MW-WTP power generation using CHP process with smart RTUs. Results indicate optimised efficiency by utilising heat for power generation during summers 2016, enhancing electricity generation capacity up to 600 MW/h.

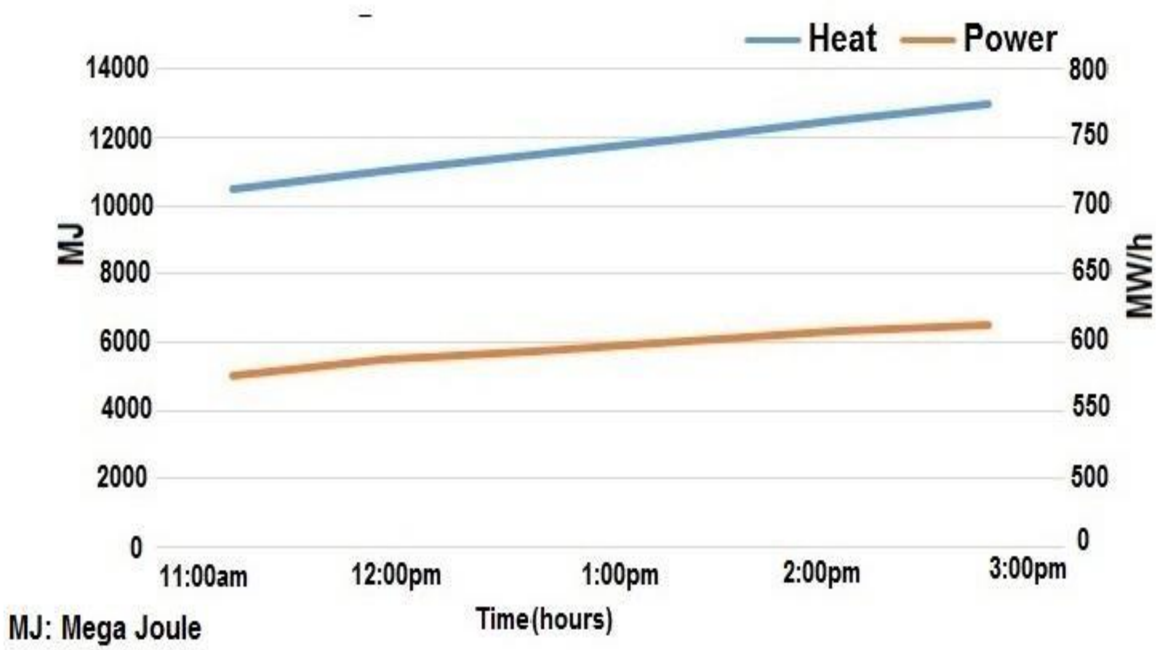


Figure 5.24 Electricity Trigeneration

5.9.3 Electricity Generation

Figure 5.25 shows power generation at MW-WTP with failsafe and redundant communication using proposed smart RTUs to develop smart grids. Results indicate that MW-WTP power efficiency increases by approximately 25% as compared to existing generation.

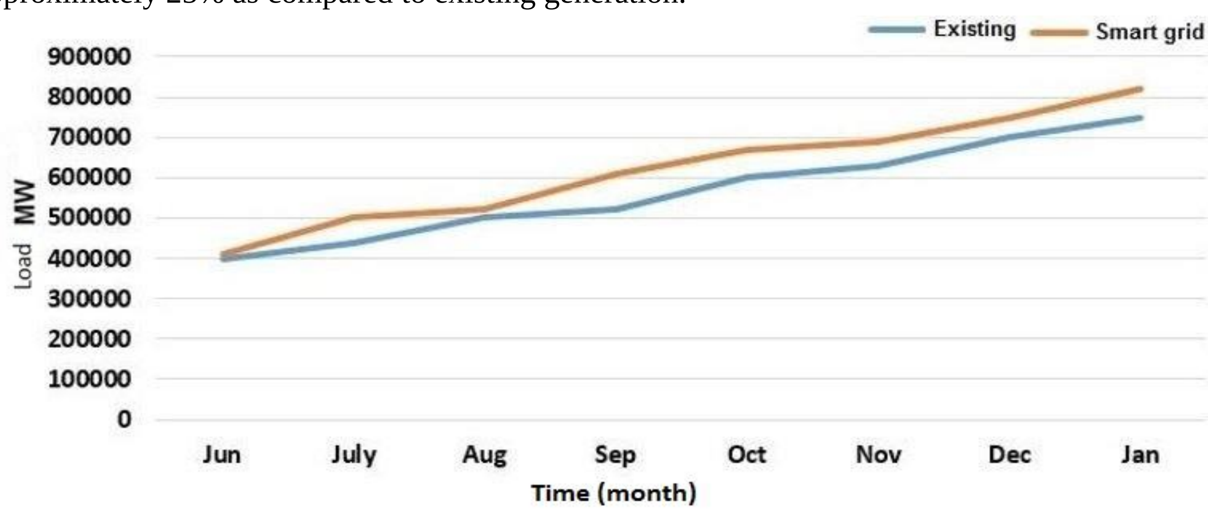
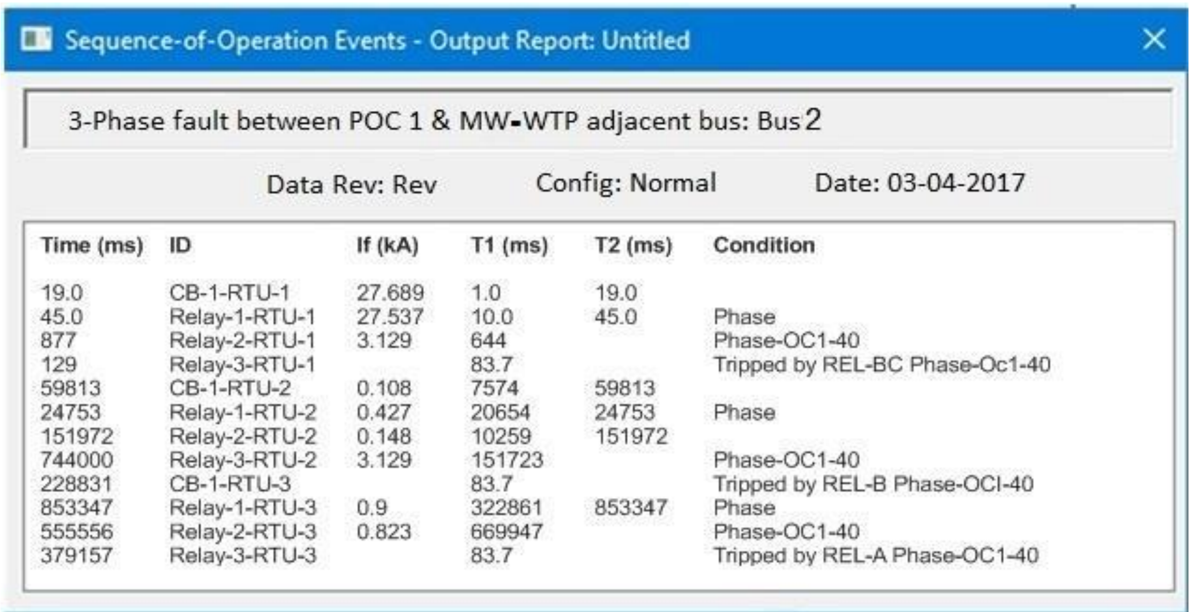


Figure 5.25 Power Generation in Smart Grid

5.9.4 Power Supplies - Sequence of Interlocking Operation

Figure 5.26 shows interlocking of power supplies via smart RTUs relay coordination system at the MW-WTP POC1. When the fault occurs, time defined, synchronised and sequential relay operation ensures redundant and failsafe power supplies to the LV switchyard of the MW-WTP POCs. This ensures a redundant and reliable PMS to achieve electricity trigeneration.



Sequence-of-Operation Events - Output Report: Untitled

3-Phase fault between POC 1 & MW-WTP adjacent bus: Bus 2

Data Rev: Rev   Config: Normal   Date: 03-04-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
19.0	CB-1-RTU-1	27.689	1.0	19.0	
45.0	Relay-1-RTU-1	27.537	10.0	45.0	Phase
877	Relay-2-RTU-1	3.129	644		Phase-OC1-40
129	Relay-3-RTU-1		83.7		Tripped by REL-BC Phase-Oc1-40
59813	CB-1-RTU-2	0.108	7574	59813	
24753	Relay-1-RTU-2	0.427	20654	24753	Phase
151972	Relay-2-RTU-2	0.148	10259	151972	
744000	Relay-3-RTU-2	3.129	151723		Phase-OC1-40
228831	CB-1-RTU-3		83.7		Tripped by REL-B Phase-OCI-40
853347	Relay-1-RTU-3	0.9	322861	853347	Phase
555556	Relay-2-RTU-3	0.823	669947		Phase-OC1-40
379157	Relay-3-RTU-3		83.7		Tripped by REL-A Phase-OC1-40

Figure 5.26 Sequential Operation for Interlocking

5.9.5 Over-Voltage Relay Operation for Busbar Protection

Simulation results at the MW-WTP shown in Figure 5.27 indicates over-voltage fault relay tripping at POC1 for busbar protection in summer seasons. The result indicates reliable equipment protection and enhanced safety, as relays trips are time synchronised. Smart RTUs can successfully synchronise sequence of operations for all fault scenarios.

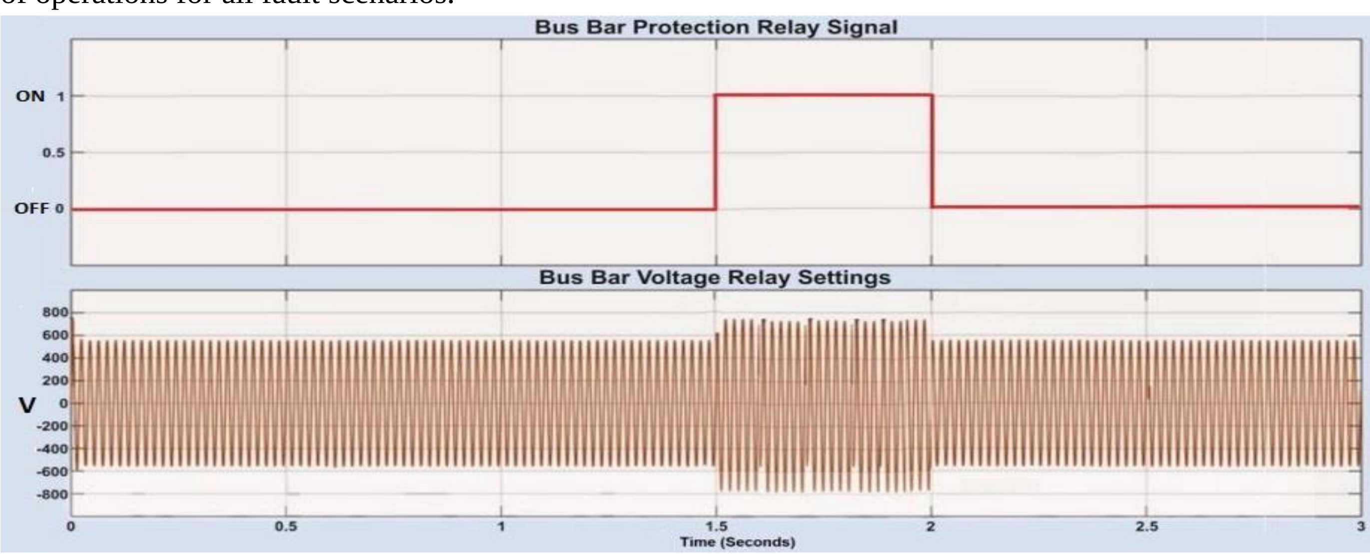


Figure 5.27 Busbar Protection Relay for POC1

5.9.6 Relays Trips via Smart RTUs on Three Scenarios

Reducing intertripping downtime minimizes power outages, shutdowns and faults at WWTPs by supporting an automated PMS. Smart RTUs provide time-synchronized trips for various scenarios of WWTP electricity cogeneration and the continuous operation ensures optimum utilization of biogas produced. Simulations at the MW-WTP shown in Figure 5.28 advanced time synchronized trips of POC1 with the zone sub-station for continuous LV power supply. Relay1 trips for zone Sub-station power supply, relay2 for self-sufficient power and relay3for reverse power generation.

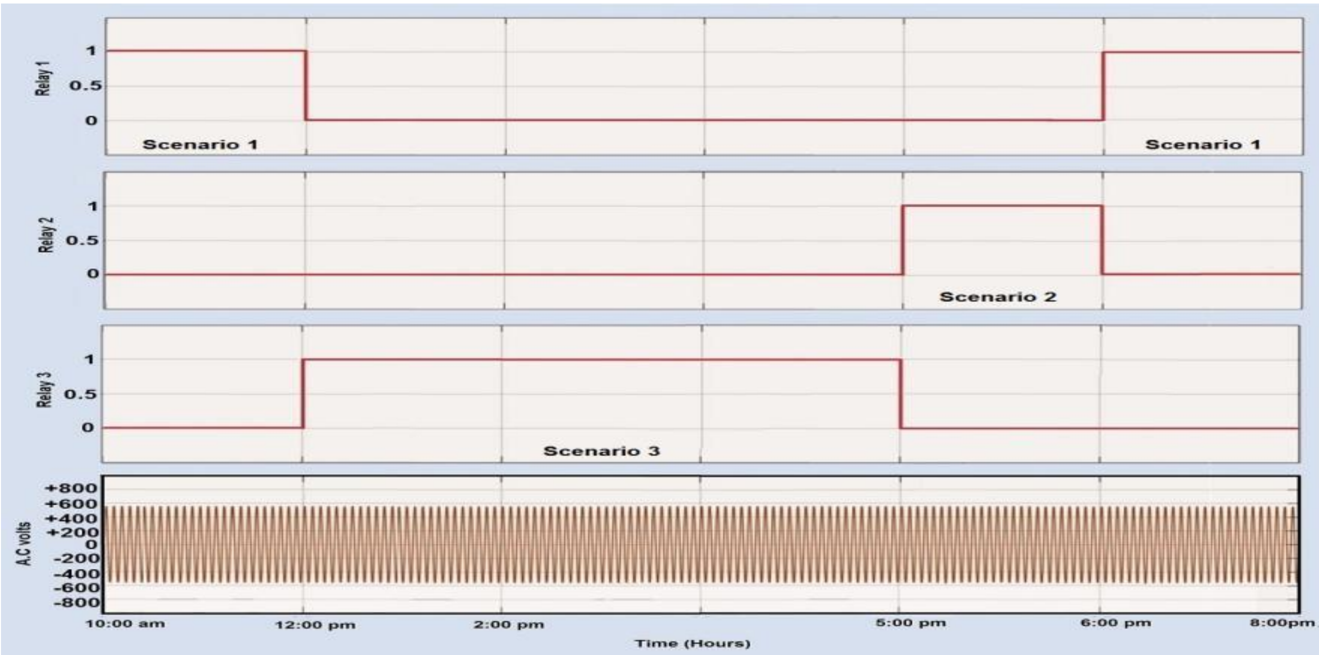


Figure 5.28 Relay trips for redundant power supply

5.10 IMPACT

5.10.1 Compatible and Sustainable Infrastructure

Smart grid and RTUs philosophy is compatible with renewable energy resources on existing and old WWTPs. The proposed design enables electricity trigeneration by integrating a sustainable resource without any expensive and major upgrades on existing infrastructure thus providing profitable results for stakeholders.

5.10.2 Intelligent and Efficient PMS

Smart grids with redundant and failsafe communication provides efficient PMS for WWTPs for demand load and power generation enhancing overall efficiency. The smart RTUs provide a perfect platform for SAS.

5.10.3 Distributed Power Generation

Distributed power systems that are achieved using smart RTUs increased average power generation, power quality, and reliability through time synchronised sequential operations. Proposed smart RTUs can be easily implemented on existing or old WWTPs enabling automated electricity trigeneration process.

5.10.4 Future Upgraded Technology

The modular nature of smart RTUs allows enough flexibility to meet future upgradations and demands for green electricity generation at WWTPs.

5.10.5 Economic Factors

Smart RTUs can easily be implemented on existing WWTPs with minimum investment. Smart grids enable optimal usage of biogas and the energy produced during the water treatment process and reduce operational and maintenance costs of WWTPs. Simulation Figure 5.29 shows saving by smart grids using modelled smart RTUs at MW-WTP. Results indicate a saving of nearly 0.5 million AUD on average.

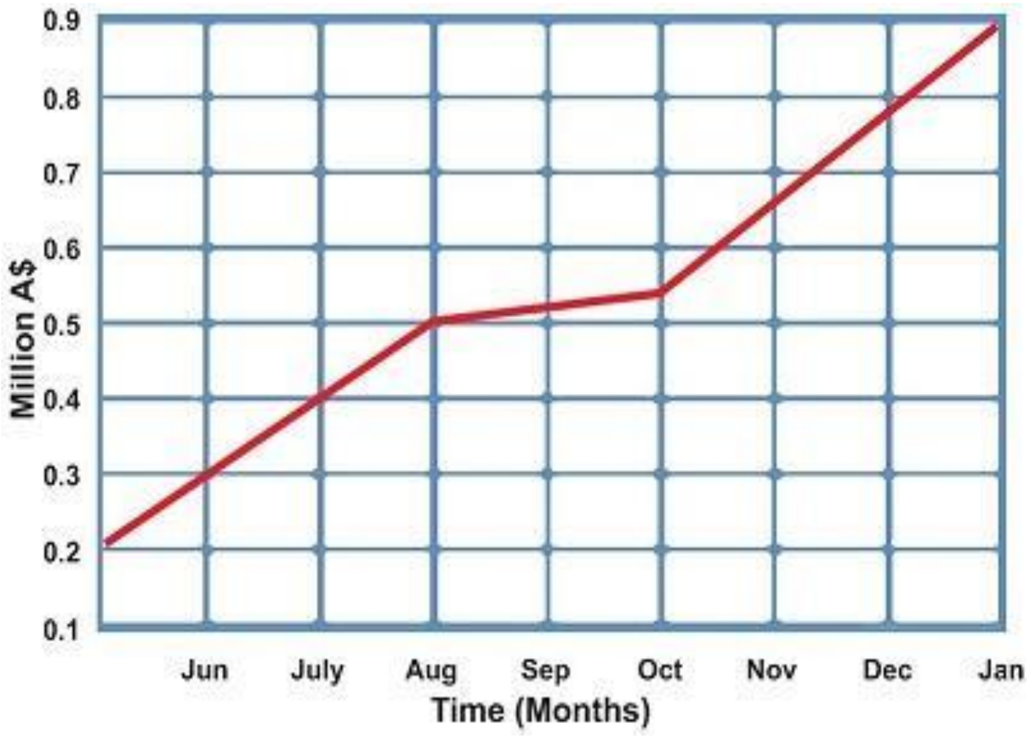


Figure 5.29 Smart Grid Savings

5.10.6 Renewable Energy Resource and OH&S

Wastewater contains about five times the amount of energy required for its treatment. Biogas is captured and utilised for electricity trigeneration. SAS reduces manual operations increases safety and health parameters

5.10.7 Environmental Impact

Wastewater treatment reduces waterborne diseases, GHG and carbon emissions using automated CHP system with smart grids and RTUs, thereby reducing the environmental footprint. Sludge is used as a soil-improving substance for agriculture and treated water can be used in many different ways. Figure 5.30 shows reduction of GHG emissions at MW-WTP using smart grids and RTUs, by 87,000 tonnes cumulative on annual basis.

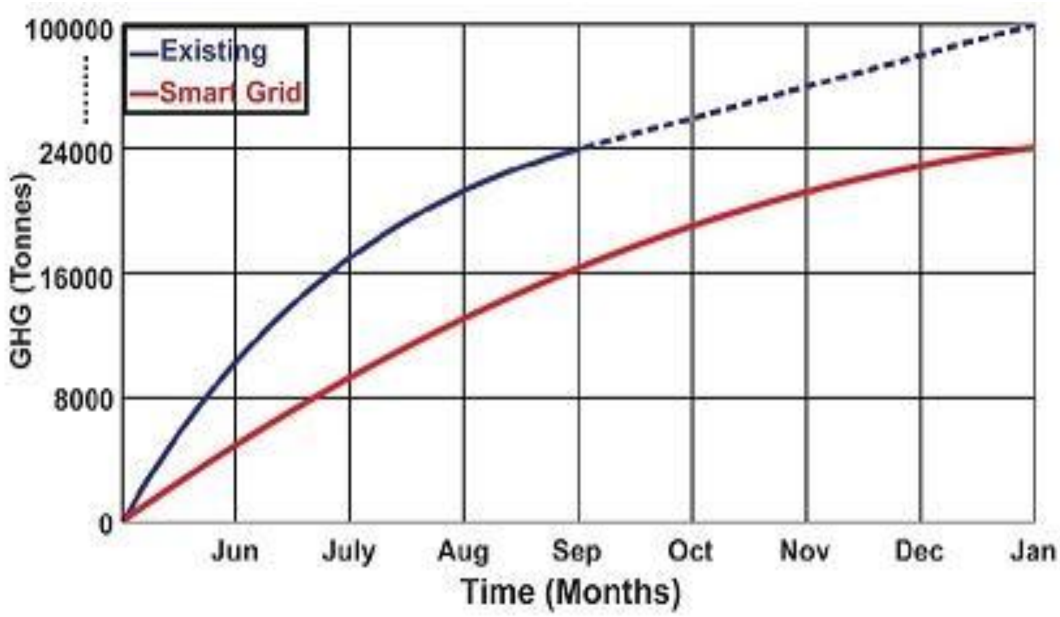


Figure 5.30 Reduction in GHG at MW-WTP

5.11 CONCLUSION

The existing power infrastructure at a WWTP requires smart grid for reliable power generation and communication network, which distributes electricity with maximum real power generated. Relay coordination with smart RTUs enables effective power management, fast fault identification and clearances, electricity trigeneration and environmental solutions. The proposed smart RTU panels implemented at MW-WTP POC provide a potential-free point, which can be replicated in existing infrastructure without any heavy investments. Smart RTUs relay coordination enhances equipment protection systems, efficiency, reliability and control on intertripping and interlocking functions of WWTP from a centralised location. This enables a failsafe and redundant WWTP communication network with increased OH&S standards.

CHAPTER: 6

FUTURE WORKS AND RECOMMENDATIONS

6.1 MODERNIZATION AT MW-WTP

The authorities and asset managers of modern WWTPs are always looking for avenues to reduce plant maintenance regime, reduce power costs and increase productivity with automation. Necessary research and development are therefore mandatory to verify the expected performance of the systems and integrate modernization with automation to increase plant safety.. Through modifications done in the existing infrastructure of Melbourne Water Western Treatment Plant Facility, smart RTUs and designed I/O philosophies are successfully implemented to provide a one stop shop to increase plant`s monitoring and control ability. The concept of cogeneration presented a feasible solution that not only addressed the electricity requirements of the treatment facility, thereby reducing the costs associated, but also implemented reverse power generation. The deployment of 8 generators at Melbourne' Water's treatment facility with a net generating capacity of 1.5 MW each, led to production of a total of 12 MW of power. Since the site's maximum electricity consumption is 8MW, therefore 4 MW is produced in surplus which is fed back to the zone sub-station i.e. PowerCOR. With this research work, optimum usage of biogas produced at WTPs has been achieved through its efficient utilization to excite on-site generators and provision of a basis for control and monitoring philosophy that can effectively feed surplus power back to the power company`s grid catering all the scenarios of WWTP biogas production. It also provides the level of protection and automation that achieves redundant and a failsafe system for any biogas producing site such as race courses, dairy farms etc. Since this research can be applied on existing or older infrastructures and sub-stations, it therefore saves the cost of developing new infrastructure and decreases pressure on Operation and Maintenance (O&M) capital works budgets. by providing same level of protection and reverse power generation. The system ensures increased on-site health and safety standards by minimizing operator`s interaction with the HV equipment.

6.2 FUTURE WORKS

6.2.1 The Modular Nature of the Smart RTUs and Integration

The existing systems with the proposed RTU interface with the HMI can also provide more room for the future up-gradation and expansion of the water treatment facility because this methodology is applied on existing and older infrastructure and does not require heavy investments for a new plant design, equipment and construction. Thus in short, with the additional RTU panel, telemetric I/Os flow can be controlled and relevant actions implemented as per the WTP designed philosophies. This redundant, failsafe and reliable solution is subject to the fact that the treatment process is constant and that the excessive energy produced through on-site biogas generation can be fed to the power distribution company grid as part of an asset management procedure. The successful results obtained show that the designed telemetric I/Os, smart RTU panel and their connectivity have enhanced the monitoring and control capacity of the sub-stations. I/Os are provided a potential free point so that it could be easily communicated to HMI through these smart panels. The modular nature of the smart RTU panels means that the level of automation can be enhanced and expanded for any future upgrades. It would allow easy functional implementation which provides each vendor with an opportunity to utilize its own design for attaining the required functionality. It also allows for data to pass through communication bus and makes the performance evaluation of sub units feasible without affecting the sub-station's usual operations.

6.2.2 The Centralized Control Room for WWTP

The HV operator could observe the HV feeding process without being physically present at the sub-station that serves to reduce the operator's tasks. Thus, the proposed smart RTU methodology provides an innovative solution for enhanced energy efficiency and productivity of the existing network and infrastructure whilst complying with IEC 61850-8 standards. The research therefore provides a failsafe and redundant platform for a centralized control room facility where these telemetric signals can be mapped on any given HMI for operator`s control and monitoring system. This communication solution for telemetric I/Os (to and from the WTP) decreases the probability of fault occurrence on the communication network and failure for power equipment in the network. Even if the network fails in the worst-case scenario, a level of protection is provided to the equipment till the problem is resolved. All these activities can now be performed from a centralized control room at the MW-WTP.

6.2.3 Increased Protection and Increased Ability for Power System

The proposed philosophies provided precise signal monitoring, implemented reverse power generation and generated green electricity through optimal usage of biogas power generation. Results demonstrated optimized performance with significantly reduced cost of operation compared to conventional electricity supply from the power distribution company of the WWTP. The designed smart RTU panel solved various issues associated with the old infrastructure and presented a flexible solution for future considerations. This added safety feature by decreasing the inter tripping down time of the circuit breakers and backups for the communication network provides the operators of the WWTP an added facility to manage the works across the site efficiently without any major shutdowns. The layout established efficient results through smooth flow of power distribution and drastically reduced intertripping downtime between sub-stations thus improving safety of the sub-stations and the power network during reverse power generation.

6.2.4 HV Network Augmentation

The system optimally uses the produced biogas by exciting the eight on-site Generators connected with the plant LV supplies and the excessive power to be fed back into power supply company`s zone sub-station. With the intertripping and interlocking and interlocking philosophies provided, the surplus amount of electricity is fed back via high frequency step-up transformers, which steps up the excessive amps and voltage level to 1kV. Intertripping and interlocking signals are established between CBs of the POCs to trip during faults while interlocking is achieved between Z.S and GS through c thus providing two layers of protect. This HV network augmentation minimizes line losses and provides a ring topology for the dual feeder fail-safe supply whilst integrating renewable energy resource.

6.2.5 Control, Monitoring and Evaluation Capacity of the WWTP

The smart RTU philosophy provides a real-time monitoring and control capacity to the WWTP which is mandatory to ensure smooth WWTP operations. The required functionality of all telemetric signals was achieved at Melbourne’s Western WTP by this increased capacity, which can be enhanced anytime with the plant expansions. The HV reticulation mechanism applied to Melbourne’s Western WTP. The smart RTU philosophy installed is comparatively easy to implement and reduces the need for complex secondary wiring in the distribution sub-station(s) for attaining interlocking and intertripping and interlocking of power supply equipment. The figure describes the power flow from main feeder to the Distribution Sub-stations POC1 and POC2. The treatment plant utilizes self-generated power on first priority and the surplus current is passed through high frequency transformers to feed to the zone sub-station (PowerCOR) via POC1 and POC2. The intertripping and interlocking mechanism ensures that power can only be supplied through site generators when there is sufficient capability while the power coming from Zone sub-station is being shut down and vice versa. The network provides a failsafe and redundant solution by implementing a ring topology. Power factor correction is necessary for on-site generated power to handle energy quality problems.

6.2.6 The Advanced Network Ability

The smart RTU provides interfaces for the FOC, DSL, hard-wired and wireless links. The patch panels can accommodate various signals independently hence increasing the data integrity. This research suggests FOCS for advance telemetric communication system to achieve redundant and failsafe communication for smart grid. Data is regularly conveyed by an electromagnetic bearer wave whose recurrence can differ from a couple of megahertz to a few hundred THz. Optical correspondence systems utilize high transporter frequencies (∼100 THz) in the obvious or close infrared locale of the electromagnetic range. They are in some cases called light wave systems to recognize them from microwave systems, whose bearer recurrence is regularly littler by five requests of size (∼1 GHz). The light wave innovation, together with microelectronics, is accepted to be a main consideration in the approach of the "data age." The target of this research portrays FOC as an extensive way of WWTP telemetric communication.

The standard IEC 61850 depicts the correspondence inside Sub-station Automation System (SAS) setting the base for new interoperating smart devices that offer data utilizing in the Ethernet protocol system. The demand of time synchronization among the SAS parts for time stamping of basic operations or synchro phasor estimation, follows the IEC 61850 working gathering for the circulated synchronization conventions like IEEE 1588. This research investigates the current circumstances at the MW-WTP, coordinating diverse usage of the IEEE 1588, and their particular precision, with the necessities of ordinary SAS applications with precision up to the milliseconds and synchronized operations required by the fault register application to the μs required by the sampled telemetric signals.

6.2.7 Connectivity and Interfaces

The control, automation and management of a water treatment facility are a sensitive and crucial task requiring a constant supervision. With the advanced sewage treatment strategies getting progressively common, communication networks need to be able to respond swiftly with robust control mechanisms and secure designs. The research proposes the following features to be included in the WWTP communication networks for smooth operation and management. In this grid integration, communication systems are crucial, which enable the accommodation of distributed renewable energy generation and play extremely important role in monitoring, operating, and protecting both renewable energy generators and power systems. This research has provided communication technologies available for grid integration of renewable energy resources. The research presents the communication systems used in a real renewable energy project. A correspondence system assumes a critical part in Sub-station automation system and different correspondence have been connected to meet the utility's goal. The proposed smart RTU philosophy provides a one stop potential free contact for all control voltage levels to interact with.

To maintain and secure a reliable grid, the utility must have greater visibility and monitoring capacity of the distribution system. This research explores ways to collect more frequent data from distant points that communicate the status of good and bad performance, enabling timely visibility into network problems. This is true for both operations in real time and long-term system planning. Our current real-time monitoring practices should be expanded beyond the Sub-station switch locations of strategic circuits, including the main infrastructure and the existing WWTP structures. Like multiple devices are connected to the network, complexity will continue to increase. This need for data will make the transition to a need for data management, processing extremely large amounts of information to evaluate the status of a increasingly complex distribution network.

Communication systems play the most crucial role in power system operations. Advanced SCADA communication systems for smart grid provide emerging two-way communication technology. DNP3 employs SCADA to control and monitor the efficiency of IEDs through smart RTUs. IEC61850 provides full compatibility and interchangeability features between the IEDs, regardless of their manufacturer. It allows the existing conventional protocols, like Modbus and DNP3, to synchronise with the IEDs and HMI. Ethernet-based switches have provisions for fibre and copper interconnections. Power network equipment is able to send and receive commands simultaneously. Every telemetric status signal is followed by an acknowledgment before any command instructions. Smart RTUs maintain connectivity of the relevant actions against them. . The noise free system and rapid data transfer has become the fundamental advantage of fibre optic communication especially in industrial automation. Hence, transmission via fibre optic connectivity (FOC) enhances the integrity of data by increasing the level and speed of communication making it a reliable source for water treatment plants or any sites where renewable energy is being produced.

6.2.8 Flexibility With Ring Topology

The ring network setup proposed with the smart RTU panel provides efficient management of treatment plants and introduces a flexible performance by re-building the network and route data immediately through a substitute path. Redundancy is one of the fundamental necessities for power system infrastructures and the WWTPS for intensive protection and automation to treatment process so that water treatment process can be operational across the clock and throughout the year. Redundant ring systems ensure constant resource availability and control to address multiple point connection failures. This flexibility of network is achieved through implementation of ring topology via smart RTU panels which are vital for the network's operation thus making it more reliable and easily manageable. The formation of ring topology basically provides an alternative path for power transmission to sub-stations in case of fault occurrence or link failures. This functionality ensures higher level of HV/LV redundancy and incurs least cost as per electricity and water standards, has least recovery time and provides a failsafe mechanism. Moreover, all power supplies are optically isolated.

6.2.9 Smart SAS systems

Smart SAS detect problems swiftly. It can identify the virtual and physical devices alterations of the distribution system and the network conditions that could endanger public and company staff.
The first step towards modernization is the visibility of all the conditions of the steady state network that may be needed to deal with, including policy violations, equipment failure, IT security, etc. visibility alone it is not enough. Hardware components that collect data from the field must be combined with software tools to analyzed this information at the same time. Situational awareness in real time will directly address the challenge faced with bidirectional power flows. The embedded smart RTU philosophy caters of these abrupt variations at the WWTPs thus providing a redundant system.

6.2.10 Service and WWTP Reliability

The proposed smart RTU philosophy embraces modernization by reducing manual tasks across the site. Manual HV operator tasks also serve to increase risks and dependency. The complex secondary designs like telemetric signals, protection relays, control gear monitoring etc. needs to be reduced to implement a flexible infrastructure with adequate redundancy. The objective of the proposed methodology is therefore to also add communication capacity to the Distribution Sub-stations while providing centralized power management to operate the plant. It will also address other aspects of automation such as enhanced performance, advanced supervisory control and reliability of power protection, which is done through several protection layers. The asset managers can therefore increase the reliability on the system to perform for their future planning and investments.

It is important to have a dependable communication network which is designed according to the plant requirements. The proposed smart RTU panels and the corresponding communication network provide a potential free point to the system. The panels provide the system experts with the opportunity to deal with locking capacities on location with a safeguarded correspondence arrangement.

The design and implementation of redundant power for industrial power distribution system aims for a service continuity and improvement of service reliability to achieve a sustainable solution. There has to be a backup power source in case primary power source fails. It must be ensured that the designed power distribution panel supports dual power inputs to control and monitor the power lost. In order to address the energy requirements of water treatment process, there needs to be a sustainable way of power generation and transmission. The proposed methodology therefore suggests sustainable delivery of electricity required which can be attained through self-generation of power. There should also be a mechanism to channelize any surplus amounts of electricity produced by feeding it back to the zone sub-station. Same should be fed by zone sub-station in case of energy deficiency, which is addressed through cogeneration.

Interlocking ensures that the power framework segments (circuit breakers and isolators) operate without any manual command. For a smooth and safe reverse power generation, the design logic behind Zone sub-station ensures that a remote trip signal conveyed from Distribution Sub-station will not cause the relevant POC to trip unless at least one of the generators is operating parallel to that particular feeder. The operation and management of this sensitive system requires status information of circuit breaker(s) positions in order to provide redundancy through smart panels with respect to communication and power flow. At the times when generators are disconnected, this will ensure that a trip and successful auto-reclose of Zone sub-station feeders would restore supply to the POC. It will also inhibit the operator initiated remote trip of the incoming feeders when the generators are not connected to the relevant feeder. Interconnectivity of the system with SCADA would also reduce the travel time of the personnel to remote parts of the treatment plant as the data could be remotely achieved from the network system implemented.

The plant sub-station must have the capacity to monitor, control and manage the process of cogeneration. It should send the surplus amount of energy produced on site back to the Zone sub-station towards grid. This will be the case when power produced at plant is greater than the power demand of the treatment plant.

6.2.11 Renewable Energy Resource Utilization

Wastewater treatment provides a renewable energy resource for green power generation and energy conservation. The advanced methods implied for the water treatment provide a good source of electricity for WWTP electricity cogeneration. This research focuses on distributed power generation concept for increased generation with the same resources. Wastewater contains nearly five times the energy required for its treatment and hence, the biogas and heat generated can be utilised for power cogeneration. Utilising these renewable resources reduces load on the power company`s grid and additionally, provides electricity in case of excess WWTP power generation. This creates new opportunities for electricity generation

In order to offset the energy requirements in WWTPs, certain strategies are adopted for efficient operation and energy consumption. Efficient utilization of biogas produced has been stressed upon which is reported as being relatively untapped source at national level in the US. It is estimated that biogas is produced by 52% wastewater treatment through anaerobic digestion where only 30% of which is utilized beneficially for energy generation. Mostly the remaining biogas is released to the atmosphere which wastes this useful source of renewable energy.

Some of the suggestions to improve energy efficiency in WWTP are to reduce costs which the process entails through usage of efficient pumps and aeration equipment. It is estimated to save approximately 400 million and 5 billion kWh annually in the US with just 10% reduction in energy use. Improving the efficiency of system operations are suggested to be done via installation of Supervisory Control and Data Acquisition (SCADA) software that enhances efficiency of process monitoring and operating control. Water and energy are closely linked in wastewater treatment. Wastewater treatment system is central to water and energy contacts because the process uses electrical energy for reducing the pollutants in wastewater. Likewise, water is also needed in production of electrical energy. According to an estimate, wastewater treatment requires about 3% of electrical load requirements in developed countries and incurs high-energy costs for treatment. To balance this energy consumption, it essential to address the system's energy demands through cutting on load through various energy saving means.

The evolution of WWTPs towards smart grids with integrated renewable energy resource will result in optimised biogas production and electricity trigeneration, to provide energy management and environmental solutions with economic growth on old or existing infrastructure.

This research considers the use of sustainable power sources in wastewater treatment plants to accomplish self-maintainability of energy. The information about MW-WTP is introduced as a contextual investigation. The essential goal is to give an inexhaustible independent power system, which fulfils most minimal conceivable discharges with the minimum lifecycle cost. Utilizing digester gas as a fuel prompt investigation, where energy component is chosen to submit to the low discharges' limitation. The examination evaluated the electrical power from renewable energy component and the use of the depleted heat for energy. The smart RTUs philosophy as proposed and discussed in this research is able to manage the extensive need of SAS and for effective power and water management at the WWTPs.

6.2.12 Utilisation of Other Energy Resources

Turbines are used for energy conversion from the flowing wastewater to produce electricity, using advanced technology. Micro turbines can be employed to generate electricity, which can be used to feed the LV of the substations to make the system not only self-sufficient but also feeding back any excess supply to the power company`s grid.

Thermal energy produced during the WWTP electricity cogeneration can be utilised effectively in CHP systems increasing their efficiency. This cogeneration model allows WWTPs to heat up their digesters, especially during the winter, to increase their temperatures for increased productivity in terms of biogas and the generated electricity.

Anaerobic digestion in biosolid digester's section produces maximum amount of methane gas through Combined Heat and Power (CHP) process. The sequential treatment flow process shows that flammable gases that are formed are burnt to produce sufficient amount of steam, which is further utilised to excite on-site generators for electricity generation. The proposed smart RTU philosophy provides a control link to integrate all these and any other available renewable energy resources like solar.

6.2.13 Utilization of Bi-Products

Biogas produced through anaerobic digestion at WWTPs is used to excite on-site biogenerators for generating electricity. This research provides a deep study and analysis on various scenarios of biogas production and their proper control on electricity generation with power flow in order to optimally utilise biogas production during the wastewater treatment process to achieve electricity cogeneration and achieve High Voltage/Low Voltage (HV/LV) redundancy. This research established a new technology driven approach to realise this process efficiently on existing WWTPs and reduce the need for additional sources of energy for a swift water treatment process. The research utilises telemetric signal monitoring for biogas production and multidirectional power flow through remote data.

- Electrical energy, heat and biofuels formed are utilised using anaerobic digesters
- Electrical energy and heat are formed from thermal conversion of biosolids
- Electrical energy from biosolid products is used for on-site energy production (e.g., pellets used in power plants, cement kilns, or industrial furnaces)
- Heating or cooling energy using the thermal energy found in plant influents or effluents as heat source to sink heat pumps

6.2.14 Biosolids

Biosolids are the supplement rich natural materials coming about because of the treatment of household sewage in a wastewater treatment office (i.e., treated sewage muck). Biosolids are a useful asset, containing fundamental plant supplements and natural issue and are reused as a manure and soil correction. Biosolids are made through the treatment of household wastewater created from sewage treatment offices. The treatment of biosolids can really start before the wastewater comes to the sewage treatment plant. In numerous wastewater treatment systems, directions require that modern offices pre-treat their wastewater to expel unsafe contaminants previously it is sent to a wastewater treatment plant. Wastewater treatment offices screen approaching wastewater streams to guarantee their recyclability and similarity with the treatment plant process. Once the wastewater reaches the plant, the sewage experiences a natural procedure that cleans the wastewater and expels the solids. The overabundance organic solids are then processed or stabilized through different procedures to lessen or dispose of pathogens. After treatment and preparing, these residuals can be reused and connected as compost to make strides furthermore, keep up gainful soils and empower plant development. Ranchers and nursery workers have been reusing biosolids for a long time, diminishing the requirement for compound manures. Biosolids are connected to advance the development of farming yields, prepare gardens and stops, and recover mining destinations. At the point when connected to crops application rates are confined to the supplement needs of the harvest. The plant supplements are gradually discharged all through the developing season empowering the yield to ingest these supplements as the harvests develop Solids are removed from the biosolids produced in WWTPs. Several types of technologies can be implemented to generate electricity from these solids. A special kind of produced dry solids can be used as landfills.

6.2.15 Biofertilisers

Wastewater treatment produces biofertilisers, which support fertility and farming. Moreover, treated sludge is used as a soil-improving substance for agriculture and treated water can also be used in many ways.
Critical amount of wastewater that is released every day is taken care of at the level of wastewater treatment plant by natural means. Given this information, the improvement of a unit is to recuperate and reuse the treated WAS as a fertilizer for the soil. The fertilizer can be blended with muck separated from the wastewater treatment plant.

6.2.16 Green Electricity

Research emphasises on the process of power generation with waste heat usage known as the combined heat and power (CHP) process. Anaerobic digestion in the biosolids digester sections of WWTPs produces maximum amount of methane gas through CHP process. Flammable gases are burnt to produce sufficient amount of steam. This steam is further utilised to excite the on-site WWTP biogenerators for electricity generation. Any surplus electricity required is imported via the power company`s grid and exported in case of any surplus generation.

Cogeneration is highly efficient for electricity generation and energy conversion at WWTPs. Cogeneration systems are ideally suited as captive power plants located at the site of use for self-generated electricity. The philosophy behind the proposed design of a smart Remote Terminal Unit (RTU) provides proper telemetric signal monitoring and a two-way power flow, enabling a failsafe mechanism at different levels of water treatment process and biogas production thus facilitating an automated WWTP electricity cogeneration.

The CCHP system has five essential segments: the fundamental total, an electric generator, a warmth recovery subsystem, a thermal unit and a control subsystem. Essential parts can be chosen from steam turbines, ignition gas turbines, the inside ignition motor, micro turbines power modules and Stirling motors. A thermal unit is chosen from current advances like the smart devices, smart devices and dehumidifier's gives a cooling or dehumidification process. Smart RTUs are mounted on these units for real time monitoring to develop the right control philosophy of the WWTP.

Trigeneration is an efficient power and energy solution for public buildings. Smart grid with renewable energy resources, such as biogas at WWTP, gives high efficiency and flexibility. Heat emissions from electricity generators, especially in hot seasons, can be utilised for thermal power plant to achieve electricity trigeneration. Trigeneration systems are CHP (Combined Heat and Power) or co-generation systems, integrated with a thermally driven refrigeration system to provide cooling as well as electrical power and heating. CHP systems consist of a power system that can be an internal combustion engine driven by biofuel. Producing electricity. A heat recovery system recovers heat from the power system and exhausts gases to be used for heating applications. Trigeneration systems can have overall efficiencies as high as 90% compared to 33% to 35% for electricity generated in central power plants.

6.2.17 Environmental Friendly Approach

Wastewater treatment plants (WWTPs) assume a critical part in forming present society's ecological prosperity. Both traditional and natural strategies were used to evaluate ecological effect of the given WWTPs with the smart RTUs implemented. The water quality change showed a remarkable improvement in the quality of water upstream, especially in the urban areas with industries and densely populated zones.

Wastewater treatment reduces waterborne diseases and keeps the ocean clean. The proposed research helps reduce GHG emissions and bad odour around the WWTP vicinity. SAS using smart RTUs also reduces heat emissions.

6.2.18 Cost Effective Solution

The expansion of savvy board turns out to be a viable substitute to address the requirements of treatment plant operations thus reducing the establishment, substitution and stock costs respectively. The budgetary evaluation demonstrates that charging and tax assessment costs partnered with power conveyance organizations are promptly limited with the on-location power era while using biogas.

Water treatment facilitates are made up of assets which are key to the treatment process and which age overtime. The quality of treatment is also compromised which affects biogas generation and consequent production of energy. With the proposed automation and networking philosophies, the life span of assets would increase and hence operational and maintenance costs would reduce. With this energy optimization process, the WWTPs can also gain a lot of benefits through management and optimization of energy used to operate the plant. This depends on the size of the plant and the optimization mechanisms of the plant owners. Wastewater treatment being operated automatically and unattended will also benefit the facility service providers by reducing labour requirements and thus saving labour costs.

6.2.18 IEC Standard Driven Design

IEC 61850, correspondence systems and systems in substations, is a worldwide standard that backings interchanges of Sub-station mechanization related data. IEC 61850 gives an exceedingly practical question arranged arrangement intended to help usage and support of Sub-station automation applications. Activities are additionally under approach to stretch out IEC 61850 to other application regions past substations, wind control systems, hydro control plants and dispersed (distributed) vitality assets.

DNP3 is an open SCADA system. DNP3 is the market-driving utility SCADA. DNP3 takes a shot at serial interfaces including RS232 and RS485, FOCs in all the arrangements.

The IEC Technical Committee 57 have developed a protocol standard for Tele control, Tele protection, and associated telecommunications for electric power systems.

The result of this work is IEC 60870-5.

IEC 60870-5 provides a communication profile for sending basic messages between two systems. Five documents specify the base IEC 60870-5

- IEC 60870-5-1 Transmission Frame Formats
- IEC 60870-5-2 Data Link Transmission Services
- IEC 60870-5-3 General Structure of Application Data
- IEC 60870-5-4 Definition and coding of Information Elements
- IEC 60870-5-5 Basic Application Functions.

6.2.19 Modernization

This research provides an automated operation that reduces risk factors and improve health and safety parameters at the WWTPs. Workers in the wastewater treatment sector are responsible for the day-to-day operation, maintenance, trouble-shooting and handling of special problems of municipal, industrial, and other wastewater treatment plants. Occupations can include Wastewater Plant Operator, Plant Operator, Senior Operator, Water Resources Specialist, Maintenance Operator, etc in both municipal and private facilities. The smart RTU philosophy provides a centralized control room for the staff to monitor and administer the facility, as well as take appropriate actions if required. Automation of all interlocking, intertripping, switching and faulty scenarios of MW-WTP has minimised the HV operator`s interaction with equipment, increasing OH&S standards. Reduced intertripping downtime has also improved safety of the power network during electricity cogeneration.

Manual operator tasks in the existing WWTPs during HV switching for maintenance shutdowns and power outages, serve to increase risks. Physical interaction with HV equipment needs will be minimised during the automated task of electricity cogeneration. Moreover, smart grid prevents greenhouse gases (GHG) and carbon emissions to enter into the atmosphere, hence reducing the environmental footprint and enables (co and tri) generation of green electricity with improved occupational health and safety (OH&S) standards.

To achieve these objectives, communication will be required for the components of the internal control systems. In a rapidly growing world, automation demands for substations are increasing. IEC 61850 specifies very stringent requirements for the message transfer period. Intelligent network security is designed to meet performance and reliability requirements using the OSI layers of protection provided by the smart RTU philosophy. This research proposes failsafe communication with the interconnected substations in the WWTP power network, in real time, complying with IEC 61850 specifications. The smart grid application in this research considers the streamlining of the power utilization as per the WWTP requirement. The control procedures utilize the capacity volume in the pipe system upstream and the WWTP to confine water during hours with high power costs, discharging the water when the value power costs decrease. This examination explores the potential for incorporating the capacity limit of the sewer arrange as part of a Smart-Grid control of a WWTP. The research introduces the approach that has been followed in the improvement of water treatment process at WWTPs.

CHAPTER 7: CONCLUSION

7.1 KEY ELEMENTS OF THE RESEARCH

Smart grids have enabled an efficient two-way communication, power distribution, control and monitoring system with minimum losses to achieve WWTP electricity cogeneration. With the world moving towards environmental friendly solutions for power generation to reduce GHG and carbon emissions, researchers are working endlessly to find alternate sources of power to generate green electricity. Smart grids can utilise multiple distributed renewable energy resources, which reduces the cost impact and environmental footprint. This research presents an advanced SCADA system with the proposed smart RTU to meet the demands of power generation and achieve different levels of protection by enabling a redundant communication of power network complying with IEC61850 and IEEE standards. This research also provides relay coordination solutions of Sub-station for enhanced protection of plant equipment and safety. Moreover, the proposed philosophy can easily be implemented on existing or old infrastructure with minimum investment as it uses LCTA principles.

SCADA system gives numerous advantages in a practical and efficient way. The deployment of SCADA systems is easy and it can be synchronised with the smart RTUs at the Sub-station level, information is gathered across various field devices on the power network of the WWTP and then made accessible to the SCADA system. Bringing every single control and generated signal into a neighbourhood controller, for example, a PLC, does this. This requires duplication of manual devices with the smart devices that is compatible with the PLCs. In different cases, mechanized smart devices may impart by means of conventions not perceived by the PLC. For instance, if a power observing smart devices has a Modbus port and the PLC does not, some sort of equipment convention interpretation smart devices should be bought, arranged and introduced.

Be that as it may, some SCADA programming bundles offer the required DNP3 and IEC60870-5-104 conventions, dispensing with the requirement for an equipment smart device by utilizing the SCADA programming as the convention interpreter for the WWTP network equipment. In substations, it may be important to change over all computerized information conventions to Ethernet and to introduce network managed or Ethernet switches. The switch would then be commonly associated back to the central SCADA stations when information is gathered and conveyed to the master station. This process is frequently required at the substation, the Smart RTU provides a perfect platform for these telemetric signals to be communicated across. This regularly requires supplementing of manual switches with programmed switches, which can be expensive and can require specific line portions to be de-stimulated for their establishment.

Ethernet is normally the choice to synchronise communication modules with the smart RTUs. It can incorporate the Internet, intranets and distributed computing on complex networks. Better data presentation for improved analysis on the SCADA systems give numerous focal points including expanded dependability, diminished costs, more prominent consumer loyalty and enhanced usage. Standard conventions particularly intended for the business, for example, DNP3 and IEC60870-5-104 empower the SCADA system to gather data with accuracy and precision required to analyse shutdowns, outages and for O&M regime of the WWTP. This cuts time for on field visits and furthermore improves safety standards amid blackouts and power cogeneration at the WWTPs. Present day SCADA systems give dynamic dashboards, solidifying recorded data with online information with a specific end goal to give important data to end users. Joining with ERP systems by means of SQL social databases permits the SCADA system to think about objectives with the continuous execution, while making this data continually accessible to approved clients through standard web programs. Utilizing these highlights, the SCADA system turns into a critical instrument not just for everyday tasks, yet in addition for vital choices. The smart RTU at the WWTPs provide that layer of integration for the SCADA and field devices.

NTP, GPS, and IRIGB are latest innovations that basically aren't suited for the prerequisites of Sub-station activities. Luckily, the IEEE1588v2 Precision Time Protocol (PTP) is outlined particularly for modern organized electrical and control systems. In view of IEEE1588, the grandmaster clock decides the reference time for the whole Sub-station control philosophy. The Ethernet switch goes about as the limit or straight forward clock, and extra smart devices, consolidating units, IEDs, and security smart devices are assigned as common tickers. All of these smart devices are composed into a slave synchronization order with the grandmaster time at the control center. PTP bundles amongst ace and slave smart devices, and naturally changing the common timekeepers, adequately synchronizes the whole system. Just the grandmaster clock needs an association with GPS timekeeping that information can be precisely circulated to whatever is left of the smart devices on the system. The redundant communication system offered by the smart RTUs offer all of these features to be integrated at the station level.

7.2 MAJOR RESEARCH AND BENEFITS

This research highlights that the existing infrastructure of WWTPs needs an advanced reliable telemetric communication network system, which can transfer generated signals securely from distant nodes to a centralised SCADA system and vice versa. Advanced modification is required for upgradation to meet relevant IEC/IEEE WWTPs electricity cogeneration standards and efficient power management system.

Sub-station automation systems manage remote monitoring and controlling of the WWTP. The intertripping and interlocking philosophies of the power supplies are also linked with the SAS that are provided via the smart RTUs interface. The convention directly utilizes SCADA protocols of IEC 60870-5-101. Despite the fact that development of the system was done, no progression was taken towards smart automation system. The smart RTU philosophy proposed in this research will provide that willingness to the asset managers of the WWTPs to invest in the renewable energy sector and to make their WWTPs green and self-sufficient with their energy demands.

Advanced computerization with smart automation is the key to modernization. It includes the utilization of Intelligent Electronic Smart devices via smart Remote Terminal Units control.

Smart Sub-station automation system makes distributed power system extremely efficient, which can easily be implemented on existing or older Sub-station at WWTP. A suitable control philosophy for the activities is developed via the smart RTUs to guarantee continuous control and monitoring of the field devices to the end clients. SCADA frames the section towards SAS.

The modelled smart RTUs in this research might be expandable or custom fitted with various field devices including communication interfaces, control and computerized I/O interfaces. In light of their broadly differing applications, RTUs come in various equipment and programming arrangements. In SCADA systems, RTU is a smart device introduced at a remote area that gathers information from substation.

The proposed research is extremely noteworthy for vitality spring. All water treatment offices require a colossal measure of vitality because the procedure includes compressors that expand with overwhelming force for their operation which creates a substantial energy load on power zone. This exploration encourages all water treatment plants to produce their energy request while measuring vitality and power requirements. If the sent gear is not used for the water treatment cycle, it will put immense costs. In this way, this proposed extra board would ensure to comprehend the issues with the current arrangement while up-grading the old framework. The positive aspects of sub-station automation framework (SAS) implements expanded power administration, repetitive and adaptable arrangements while considering water treatment requirements. The exploration likewise ensures ideal utilization of biogas created. The research not only provides a mechanism to accomplish HV/LV access for a water treatment plant but it also executes multiple layers of security to the plant hardware by commissioning interlocking and intertripping and interlockingand activation of ring topologies between the power produced and the request stack.

With the execution of electrical boards and the topologies discussed in this research, the necessity to close down the plant amid capital work or system up-gradation has been minimized. The methodology encourages disengagement of the plant section where the works are being done without influencing the entire water treatment processes and activities. This lessens the load on O&M assets minimizing the costs utilized on system maintenance. The proposed philosophy has been rehearsed and found reliable for interlocking methods giving a dependable and repetitive power supply for any biogas generating site. The philosophies guarantee a ceaseless stream of dark water at the treatment destinations and a successful method for checking and controlling force supplies.

Biogas being one of the important renewable resource asset compensates the energy intensive treatment operation and supported innovations. The ideal utilization of anaerobic processing actualizes a double capacity of waste treatment and creation of power through biogas. The proposed look into gives an imaginative arrangement of associating destinations delivering power from renewable asset to the principle supply matrix. It will urge speculators to execute renewable assets on location to accomplish most extreme effectiveness and yield for their ventures.

The environmental benefits of the process are the efficient utilization of biogas produced which was otherwise released in the environment, not only polluting it but also was wastage of this important resource. The process of biogas generation itself is the conversion of wastes item into a profitable resource. This consistent treatment of wastewater brings about appropriate asset administration. The research provides an approach which limits natural dangers by giving environmental friendly energy generation to water treatment plant and the power zone.

Many cases appear due to electric risks faced by the operators and electricity personnel. The conceivable outcomes of electrical dangers faced by engineers, circuit testers, control line labourers and related staff to electric stun, electric shock, wounds, and blasts are enormously decreased because of safeguard, access, and dependable execution. HV administrator assignments are limited to keep away from dangers, and manual reliance as the usage is consistent with electrical wellbeing principles.

The RTU boards give access and safeguard to operations and maintenance of water treatment plants. The cogeneration guarantees that the plant operations are not dependent alone on biogas or the energy originating from power conveyance organizations. The usage of this examination on destinations will lessen the need for HV and LV administrators to frequently contact the electrical departments or zone power stations.

This research provides new advanced methods for power generation with distributed resources for reduced pressure on external grid stations. Efficient WWTP cogeneration and trigeneration enhances plant production and power to make this system independent of external power resources but also supply power to external grids for distribution.

Smart grid`s goal is to achieve efficient, sustainable, economic and safe distribution of electricity.
The smart RTU philosophy discussed in this research incorporates all of these processes in an orderly fashion to develop an automated system for the WWTP.

Smart grid enables reliable power generation and a communication network system, which distributes the maximum real power generated. Relay coordination with smart RTUs enables effective power management, fast fault identification and clearances, electricity trigeneration and environmental solutions. This research provides modernisation of both the transmission and distribution grids with digital upgrade. Advanced telemetric communication, power management and two-way power flow is successfully achieved using SCADA system with smart RTUs. Smart grid prevents greenhouse gases (GHG) and carbon emissions to enter into the atmosphere, hence reducing the environmental footprint and enables (co and tri) generation of green electricity with improved occupational health and safety (OH&S) standards. Therefore, the increased efficiency and reliability of the grid is expected to save money and help reduce CO_2 emissions.

7.3 COMPARISON WITH OTHER WWTPs ACROSS THE GLOBE

This work presents a comparative review of the energy consumption of different wastewater treatment plants, aiming at a better understanding and management of the processes. Term Equivalent Persons (EP) used here has the same meaning as Person Equivalents used in European literature.

This research provides an opportunity to wastewater industry to generate self-sufficient electricity generation and environmental solution with multiple other benefits. Comparing with most of the existing WWTP where the requirement of energy is much higher as compare to power generation make this process very expansive. Table 7.1 indicated that energy effluent final disposal and reuse Australia has maximum energy consumption. This research simulation results show that it reduces the cost and improve electricity generation with more effect way which can be implemented easily on old or existing infrastructure of WWTP.

Table 7.1 Show Energy Consumption at Different Level of WTP

Process Step	Country	Consumption (kWh / m^3)
Wastewater collection	California	0.003 - 0.04
	Canada	0.02 - 0.1
	Hungary	0.045 - 0.4
	Australia	0.1 - 0.37
	USA	0.04
	New Zeland	0.04 - 0.19
	India	0.07 - 0.11
	World average	0.022 - 0.042
Sludge management	World average	0.074 - 0.15
	Australia	0.02
Effluent final disposal and reuse	World average	0.18 - 0.63
	Israel	0.72
	Singapura	0.93
	Australia	2.5 - 4.5

Table 7.2, 7.3 shows energy consumption at basic three level of wastewater treatment of different countries. COD biochemical process is one of the most efficient process can produced maximum amount of biogas reduced cost. This research concludes biochemical CHP and CCHP process for biogas production. Simulation results prove that power generated more than WWT process demand [175].

Table 7.2 Show Energy Consumption of Basic Water Treatment Process

Local	Treatment	Process	Consumption (kWh/m³)
World average	Preliminary	Railing	2.9x10-5 - 0.013
World average	Preliminary	Decantation tanks with mechanical scrapers	4.3x10-5 - 7.1x10-5
China	Preliminary		0.002 - 0.076 kWh/t
Ireland	Preliminary	Aerated filter	50.01 kWh/day
Australia	Primary		0.01 - 0.37
World average	Primary	Decanting	4.3x10-5 - 7.1x10-5
World average	Secondary	Sludge separation	0.0084 - 0.012
World average	Secondary	Sludge circulation	0.047 - 0.01
World average	Secondary	Blending	0.053 - 0.12
World average	Secondary	Aeration	0.18 - 0.8
China	Secondary	Biochemical	0.008 - 0,229 kWh/t
Japan	Secondary		0.34
Sweden	Secondary		0.42
China	Secondary		0.29
USA	Secondary		0.2
Australia	Secondary		0.305
Ireland	Secondary	Activated Sludges	1,366.9 kWh/day
Ireland	Secondary	Activated Sludges	450 kWh/day
World average	Terciary		0.40 - 0.50
China	Terciary		0.25
Germany	Terciary		0.67
Spain	Terciary	Membrane	0.8
Saudi Arabia	Terciary	Membrane	1.6
China	Terciary		0.001 - 0.009 kWh/t
World average	Terciary	UV	0.045 - 0.11
World average	Terciary	Chlorine Dosers	0.009 - 0.015
World average	Terciary	Filtration	0.0074 - 0.0027
World average	Sludge	Centrifugation	0.018. 0.027
China	Sludge		0.001 – 0.0043 kWh/t

Table 7.3 Show Energy Consumption Country wise of Different Processes

Country	Capacity	Process	Consumption (kWh/m^3)
World average			0.38 - 1.122
Spain		Conventional activated sludge	0.5
Spain		Activated sludge with filtration	1.2
Spain		Immersed biological membrane reactors	0.8
Spain		External membrane reactors	1.0
World average		Conventional Activated Sludge	0.3 - 0.65
World average	2.000 EP		3.01 Wh/kg COD
World average	100.000 EP		0.69 kWh/kg COD
South Africa		Stabilization ponds	0.079 - 0.28
South Africa		Thickening filter	0.19 - 0.41
South Africa		Activated sludge	0.33 - 0.61
South Africa		Aeration Ditch	0.48 - 1.03
India			0.19
India		Conventional Activated Sludge	0,26
South Korea			0.243
Germany			0.95 kWh / kg COD
Germany			0.4 - 0.43
China			0.12 - 0.38 kWh/t
China		Anoxide-anaerobic-oxide	0.254 - 0.31
China	2x106 m^3/day	Anoxide-anaerobic-oxide	0.13
China		Membrane	0.6
China		Anoxide-anaerobic-oxide	0.45
China		Humic filter	0.25
China		Aeration trench or anoxide-oxide system or rapid infiltration	0.4 - 0.5
China	45 m^3/day	Humus biofilter	0.15
Greece	380 m^3/day	Gikas method	0.087
Brazil			0.24
Brazil		Conventional activated sludge system	057
Canada			1.65 kWh/kg COD
France			3.33 kWh/kg COD
Spain			0.97 kWh/kg COD
Italy			0.85 kWh/kg COD
USA			1.31 kWh/kg COD
USA	1,5x104 - 106 m^3/day		0.52 – 0.55
USA		With chlorine disinfection	0.287
USA		With UV disinfection	1.12
Egypt, Spain and France		Vertical flow bed	0.45 kJ EP/day
		Activated sludge	464 kJ EP/day
		Activated sludge + polishing pond	668 kJ EP/day

7.3.1 Energy Generation Potential in the WWTPs

WWTP produce biogas which is captured and turned into renewable energy by generating co/tri generation electricity. The Western Treatment Plant generates of its own annual electricity needs, and providing electricity to the distribution grids. Capturing and using biogas to generate electricity also means greenhouse gas and odour emissions are reduced.

7.3.2 Melbourne Water Western Wastewater Treatment Plant

Around 90% of odour emissions are being reduced from the Western Treatment Plant by the implementation of the smart RTUs. 14 Hydroelectric power stations are being installed in the water supply network which generate up to 69,500 megawatt hours of electricity each year in the state of Victoria, Australia. These power stations generate energy from the flow and pressure of moving water. The power generated using biogas and the hydropower are sychrnized at a bus, utilised and any excessive electricity is fed back into the power company`s grid. By operating these power stations, 75,800 tonnes of carbon dioxide emissions are reduced each year to enter into the atmosphere [176].

7.3.3 Sydney Wastewater Treatment Plant

Sydney Water currently generates more than 20% of its total energy needs across its network. It also exports 8000 megawatt hours MWh to the electricity grid over a year. Reducing greenhouse gas emissions by over 70,000 tonnes a year [177].

Consider all research impact it simulated about 15% increase can be easily implemented in power generation of old or existing WTPs of the world

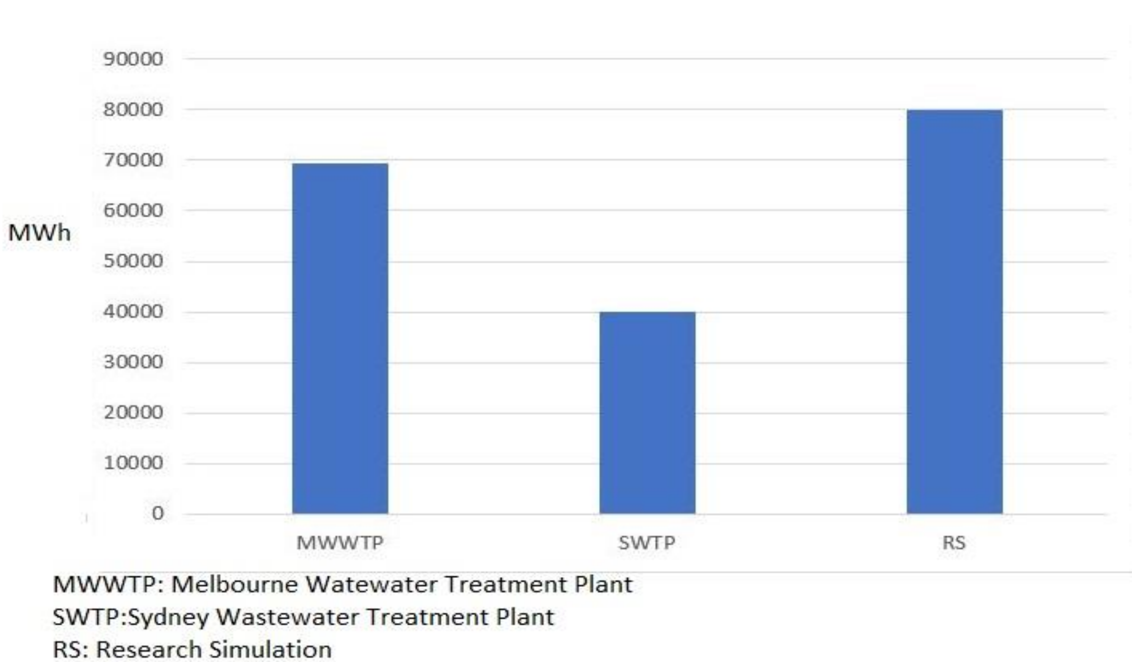


Figure 7.1 Power Generation Impact of Research

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Appendix A - List of Equipment and Technical Specifications

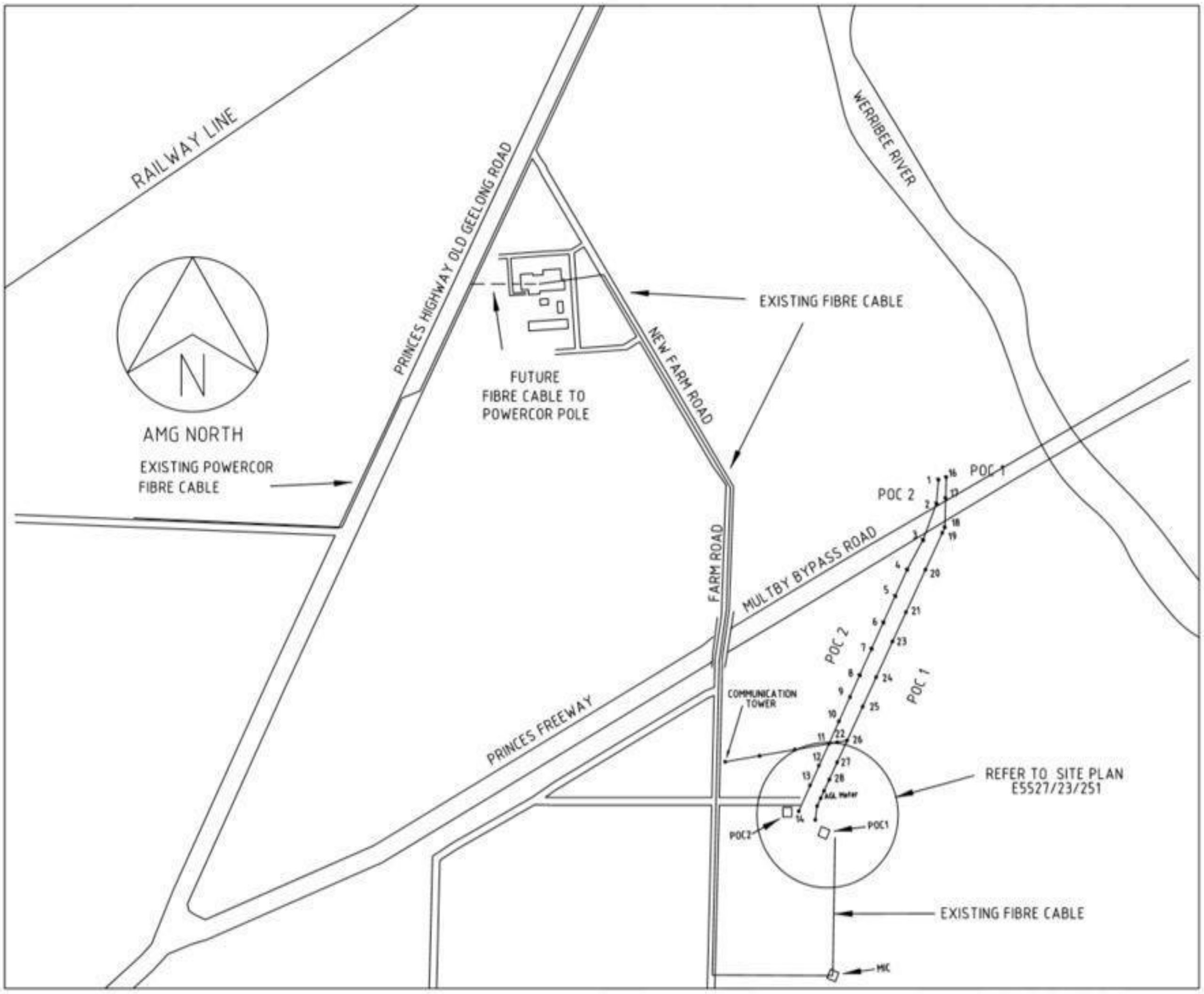


Figure A 1.1.a Location Plan for Sub-stationPOC1 and POC2 at MW-WTP

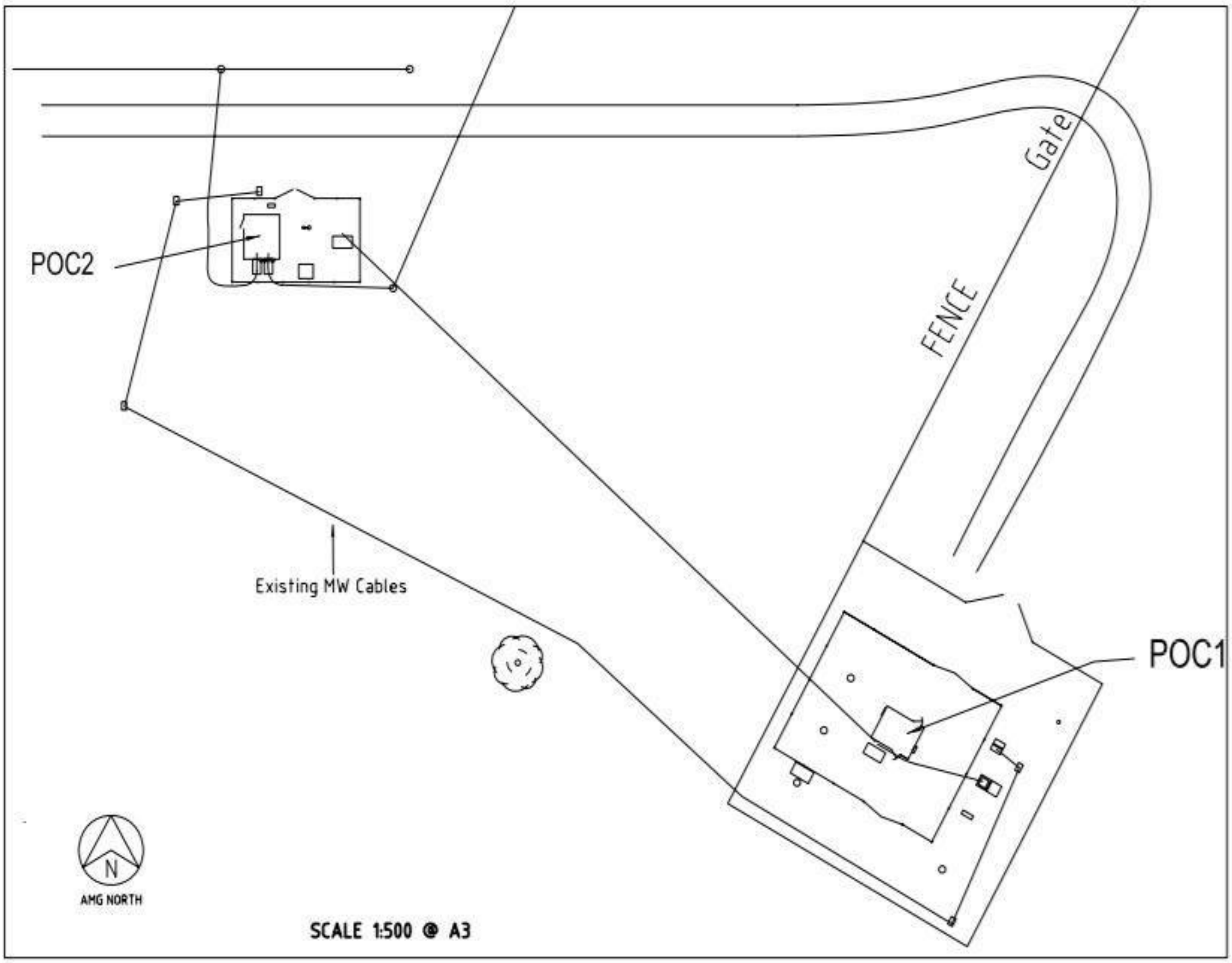
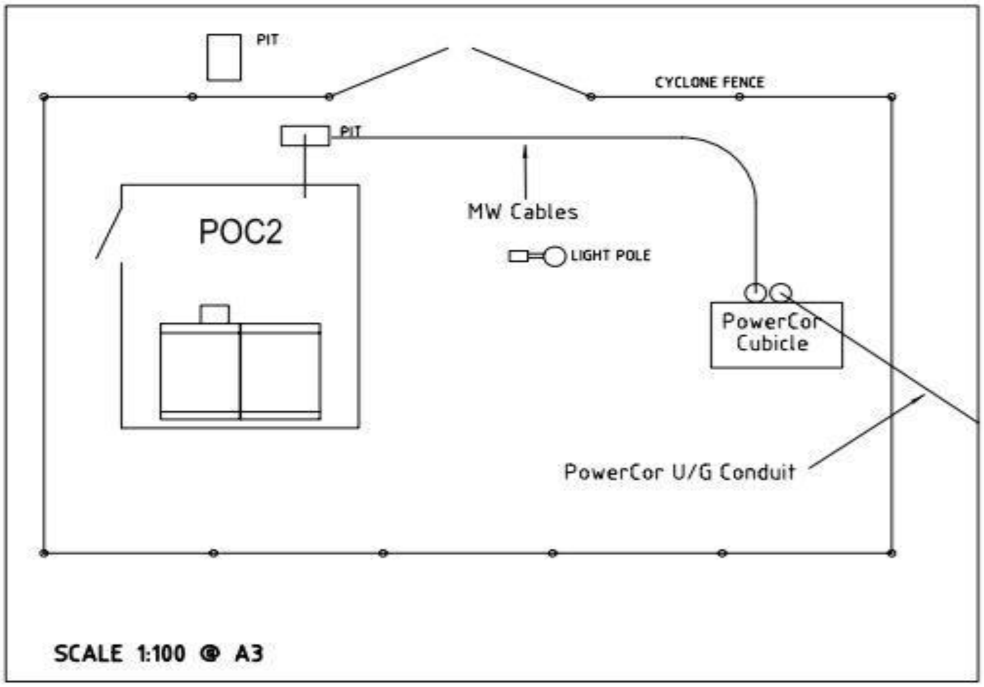
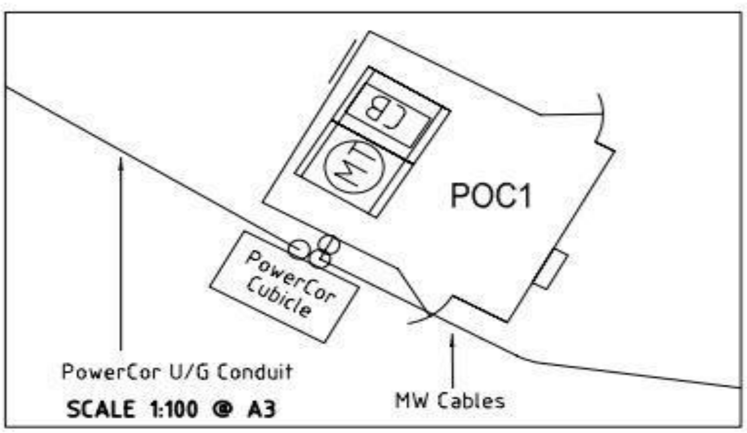


Figure A 1.2.b Export Power Site Plan at MW-WTP

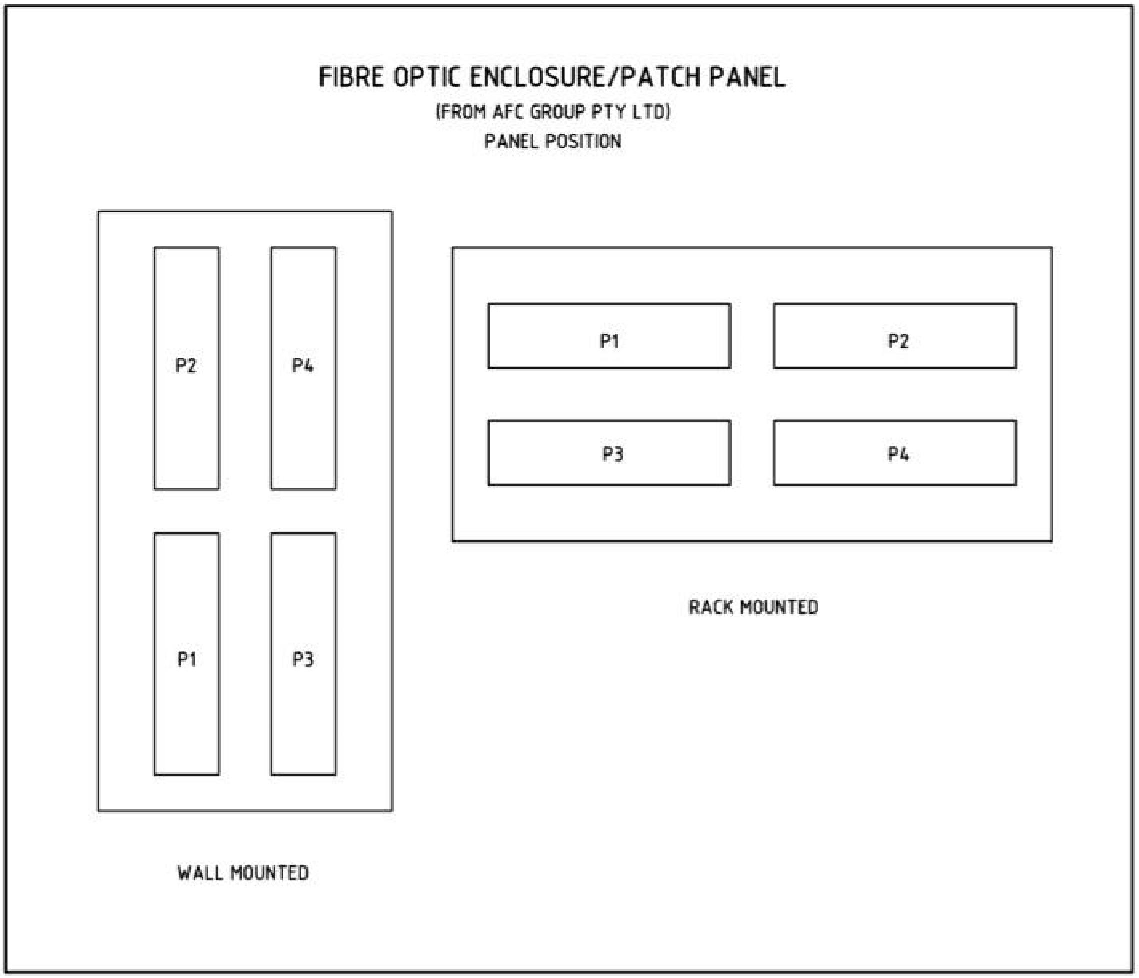


POC2 LAYOUT



POC1 LAYOUT

Figure A 1.3.c Export Power POC-1 and POC-2 Layout at MW-WTP



FIBRE PATCHING		
FROM	TO	FOR
P1 - 1/2	ETHERNET SWITCH	HORS ETHERNET LOOP
P3 - 1/2	ETHERNET SWITCH	HORS ETHERNET LOOP

Figure A 1.4.a POC-1 Hut Fibre Terminal and Patching Details

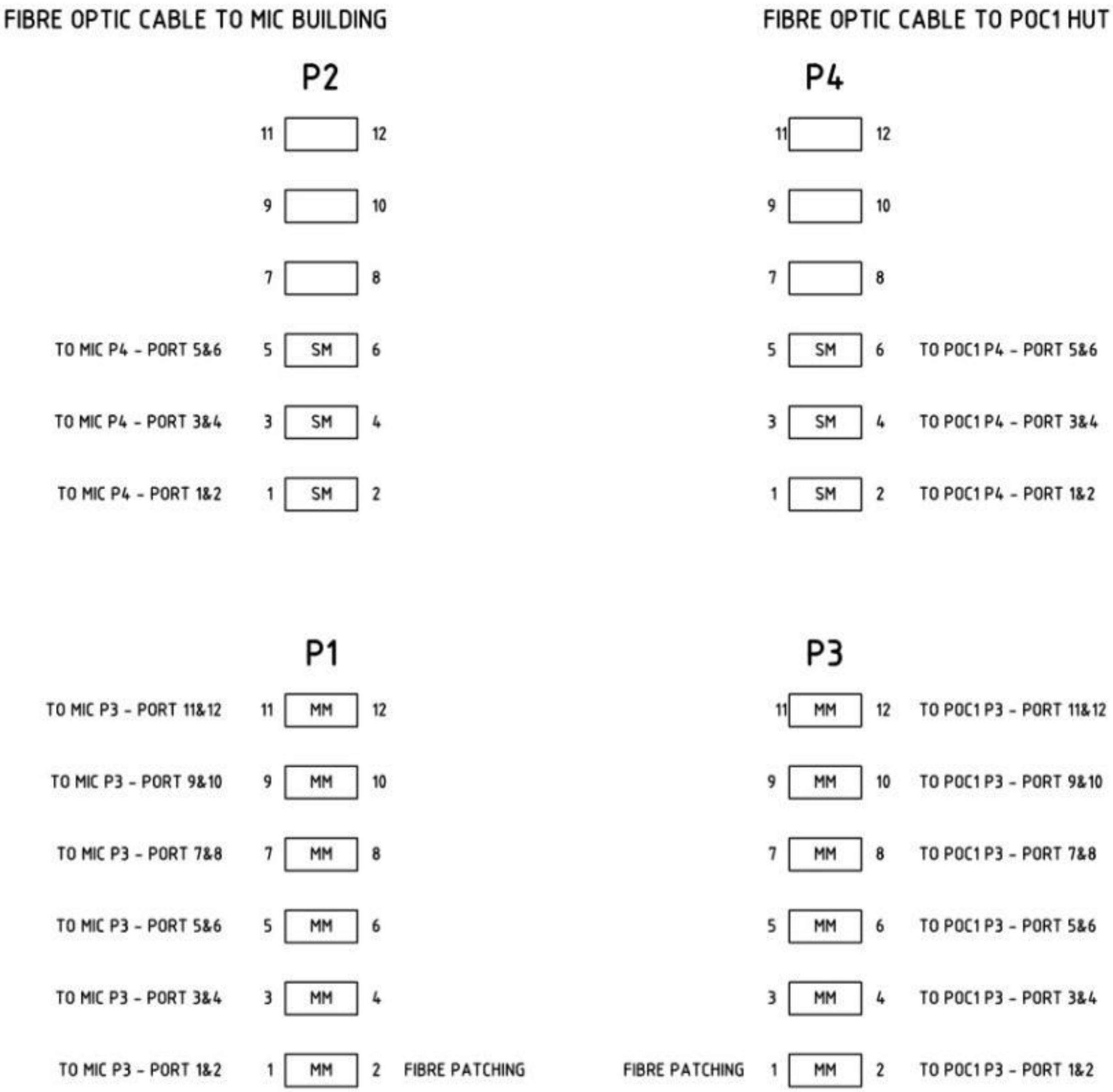


Figure A 1.4.b POC-1 Hut fibre Terminal and Patching Details

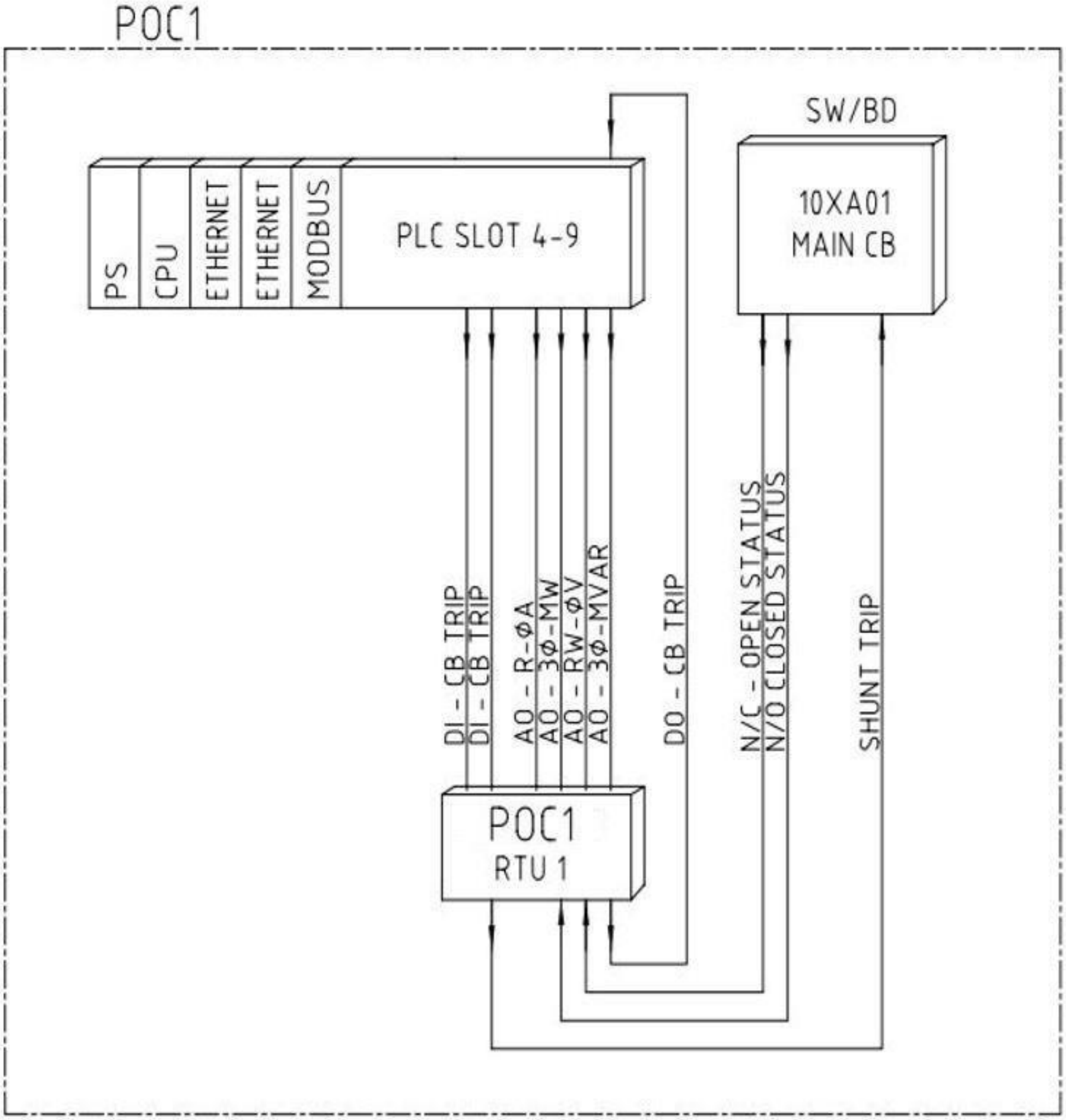


Figure A 1.5.a POC-1 Inter switching Block Diagram

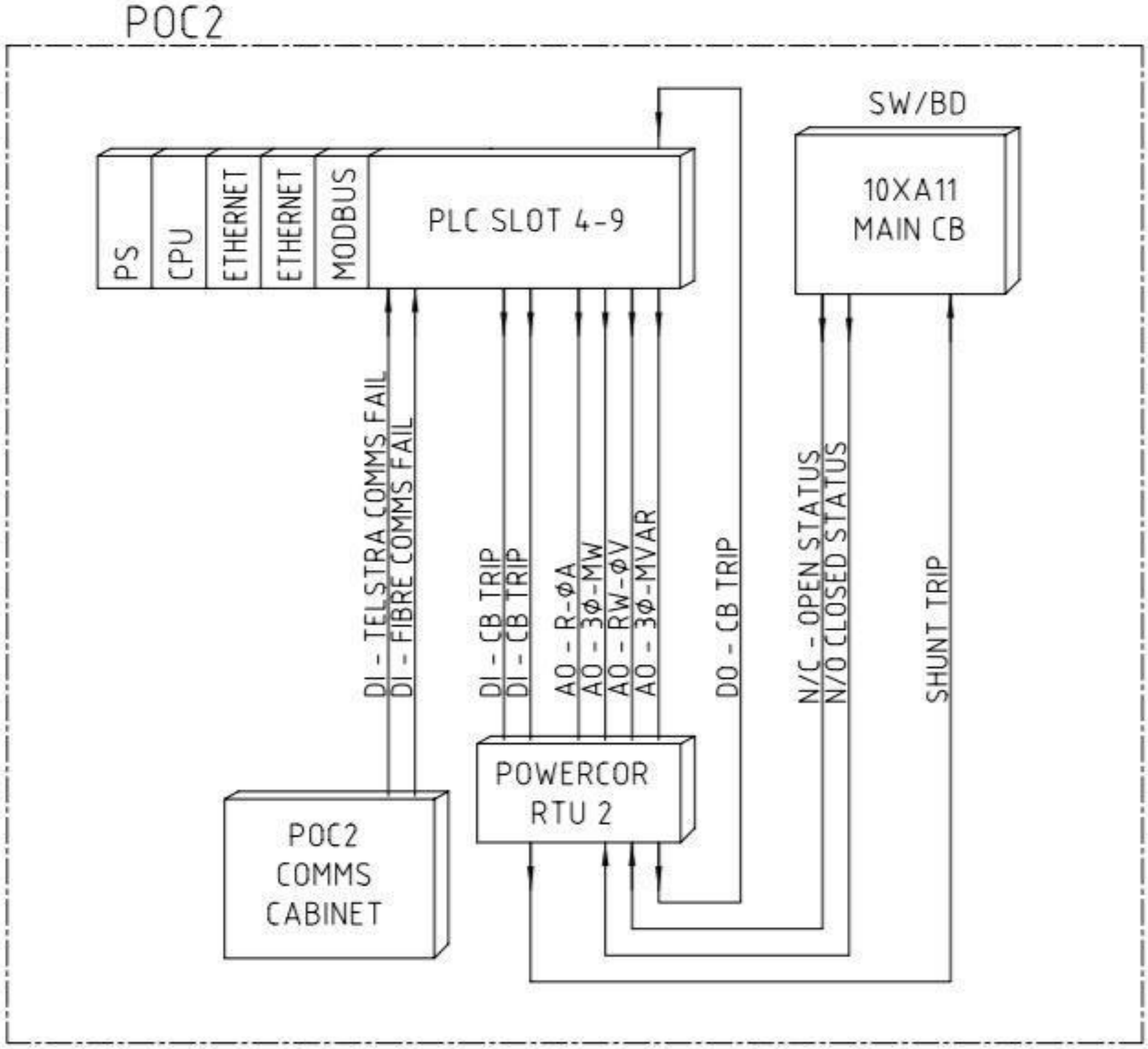


Figure A 1.5.b POC-2 Inter Switching Block Diagram

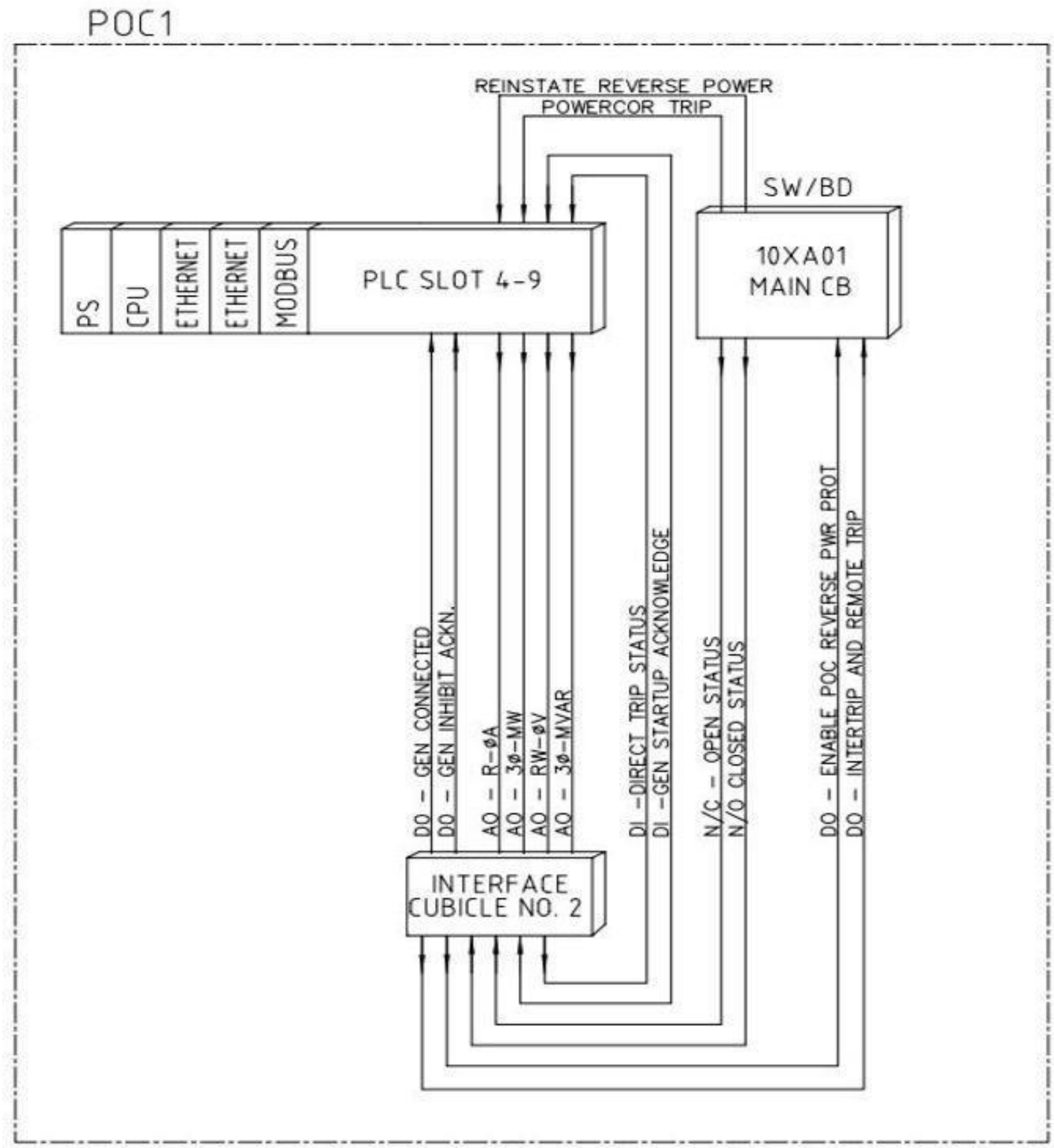


Figure A 1.6.a POC-1 Export Power Inter Switching Block Diagram

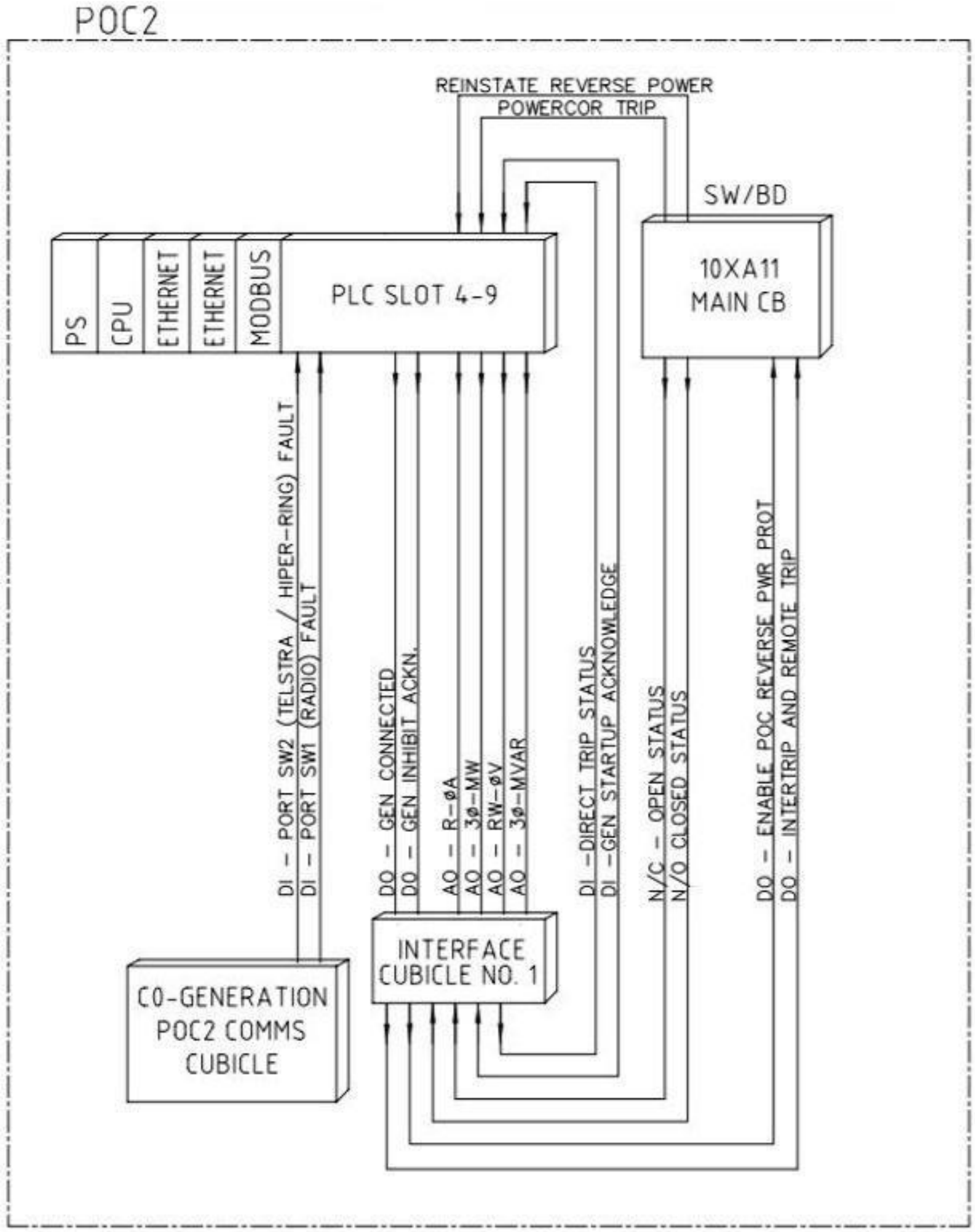


Figure A 1.6.b POC-2 Export Power Interswitching Block Diagram

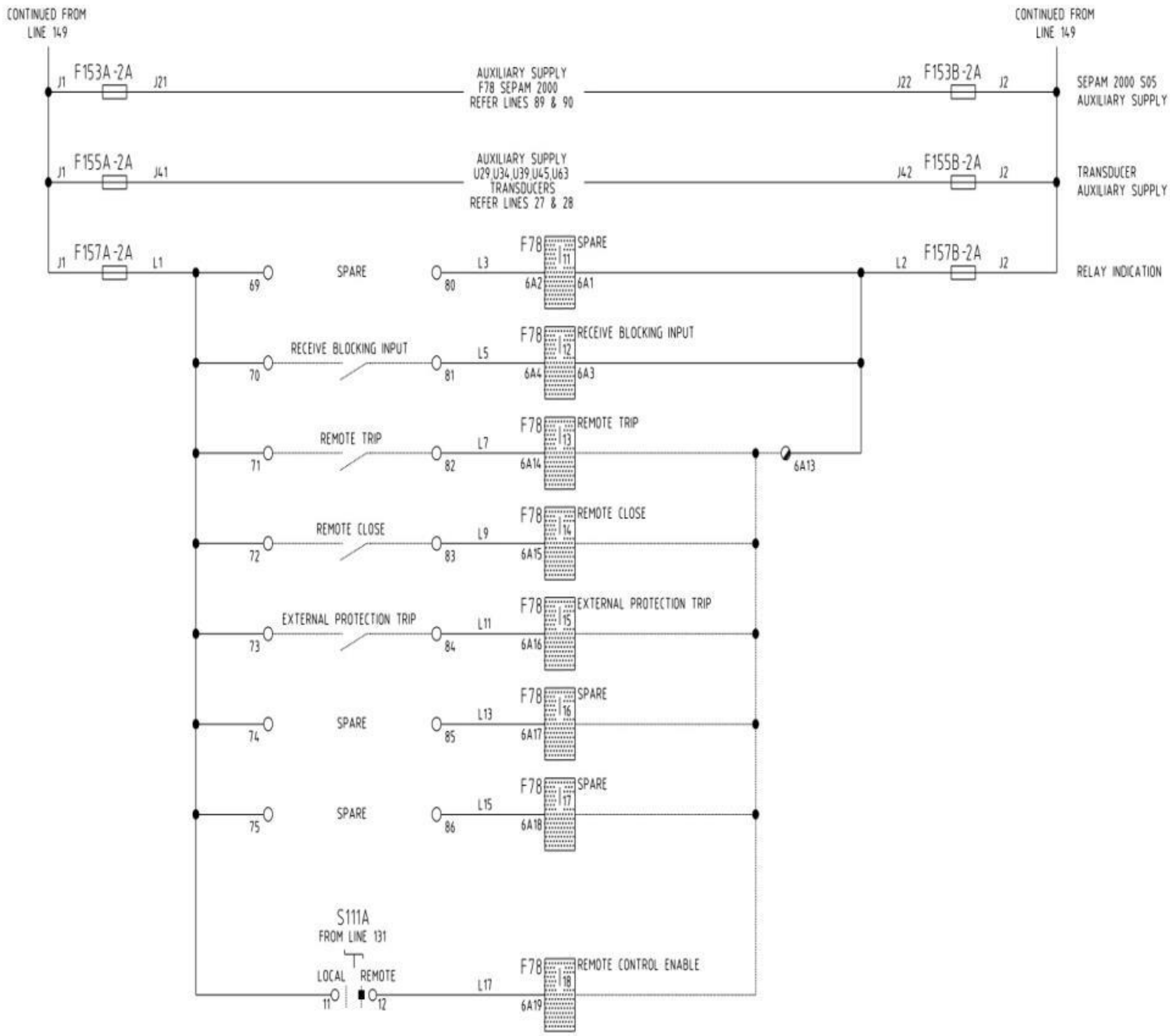


Figure A 1.6.a POC-1 Feeder Circuit Breaker 22kV Schematic Diagram

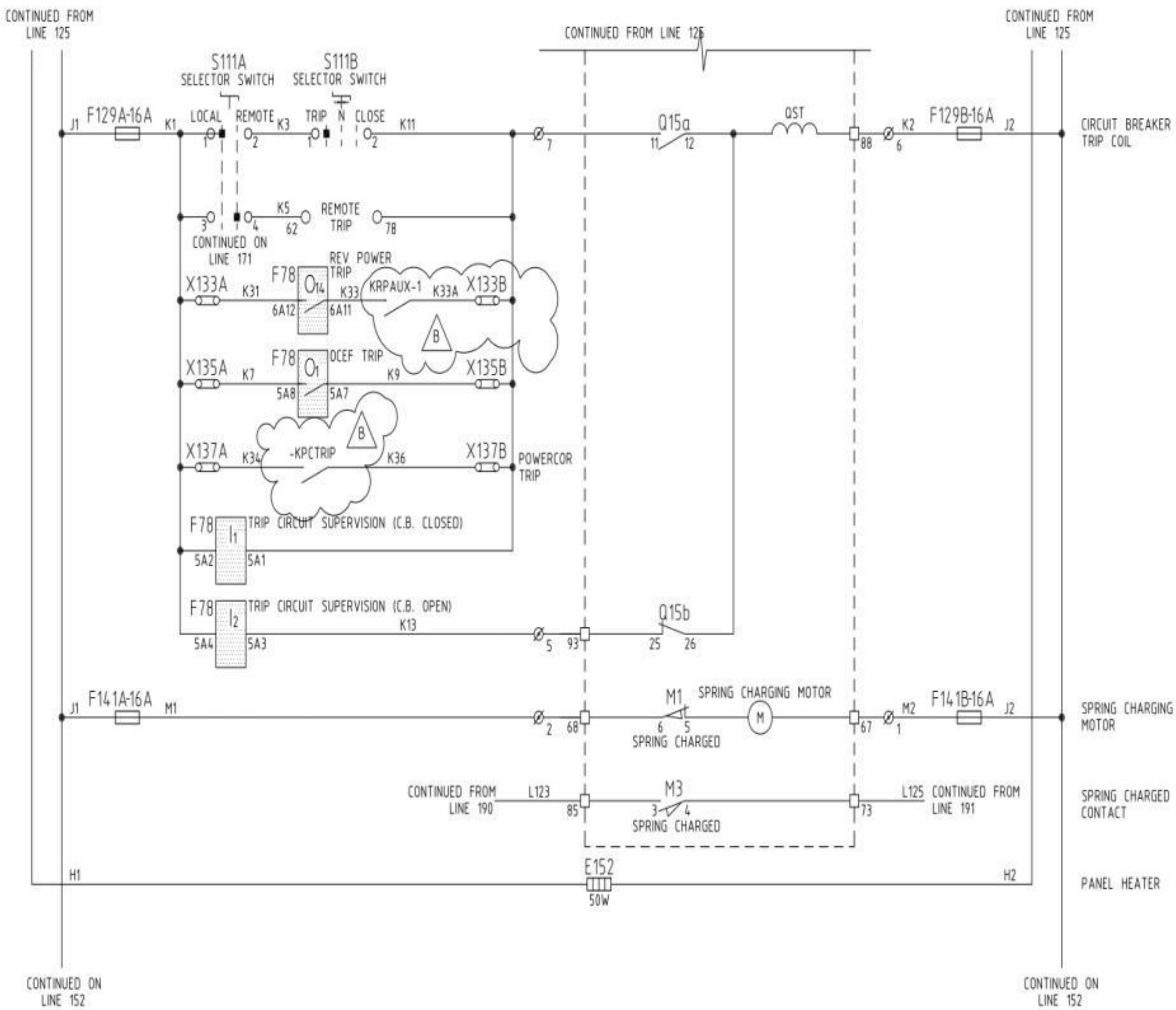


Figure A 1.6.b WTP Feeder Circuit Breaker 22kV Schematic Diagram

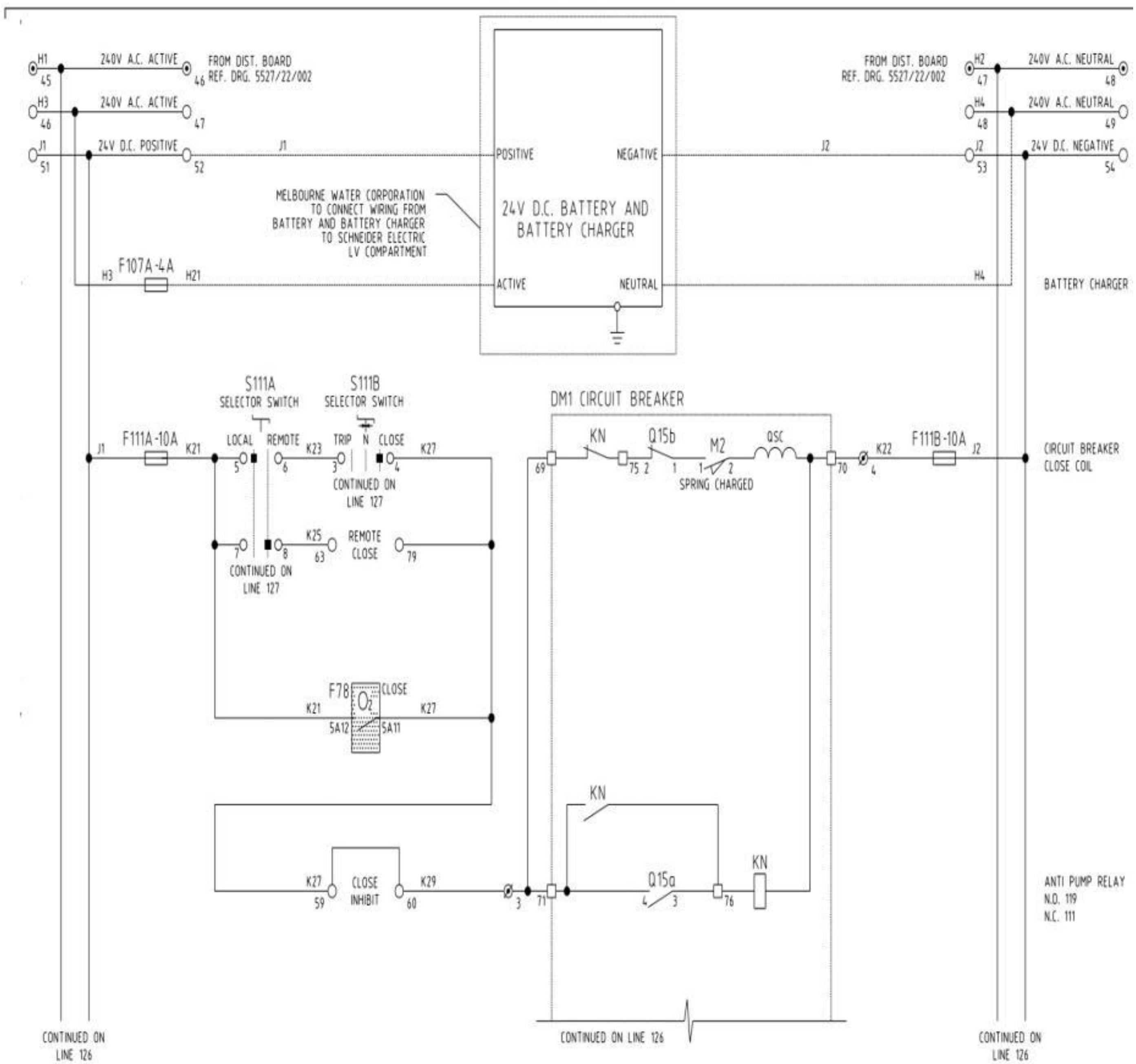


Figure A 1.6.c POC-2 Feeder Circuit 22kV Switching Schematic Diagram

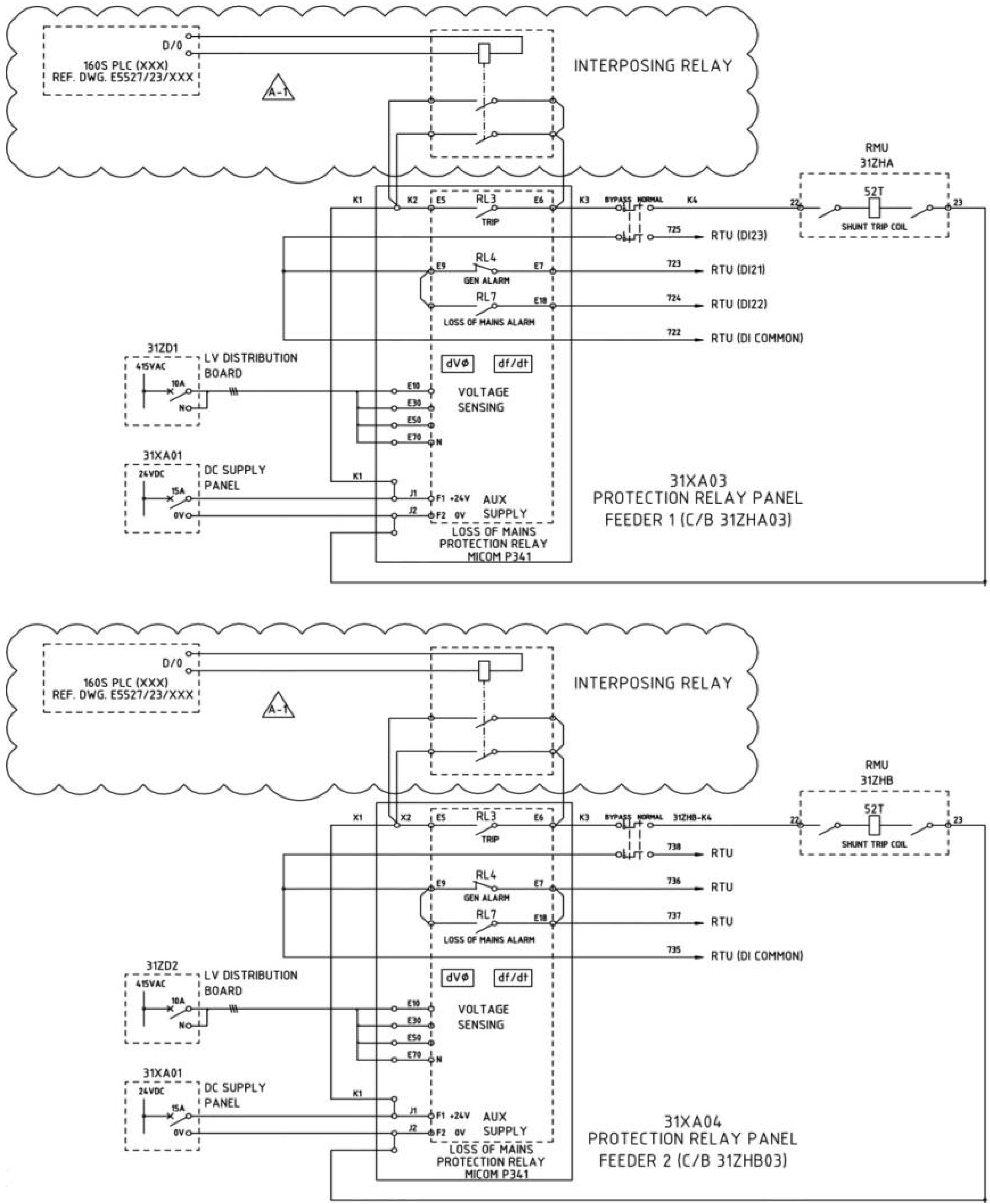


Figure A 1.7.a POC-1 Protection and SCADA RTU Schematic Wiring Diagram

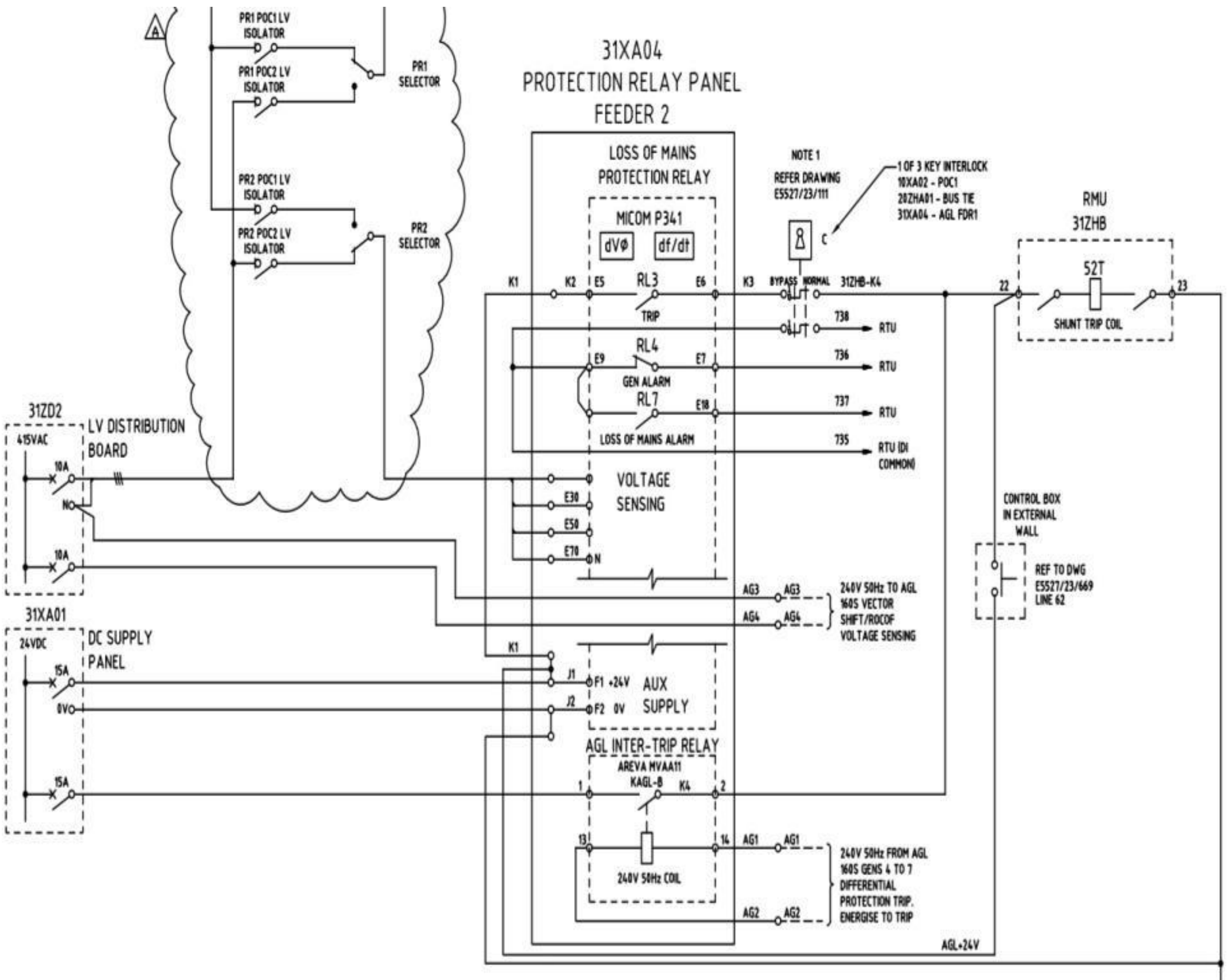


Figure A 1.7.b POC-1 Protection Relay Panel and SCADA RTU Schematic Wiring Diagram

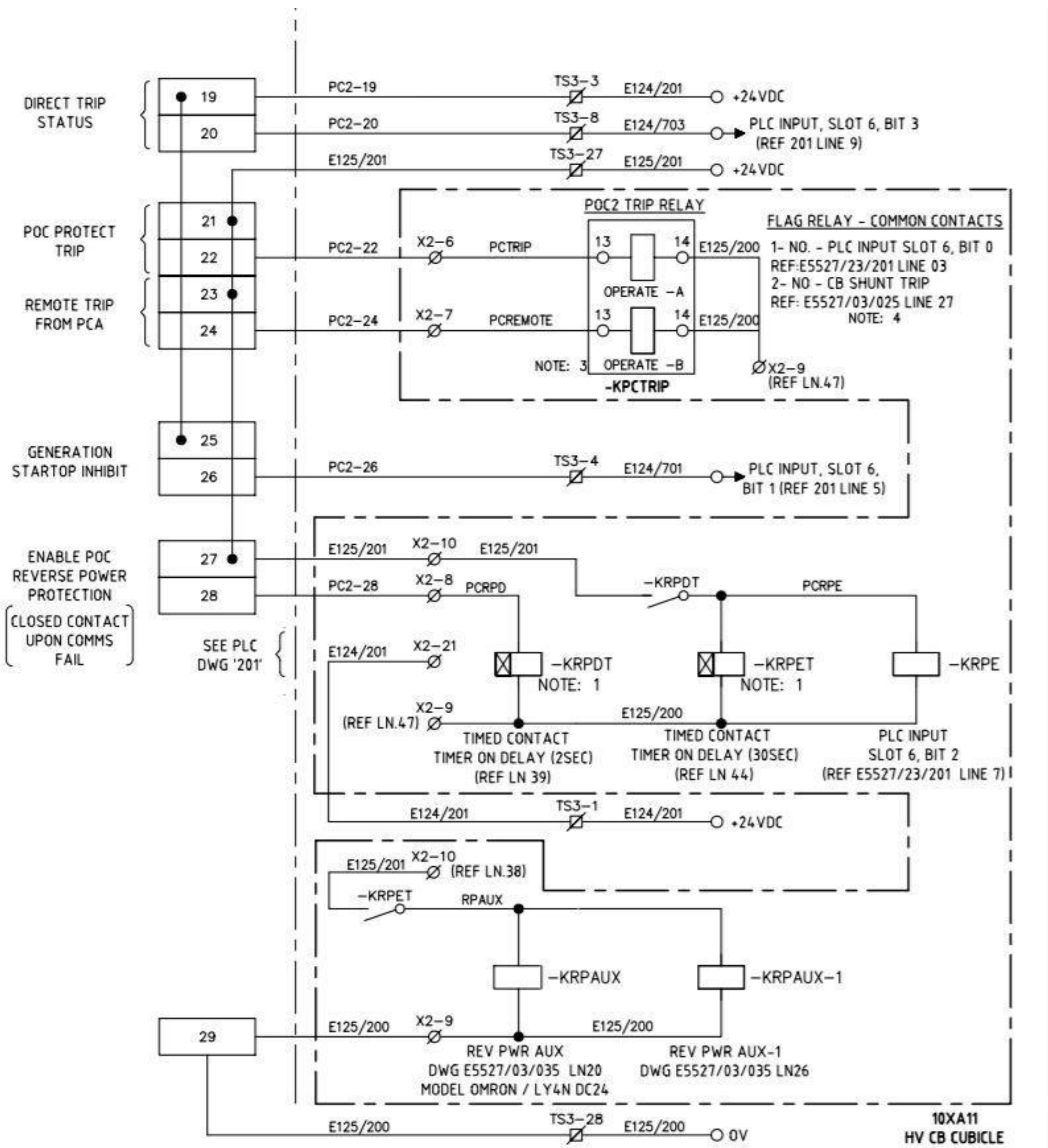


Figure A 1.8.a POC-1 Status Monitoring and Control Schematic Diagram

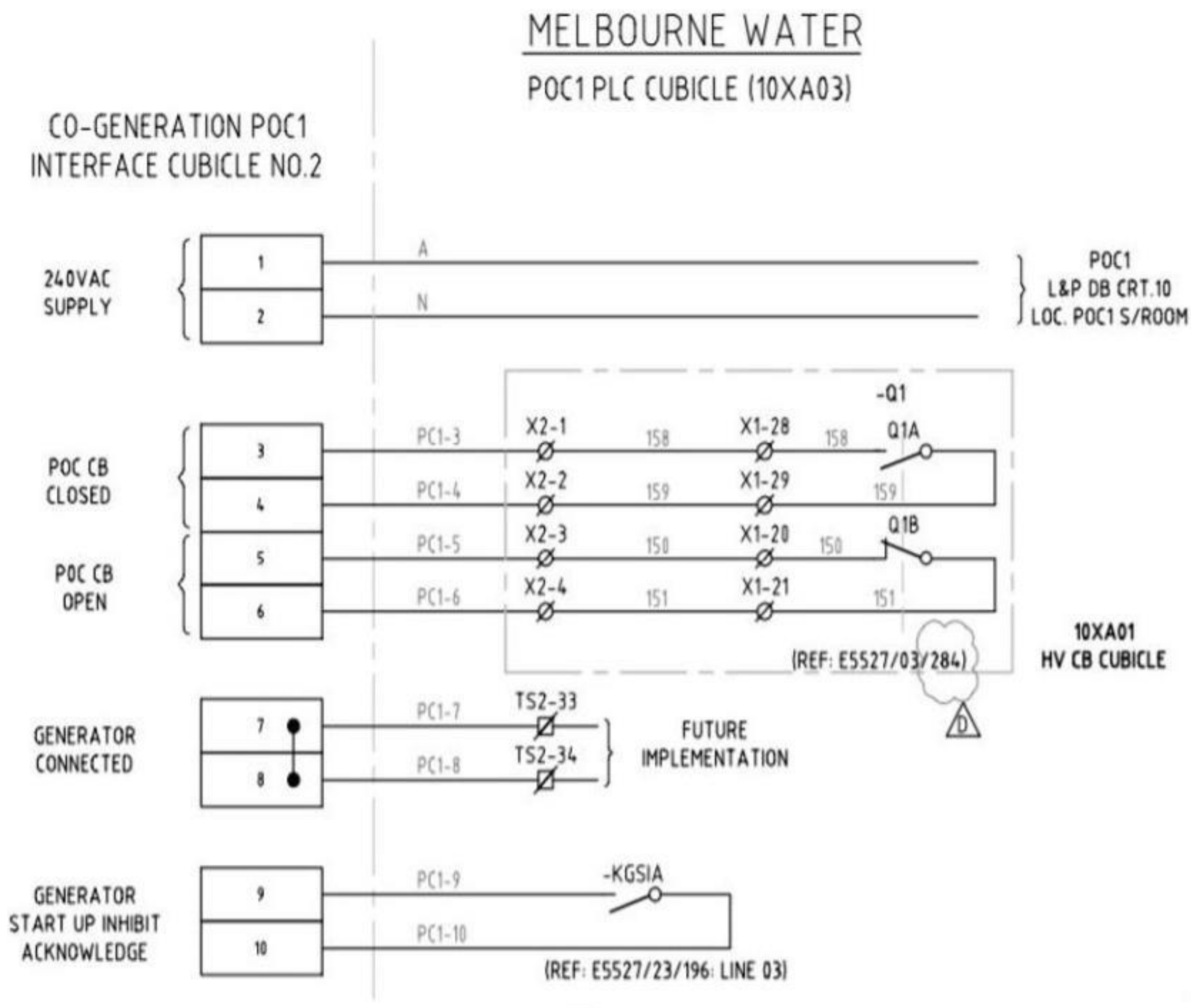


Figure A 1.8.b POC-1 Status Monitoring Control and Telemetry Connection Schematic Diagram

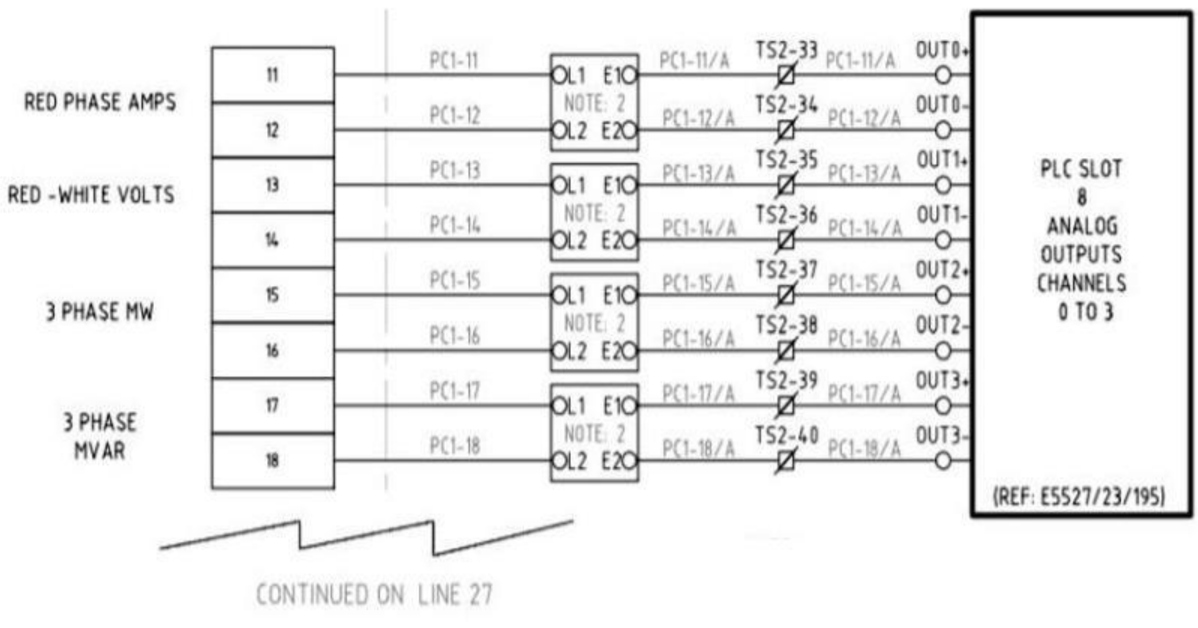


Figure A 1.8.c POC-1 Status Monitoring Control and Telemetry Connection Schematic Diagram

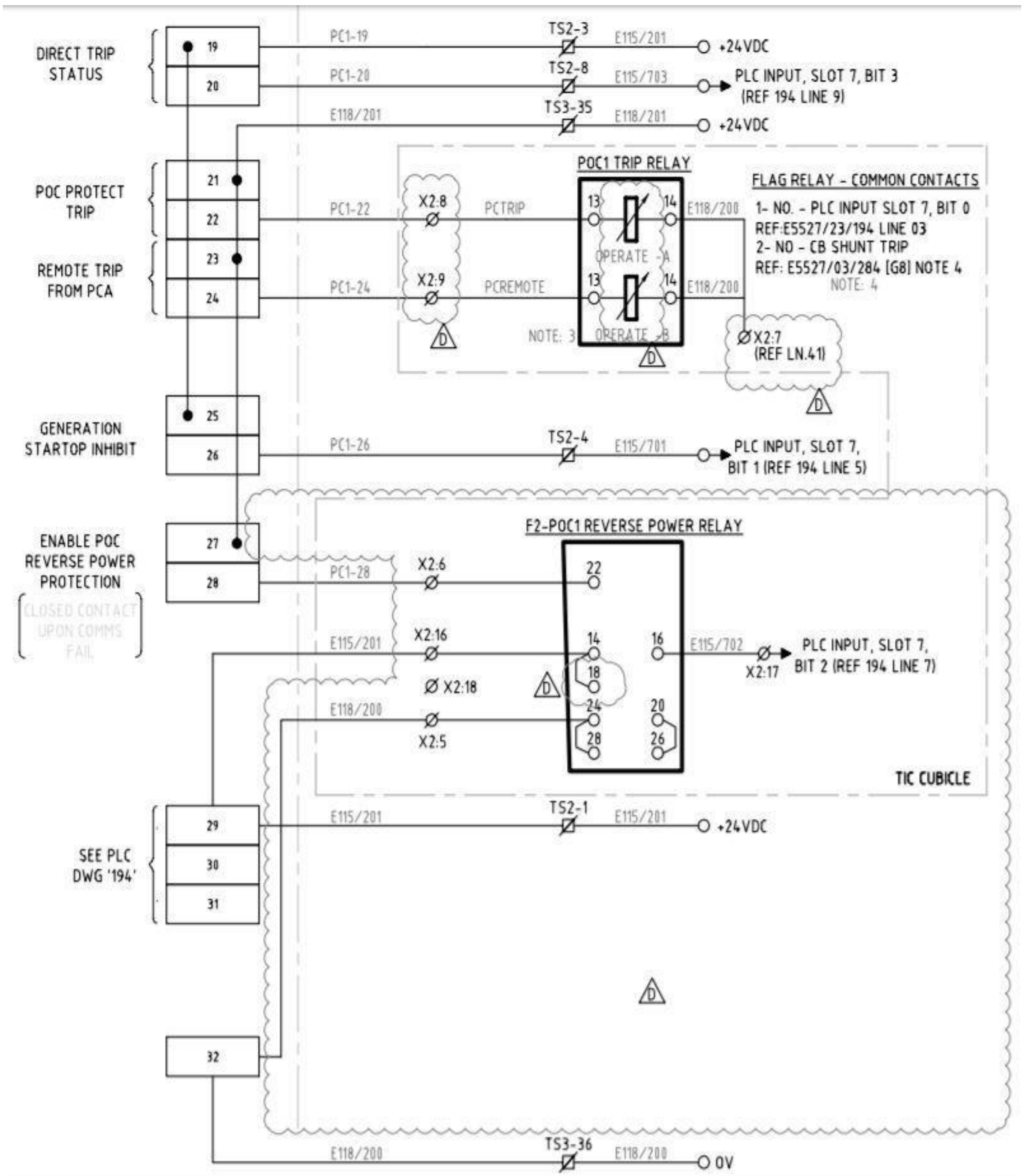


Figure A 1.8.d POC-1 Status Monitoring Control and Telemetry Connection Schematic Diagram

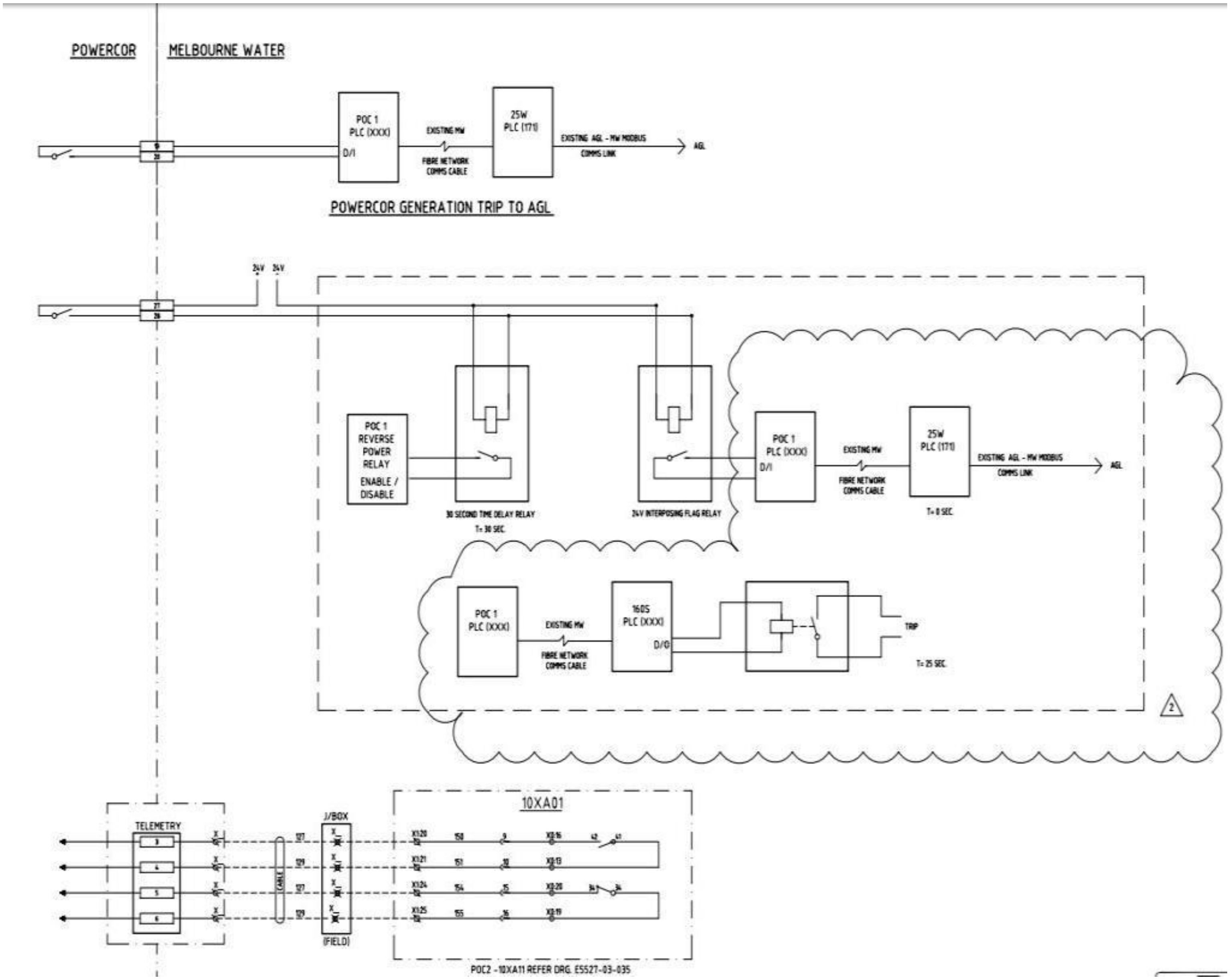


Figure A 1.9 POC-1 HV Switchboard Auxiliary Contacts Schematic Diagram

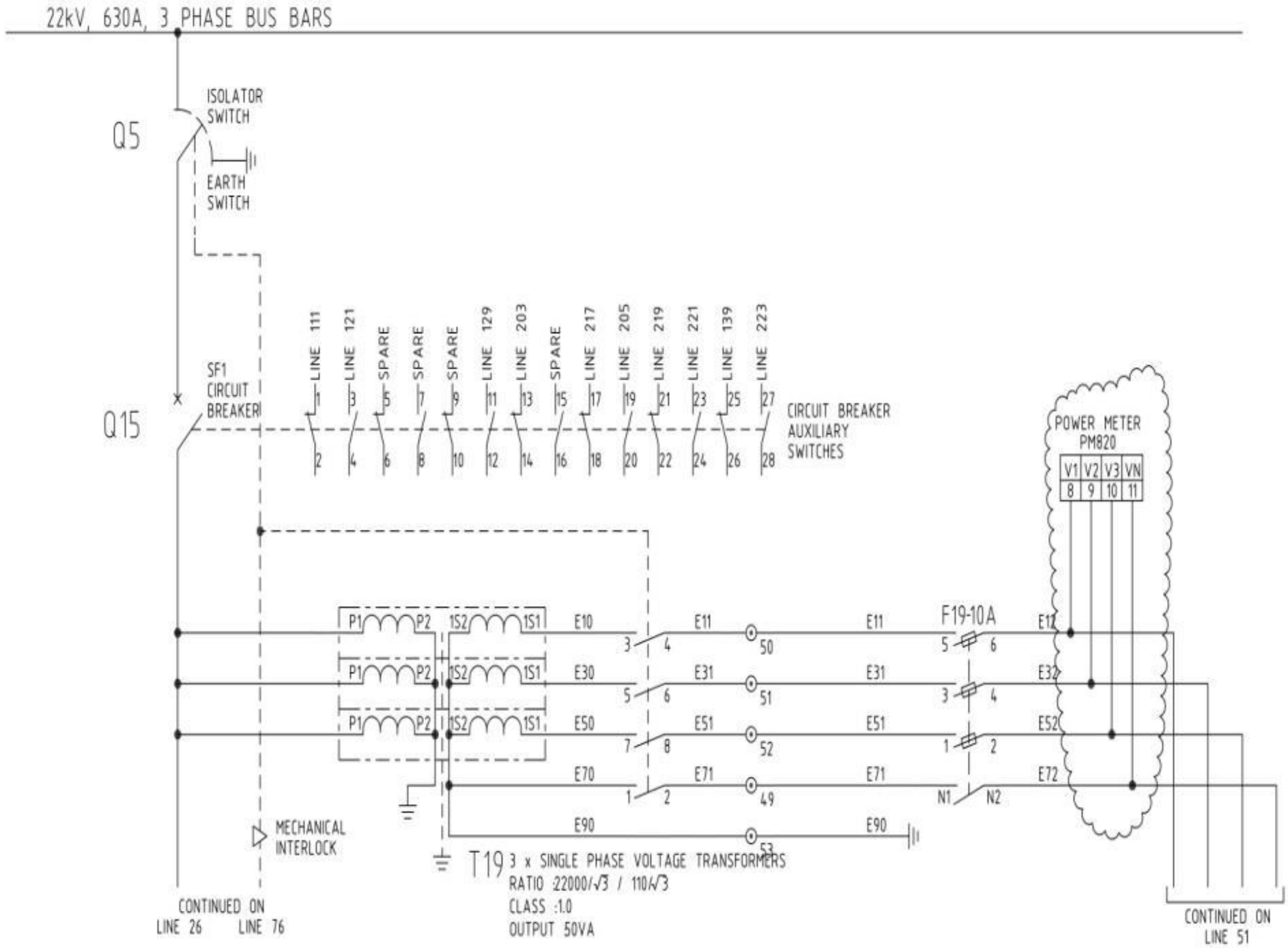


Figure A 1.10.a Feeder Circuit Breaker 22kV Schematic Diagram

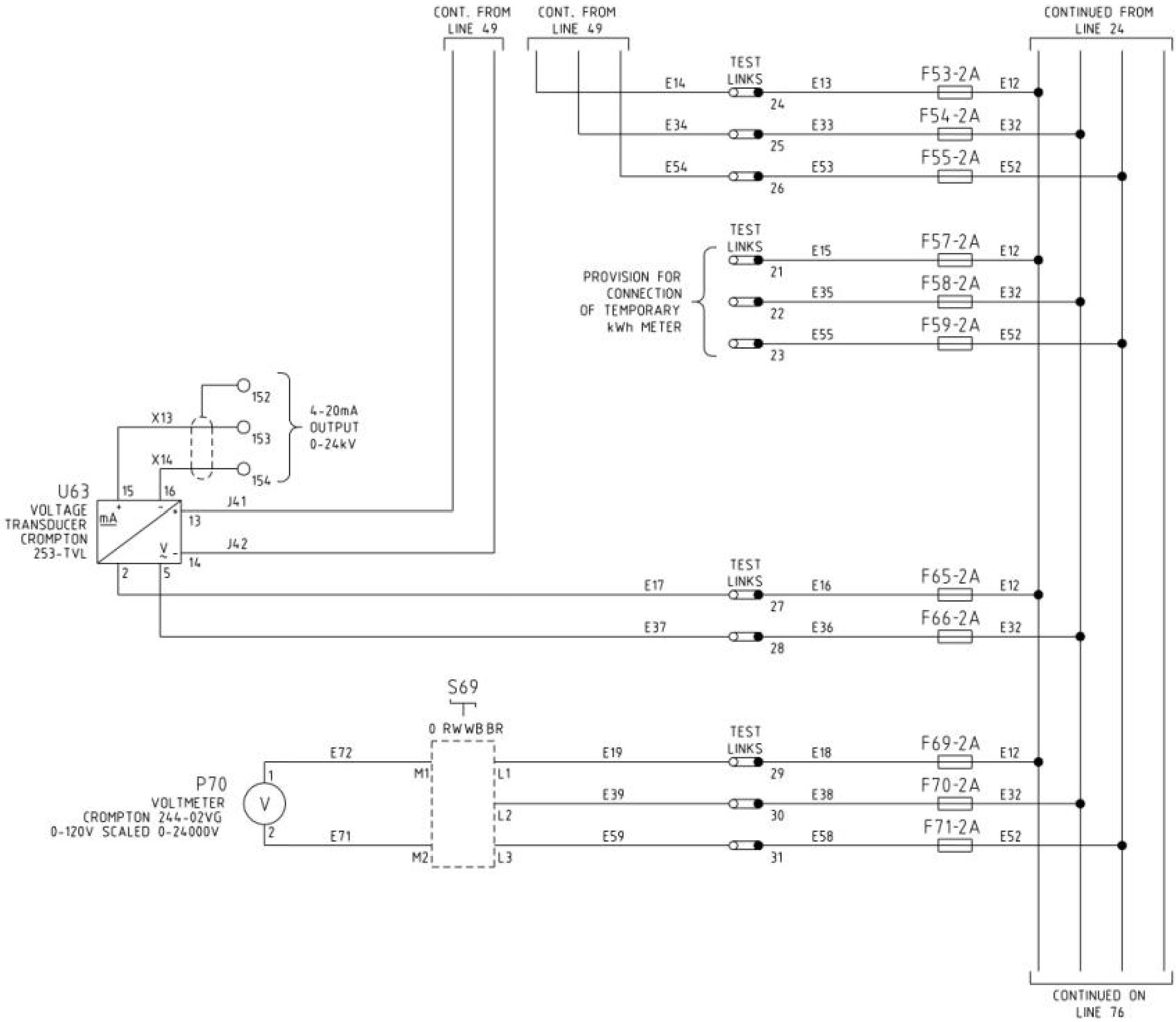


Figure A 1.10.b Feeder Circuit Breaker 22kV Schematic Diagram

Appendix B - Devices Configurations

Melbourne Water Western Treatment Plant

AGL Biogas Generation

External Grid Interface Description

Table B.1 Data Details for Analogue and Digital Signals with Smart RTU

Ref	Signal	Format	Description	Remarks
			POWER SUPPLIES	
P1	240VAC Supply			As discussed a backup supply from the other POC should be provided. For example, a supply from POC 1 should be provided for POC 2 with a no-volts relay for changeover
			DIGITAL SIGNALS FROM MWC TO POWERCOR	
Q1	POC Closed	Normally Open Contact	Contact closes when 22kV circuit breaker is closed	Direct from ACB auxiliary
Q2	POC Open	Normally Closed Contact	Contact closes when 22kV circuit breaker is open	Direct from ACB auxiliary. Contact is shown as normally close but in fact closes when ACB is open.
Q3	Gen Connected	Normally Open Contact	Contact closes when any AGL generator is grid paralleled on this POC. Fail safe signal. If link to AGL is lost then this contact closes.	Use mobus addresses 00020 to 00026 (Generator x Running) in AGL->MWC link in 25W PLC along with 00029 to 00035 (Generator x POC Connection) and 00006 (AGL Heartbeat) to derive this logic
Q4	Generation Startup Inhibit Acknowledge	Normally Open Contact	Signal passed back from AGL to MWC to acknowledge signal number	A new modbus signal (suggest 00007 and 00008 AGL Acknowledge Generation Startup Inhibit POC x) is required to be transferred form AGL to MWC via modbus link to 25W. Signal dropped on comms failure.
			ANALOGUE SIGNALS FROM MWC TO POWERCOR	
AQ1	Red Phase Amps	4-20mA	mA proportional to POC Amps	Scaling to be advised by Powercor
AQ2	R-W Volts	4-20mA	mA proportional to POC Volts	Scaling to be advised by Powercor
AQ3	3 phase MW	4-20mA	mA proportional to Real Power	Scaling to be advised by Powercor. Note 4mA will be negative i.e. Import Power, 12mA will be zero, 20mA will be positive i.e. export power.
AQ4	4 phase MVAr	4-20mA	mA proportional to Reactive Power	Scaling to be advised by Powercor. Note 4mA will be negative i.e. Import Power, 12mA will be zero, 20mA will be positive i.e. export power.

Melbourne Water Western Treatment Plant

AGL Biogas Generation

External Grid Interface Description

Table B.2 Data Details for Analogy and Digital Signals with Smart RTU

Ref	Signal	Format	Description	Remarks
			DIGITAL SIGNALS FROM POWERCOR TO MWC	
I1	Generator Trip	Normally Open Contact	Sends command to AGL to trip all generators	There is an issue with the timing of some of these commands. By the time we account for the cycle time of MWC's network, the update time of the modbus link MWC->AGL and vice versa the reaction time may be too slow for Powercor This issue needs to be raised with Powercor. A trial is required to determine what the current update time is. One possible solution if it's too slow is to add some hardware to MWC's PLC network at AGL's 160S site and provide a direct (virtual) link between to POC 1/2 PLC's.
I2	POC Trip	Normally Open Contact	Energises POC shunt trip coil	
I3	Remote Trip from PCA Control Centre	Normally Open Contact	Energises POC shunt trip coil	Confirm this with Powercor. It seems to duplicate Signal I1.
I4	Comms Fail (Trip via Timer)	Normally Closed Contact	Contact closes on comms/equipment failure	Connect a hardwired on-delay timer such that if signal Q3 (Generator Connected) is asserted for longer than 30s while this signal is asserted POC trips.
I5	Generation Startup Inhibit	Normally Open Contact	When this contact closes AGL will not start any generators.	See also Q4. When this signal is asserted MWC sends it to AGL along the modbus link at 25W. (Suggest 10027 and 10032 AGL Acknowledge Generation Startup Inhibit POC x). On receipt of this signal AGL will not start any stopped generators on the relevant POC. If a generator is already grid paralleled then this signal has no effect. AGL holds signal Q4 on whenever they see this signal.

External Grid Data Exchange Dictionary

AGL Werribee Phase 2

MWC Data Exchange Point List

Table B.3 Modbus-1 Data Table POC-1

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
Gas Blower 1 Running	MWC	AGL	Digital	10001		1 = Running
Gas Blower 1 Healthy	MWC	AGL	Digital	10002		1 = Healthy
Gas Blower 1 Available	MWC	AGL	Digital	10003		1 = Available
Spare Digital Coil	MWC	AGL	Digital	10004		
Spare Digital Coil	MWC	AGL	Digital	10005		
Spare Digital Coil	MWC	AGL	Digital	10006		
Gas Blower 2 Running	MWC	AGL	Digital	10007		1 = Running
Gas Blower 2 Healthy	MWC	AGL	Digital	10008		1 = Healthy
Gas Blower 2 Available	MWC	AGL	Digital	10009		1 = Available
Spare Digital Coil	MWC	AGL	Digital	10010		
Spare Digital Coil	MWC	AGL	Digital	10011		
Spare Digital Coil	MWC	AGL	Digital	10012		
Gas Blower 3 Running	MWC	AGL	Digital	10013		1 = Running
Gas Blower 3 Healthy	MWC	AGL	Digital	10014		1 = Healthy
Gas Blower 3 Available	MWC	AGL	Digital	10015		1 = Available
Spare Digital Coil	MWC	AGL	Digital	10016		
Spare Digital Coil	MWC	AGL	Digital	10017		
Spare Digital Coil	MWC	AGL	Digital	10018		
Spare Digital Coil	MWC	AGL	Digital	10019		
Spare Digital Coil	MWC	AGL	Digital	10020		
Spare Digital Coil	MWC	AGL	Digital	10021		
Spare Digital Coil	MWC	AGL	Digital	10022		
Spare Digital Coil	MWC	AGL	Digital	10023		
Spare Digital Coil	MWC	AGL	Digital	10024		
POC 1 CB Closed	MWC	AGL	Digital	10025		1 = Closed
POC 1 CB Tripped	MWC	AGL	Digital	10026		1 = Tripped
Spare Digital Coil	MWC	AGL	Digital	10027		
Spare Digital Coil	MWC	AGL	Digital	10028		
Spare Digital Coil	MWC	AGL	Digital	10029		
POC 2 CB Closed	MWC	AGL	Digital	10030		1 = Closed
POC 2 CB Tripped	MWC	AGL	Digital	10031		1 = Tripped
Spare Digital Coil	MWC	AGL	Digital	10032		

Table B.4 Modbus-1 Data Table POC-1

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
Spare Digital Coil	MWC	AGL	Digital	10033		
Spare Digital Coil	MWC	AGL	Digital	10034		
Capacitor Bank 1 On-Line	MWC	AGL	Digital	10035		1 = Shunt capacitors connected
Capacitor Bank 2 On-Line	MWC	AGL	Digital	10036		2 = Shunt capacitors connected
Spare Digital Coil	MWC	AGL	Digital	10037		
Spare Digital Coil	MWC	AGL	Digital	10038		
Pond 1 Aeration Sheddable Load	MWC	AGL	Digital	10039		1 = Load Sheddable
Spare Digital Coil	MWC	AGL	Digital	10040		
Spare Digital Coil	MWC	AGL	Digital	10041		
'Contract Load Shed Request Acknowledgement' Signal	MWC	AGL	Digital	10042		
Contract Group 1 Load Shedding Successful	MWC	AGL	Digital	10043		1 = Shedding Successful
Contract Group 2 Load Shedding Successful	MWC	AGL	Digital	10044		1 = Shedding Successful
Contract Group 3 Load Shedding Successful	MWC	AGL	Digital	10045		1 = Shedding Successful
Contract Group 4 Load Shedding Successful	MWC	AGL	Digital	10046		1 = Shedding Successful
Spare Digital Coil	MWC	AGL	Digital	10047		
Spare Digital Coil	MWC	AGL	Digital	10048		
Spare Digital Coil	MWC	AGL	Digital	10049		
Spare Digital Coil	MWC	AGL	Digital	10050		
Contract Group 1 Loads in Restoration	MWC	AGL	Digital	10051		1 = Restoration in progress
Contract Group 2 Loads in Restoration	MWC	AGL	Digital	10052		1 = Restoration in progress
Contract Group 3 Loads in Restoration	MWC	AGL	Digital	10053		1 = Restoration in progress
Contract Group 4 Loads in Restoration	MWC	AGL	Digital	10054		1 = Restoration in progress
Contract Group 1 Load Shedding Accepted	MWC	AGL	Digital	10055		1 = G1 Shedding Accepted
Contract Group 2 Load Shedding Accepted	MWC	AGL	Digital	10056		1 = G2 Shedding Accepted
Contract Group 3 Load Shedding Accepted	MWC	AGL	Digital	10057		1 = G3 Shedding Accepted
Contract Group 4 Load Shedding Accepted	MWC	AGL	Digital	10058		1 = G4 Shedding Accepted
Contract Group 1 Load Shedding Rejected	MWC	AGL	Digital	10059		1 = G1 Shedding Rejected
Contract Group 2 Load Shedding Rejected	MWC	AGL	Digital	10060		1 = G2 Shedding Rejected
Contract Group 3 Load Shedding Rejected	MWC	AGL	Digital	10061		1 = G3 Shedding Rejected
Contract Group 4 Load Shedding Rejected	MWC	AGL	Digital	10062		1 = G4 Shedding Rejected
Spare Digital Coil	MWC	AGL	Digital	10063		
Spare Digital Coil	MWC	AGL	Digital	10064		
Gas Blower 5 Running	MWC	AGL	Digital	10065		1 = Running
Gas Blower 5 Healthy	MWC	AGL	Digital	10066		1 = Healthy

AGL Werribee Phase 2

MWC Data Exchange Point List

Modbus Data Table

Table B.5 Modbus-2 Data Table POC-1

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
Gas Blower 5 Available	MWC	AGL	Digital	10067		1 = Available
Spare Digital Coil	MWC	AGL	Digital	10068		
Spare Digital Coil	MWC	AGL	Digital	10069		
Spare Digital Coil	MWC	AGL	Digital	10070		
Gas Blower 6 Running	MWC	AGL	Digital	10071		1 = Running
Gas Blower 6 Healthy	MWC	AGL	Digital	10072		1 = Healthy
Gas Blower 6 Available	MWC	AGL	Digital	10073		1 = Available
Spare Digital Coil	MWC	AGL	Digital	10074		
Spare Digital Coil	MWC	AGL	Digital	10075		
Spare Digital Coil	MWC	AGL	Digital	10076		
Gas Blower 7 Running	MWC	AGL	Digital	10077		1 = Running
Gas Blower 7 Healthy	MWC	AGL	Digital	10078		1 = Healthy
Gas Blower 7 Available	MWC	AGL	Digital	10079		1 = Available
Spare Digital Coil	MWC	AGL	Digital	10080		
Spare Digital Coil	MWC	AGL	Digital	10081		
Spare Digital Coil	MWC	AGL	Digital	10082		
Gas Blower 8 Running	MWC	AGL	Digital	10083		1 = Running
Gas Blower 8 Healthy	MWC	AGL	Digital	10084		1 = Healthy
Gas Blower 8 Available	MWC	AGL	Digital	10085		1 = Available
Spare Digital Coil	MWC	AGL	Digital	10086		
Spare Digital Coil	MWC	AGL	Digital	10087		
Spare Digital Coil	MWC	AGL	Digital	10088		
55E Isolation Valve Closed	MWC	AGL	Digital	10089		1 = Closed
55E Isolation Valve Open	MWC	AGL	Digital	10090		1 = Open
25W Isolation Valve Closed	MWC	AGL	Digital	10091		1 = Closed
25W Isolation Valve Open	MWC	AGL	Digital	10092		1 = Open

AGL Werribee Phase 2

MWC Data Exchange Point List

Table B.6 Modbus-1 Data Table POC-2

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
Position Of MWC Header Pressure Control Valve 1	MWC	AGL	Analogue	30001	0-10000	0-100%
Position Of MWC Header Pressure Control Valve 2	MWC	AGL	Analogue	30002	0-10000	0-100%
Spare Analogue Register	MWC	AGL	Analogue	30003		
Spare Analogue Register	MWC	AGL	Analogue	30004		
Gas Flow From MWC Header To AGL	MWC	AGL	Analogue	30005	0-20000	0-2000 m3/h
Gas Flow To No.1 Flare	MWC	AGL	Analogue	30006	0-20000	0-2000 m3/h
Gas Flow To No.2 Flare	MWC	AGL	Analogue	30007	0-20000	0-2000 m3/h
Gas Header Pressure	MWC	AGL	Analogue	30008	0-10000	0-100 kPa
Gas Blower 1 Actual Speed	MWC	AGL	Analogue	30009	0-10000	0-100%
Gas Blower 2 Actual Speed	MWC	AGL	Analogue	30010	0-10000	0-100%
Gas Blower 2 Actual Speed	MWC	AGL	Analogue	30011	0-10000	0-100%
Spare Analogue Register	MWC	AGL	Analogue	30012		
Spare Analogue Register	MWC	AGL	Analogue	30013		
Spare Analogue Register	MWC	AGL	Analogue	30014		
Import MW At POC1	MWC	AGL	Analogue	30015	0-20000	0-20MW
Import MW At POC2	MWC	AGL	Analogue	30016	0-20000	0-20MW
Spare Analogue Register	MWC	AGL	Analogue	30017		
Spare Analogue Register	MWC	AGL	Analogue	30018		
Feeder 1 Voltage (160S Switchroom)	MWC	AGL	Analogue	30019	0-30000	0-30000V (L-L)
Feeder 2 Voltage (160S Switchroom)	MWC	AGL	Analogue	30020	0-30000	0-30000V (L-L)
Spare Analogue Register	MWC	AGL	Analogue	30021		
Spare Analogue Register	MWC	AGL	Analogue	30022		
Spare Analogue Register	MWC	AGL	Analogue	30023		
Spare Analogue Register	MWC	AGL	Analogue	30024		
Gas Blower 5 Actual Speed	MWC	AGL	Analogue	30025	0-10000	0-100%
Gas Blower 6 Actual Speed	MWC	AGL	Analogue	30026	0-10000	0-100%
Gas Blower 7 Actual Speed	MWC	AGL	Analogue	30027	0-10000	0-100%
Gas Blower 8 Actual Speed	MWC	AGL	Analogue	30028	0-10001	0-100%
Spare Analogue Register	MWC	AGL	Analogue	30029		
Spare Analogue Register	MWC	AGL	Analogue	30030		
Spare Analogue Register	MWC	AGL	Analogue	30031		
Spare Analogue Register	MWC	AGL	Analogue	30032		

AGL Werribee Phase 2

MWC Data Exchange Point List

Table B.7 Modbus-1 Data Table POC-2

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
Position Of MWC Header Pressure Control Valve 1	MWC	AGL	Analogue	30001	0-10000	0-100%
Position Of MWC Header Pressure Control Valve 2	MWC	AGL	Analogue	30002	0-10000	0-100%
Spare Analogue Register	MWC	AGL	Analogue	30003		
Spare Analogue Register	MWC	AGL	Analogue	30004		
Gas Flow From MWC Header To AGL	MWC	AGL	Analogue	30005	0-20000	0-2000 m3/h
Gas Flow To No.1 Flare	MWC	AGL	Analogue	30006	0-20000	0-2000 m3/h
Gas Flow To No.2 Flare	MWC	AGL	Analogue	30007	0-20000	0-2000 m3/h
Gas Header Pressure	MWC	AGL	Analogue	30008	0-10000	0-100 kPa
Gas Blower 1 Actual Speed	MWC	AGL	Analogue	30009	0-10000	0-100%
Gas Blower 2 Actual Speed	MWC	AGL	Analogue	30010	0-10000	0-100%
Gas Blower 2 Actual Speed	MWC	AGL	Analogue	30011	0-10000	0-100%
Spare Analogue Register	MWC	AGL	Analogue	30012		
Spare Analogue Register	MWC	AGL	Analogue	30013		
Spare Analogue Register	MWC	AGL	Analogue	30014		
Import MW At POC1	MWC	AGL	Analogue	30015	0-20000	0-20MW
Import MW At POC2	MWC	AGL	Analogue	30016	0-20000	0-20MW
Spare Analogue Register	MWC	AGL	Analogue	30017		
Spare Analogue Register	MWC	AGL	Analogue	30018		
Feeder 1 Voltage (160S Switchroom)	MWC	AGL	Analogue	30019	0-30000	0-30000V (L-L)
Feeder 2 Voltage (160S Switchroom)	MWC	AGL	Analogue	30020	0-30000	0-30000V (L-L)
Spare Analogue Register	MWC	AGL	Analogue	30021		
Spare Analogue Register	MWC	AGL	Analogue	30022		
Spare Analogue Register	MWC	AGL	Analogue	30023		
Spare Analogue Register	MWC	AGL	Analogue	30024		
Gas Blower 5 Actual Speed	MWC	AGL	Analogue	30025	0-10000	0-100%
Gas Blower 6 Actual Speed	MWC	AGL	Analogue	30026	0-10000	0-100%
Gas Blower 7 Actual Speed	MWC	AGL	Analogue	30027	0-10000	0-100%
Gas Blower 8 Actual Speed	MWC	AGL	Analogue	30028	0-10001	0-100%
Spare Analogue Register	MWC	AGL	Analogue	30029		
Spare Analogue Register	MWC	AGL	Analogue	30030		
Spare Analogue Register	MWC	AGL	Analogue	30031		
Spare Analogue Register	MWC	AGL	Analogue	30032		

Table B.8 Modbus-1 Data Table POC-2

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
'Group 1 Contract Load Shedding Requested' Signal	AGL	MWC	Digital	00001		1 = Request to Shed Load
'Group 2 Contract Load Shedding Requested' Signal	AGL	MWC	Digital	00002		1 = Request to Shed Load
'Group 3 Contract Load Shedding Requested' Signal	AGL	MWC	Digital	00003		2 = Request to Shed Load
'Group 4 Contract Load Shedding Requested' Signal	AGL	MWC	Digital	00004		2 = Request to Shed Load
Cancel Contractural Load shed Request	AGL	MWC	Digital	00005		Cancel Load Shed request
Spare Digital Coil	AGL	MWC	Digital	00006		
Spare Digital Coil	AGL	MWC	Digital	00007		
Spare Digital Coil	AGL	MWC	Digital	00008		
Spare Digital Coil	AGL	MWC	Digital	00009		
Spare Digital Coil	AGL	MWC	Digital	00010		
Generator No 1 Available	AGL	MWC	Digital	00011		Available/Fault
Generator No 2 Available	AGL	MWC	Digital	00012		Available/Fault
Generator No 3 Available	AGL	MWC	Digital	00013		Available/Fault
Generator No 4 Available	AGL	MWC	Digital	00014		Available/Fault
Generator No 5 Available	AGL	MWC	Digital	00015		Available/Fault
Generator No 6 Available	AGL	MWC	Digital	00016		Available/Fault
Generator No 7 Available	AGL	MWC	Digital	00017		Available/Fault
Spare Digital Coil	AGL	MWC	Digital	00018		
Spare Digital Coil	AGL	MWC	Digital	00019		
Generator No 1 Running	AGL	MWC	Digital	00020		Running/Stopped
Generator No 2 Running	AGL	MWC	Digital	00021		Running/Stopped
Generator No 3 Running	AGL	MWC	Digital	00022		Running/Stopped
Generator No 4 Running	AGL	MWC	Digital	00023		Running/Stopped
Generator No 5 Running	AGL	MWC	Digital	00024		Running/Stopped
Generator No 6 Running	AGL	MWC	Digital	00025		Running/Stopped
Generator No 7 Running	AGL	MWC	Digital	00026		Running/Stopped
Spare Digital Coil	AGL	MWC	Digital	00027		
Spare Digital Coil	AGL	MWC	Digital	00028		
Generator No 1 POC Connection	AGL	MWC	Digital	00029		POC1/POC2
Generator No 2 POC Connection	AGL	MWC	Digital	00030		POC1/POC2
Generator No 3 POC Connection	AGL	MWC	Digital	00031		POC1/POC2
Generator No 4 POC Connection	AGL	MWC	Digital	00032		POC1/POC2

AGL Werribee Phase 2

MWC Data Exchange Point List

Modbus Data Table

Table B.9 Modbus-2 Data Table POC-2

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
Generator No 5 POC Connection	AGL	MWC	Digital	00033		POC1/POC2
Generator No 6 POC Connection	AGL	MWC	Digital	00034		POC1/POC2
Generator No 7 POC Connection	AGL	MWC	Digital	00035		POC1/POC2
Spare Digital Coil	AGL	MWC	Digital	00036		
Spare Digital Coil	AGL	MWC	Digital	00037		
Spare Digital Coil	AGL	MWC	Digital	00038		
Spare Digital Coil	AGL	MWC	Digital	00039		
Spare Digital Coil	AGL	MWC	Digital	00040		
Spare Digital Coil	AGL	MWC	Digital	00041		
Spare Digital Coil	AGL	MWC	Digital	00042		
Spare Digital Coil	AGL	MWC	Digital	00043		
Spare Digital Coil	AGL	MWC	Digital	00044		
Spare Digital Coil	AGL	MWC	Digital	00045		
Spare Digital Coil	AGL	MWC	Digital	00046		
Spare Digital Coil	AGL	MWC	Digital	00047		
Spare Digital Coil	AGL	MWC	Digital	00048		
Spare Digital Coil	AGL	MWC	Digital	00049		
Spare Digital Coil	AGL	MWC	Digital	00050		
Spare Digital Coil	AGL	MWC	Digital	00051		
Spare Digital Coil	AGL	MWC	Digital	00052		
Spare Digital Coil	AGL	MWC	Digital	00053		
Spare Digital Coil	AGL	MWC	Digital	00054		
Spare Digital Coil	AGL	MWC	Digital	00055		
Spare Digital Coil	AGL	MWC	Digital	00056		
Spare Digital Coil	AGL	MWC	Digital	00057		
Spare Digital Coil	AGL	MWC	Digital	00058		
Spare Digital Coil	AGL	MWC	Digital	00059		
Spare Digital Coil	AGL	MWC	Digital	00060		
Spare Digital Coil	AGL	MWC	Digital	00061		
Spare Digital Coil	AGL	MWC	Digital	00062		
Spare Digital Coil	AGL	MWC	Digital	00063		
Spare Digital Coil	AGL	MWC	Digital	00064		
Gas Flow Into AGL Compound	AGL	MWC	Analogue	40001	0-50000	0-5000 m3/h
Spare Analogue Register	AGL	MWC	Analogue	40002		

AGL Werribee Phase 2

MWC Data Exchange Point List

Table B.10 Modbus-2 Data Table POC-2

AGL PLC	Modbus Master	Address = 1			Digital MWC -> AGL	
MWC PLC	Modbus Slave	Address = 2			Analogue MWC -> AGL	
* All registers 16 bit					Digital AGL -> MWC	
					Analogue AGL -> MWC	
		Changes highlighted in yellow				
				Modbus Register/Coil		
Description	From	To	Type	(in MWC PLC)	Raw	Engineering Units
Methane Concentration	AGL	MWC	Analogue	40003	0-10000	0-100%
Spare Analogue Register	AGL	MWC	Analogue	40004		
Hydrogen Sulphide Content	AGL	MWC	Analogue	40005	0-50000	0-5000 ppm
Spare Analogue Register	AGL	MWC	Analogue	40006		
Spare Analogue Register	AGL	MWC	Analogue	40007		
Spare Analogue Register	AGL	MWC	Analogue	40008		
Spare Analogue Register	AGL	MWC	Analogue	40009		
Total Generation kW	AGL	MWC	Analogue	40010	0-20000	0-20,000kW
Nett generation kW	AGL	MWC	Analogue	40011	0-20000	0-20,000kW
Generator No 1 Output	AGL	MWC	Analogue	40012	0-2000	0-2,000kW
Generator No 2 Output	AGL	MWC	Analogue	40013	0-2000	0-2,000kW
Generator No 3 Output	AGL	MWC	Analogue	40014	0-2000	0-2,000kW
Generator No 4 Output	AGL	MWC	Analogue	40015	0-2000	0-2,000kW
Generator No 5 Output	AGL	MWC	Analogue	40016	0-2000	0-2,000kW
Generator No 6 Output	AGL	MWC	Analogue	40017	0-2000	0-2,000kW
Generator No 7 Output	AGL	MWC	Analogue	40018	0-2000	0-2,000kW
Spare Analogue Register	AGL	MWC	Analogue	40019		
Number of Engines Operating on Feeder 1	AGL	MWC	Analogue	40020	0-10	Number
Feeder 1 Total Generation	AGL	MWC	Analogue	40021	0-20000	0-20,000kW
Feeder 1 Spinning Reserve	AGL	MWC	Analogue	40022	0-20000	0-20,000kW
Feeder 1 Capacity of Unavailable Machines	AGL	MWC	Analogue	40023	0-20000	0-20,000kW
Spare Analogue Register	AGL	MWC	Analogue	40024		
Spare Analogue Register	AGL	MWC	Analogue	40025		
Number of Engines Operating on Feeder 2	AGL	MWC	Analogue	40026	0-10	Number
Feeder 2 Total Generation	AGL	MWC	Analogue	40027	0-20000	0-20,000kW
Feeder 2 Spinning Reserve	AGL	MWC	Analogue	40028	0-20000	0-20,000kW
Feeder 2 Capacity of Unavailable Machines	AGL	MWC	Analogue	40029	0-20000	0-20,000kW
Spare Analogue Register	AGL	MWC	Analogue	40030		
Spare Analogue Register	AGL	MWC	Analogue	40031		
Spare Analogue Register	AGL	MWC	Analogue	40032		