A NEW APPROACH TO ASSESSMENT AND UTILISATION OF DISTRIBUTION POWER TRANSFORMERS

by

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DECLARATION OF ORIGINALITY OF WORK

I, Selver Corhodzic, declare that the PhD thesis entitled *A New Approach to Assessment and Utilisation of Distribution Power Transformers* is no more than 100,000 words in length, exclusive of tables, figures, appendices, references and footnotes. The 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.

[redacted]

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ABSTRACT

Electrical power systems utilise several voltage levels using power transformers to transfer voltages and connect parts of the power system with different voltage levels. One of these voltage transformations is being performed in the key component of the electrical power system: the distribution power transformer. It connects the Medium Voltage (MV) 11 kV - 33 kV networks and the Low Voltage (LV) 415 V networks, enabling connection of a large number of LV customers as well as (though to a much smaller extent) access of embedded generators to the electrical distribution network.

Although the Australian distribution power transformers are considered to be very efficient devices (Minimum Energy Performance Standards - MEPS *Fact Sheet,* 2004), still roughly 3.2% of distribution transformers' throughput electricity is lost due to their inefficiencies. The magnitude of these significant losses attributed to distribution transformers is a consequence of:

- inefficiencies due to the design, materials and technologies used in distribution transformers;
- inadequate type and rating of transformers selected for a particular application.

The commitments of various Australian stakeholders (the public, the government agencies, distribution utilities, regulators, electricity industry trade associations, etc.) to limit emissions of greenhouse gases and to actively contribute to the global efforts to protect our environment are closely related to the energy market reform. The recent partial deregulation of the Australian electrical supply industry has introduced competition in retail and generation sectors and also significantly changed the operational environment for the electrical distribution companies. The era of increased competition for capital has commenced. The state based regulators have reduced incentives for over-investments, however, they still request enhancement of quality of supply and improvements of customer services. These, sometimes conflicting requirements have forced the electrical distribution utilities to move focus from improving economic efficiency of electricity supply and abandon long established practices for evaluation of distribution system performances applying multi-level economic analyses and systematic assessment of performances of key system components. It seems that "low initial cost" method (without proper assessment of total life cycle costs) is becoming much more attractive solution for selection of distribution equipment.

The expected steady increases in energy demands and the need to undertake effective measures to protect the environment could be partially solved by improving energy efficiency of electrical equipment. The recent focus of the Australian government on the environmental costs associated with use of electrical energy has brought the efficiency of electrical equipment (including distribution transformers) under the spotlight.

Highly efficient, yet cost-effective distribution power transformers, which are fully optimised for the expected service conditions (the likely load and the operating environment), are obviously the right solution for reduction of electrical losses. Introduction and use of such equipment would present significant challenge for electrical distribution utilities and private users of distribution transformers as this would have a considerable impact on their competitive position under the new industry structure.

This research explores potential design improvements and increase in efficiencies for distribution transformers trough analysis of existing design and manufacturing technologies, relevant international regulatory developments, technological advancements and general trends in the context of the Australian market. It analyses the recently introduced mandatory Minimum Energy Performance Standards (MEPS) for distribution transformer and suggests courses of action for industry, regulatory bodies and the end users, which could help to ensure that those actions are part of the global solution for complex environmental issues.

In addition, this research investigates a new two-stage approach for evaluation, assessment and utilisation of distribution power transformers and as such, to some extent, is directed towards a rational risk management and technical methodology to allow Australian electrical utilities and other interested parties to deal cost-effectively with present conventional technologies for distribution transformer used by major Australian manufacturers.

The new assessment method for distribution transformers is based on:

- development of cost efficiency schedules for selected designs and representative kVA ratings;
- thorough financial analysis of distribution transformer losses.

This refined methodology highlights importance of design and costing stages in the assessment process. Further, it recommends moving from simple capitalisation of transformer losses by extending evaluation of the total operating costs through introduction of new evaluation factors based on life cycle cost concepts and on expected service and loading conditions.

Abstract

This research is a contribution towards development of new procedures and methodologies, which will provide guidelines and recommendations for improvement of distribution transformer performances and increase compatibility of needs and capabilities of various stakeholders: end users, standards' setting bodies, regulators, research organisations, equipment manufacturers, designers and consultants.

ACKNOWLEDGMENTS

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Selver Corhodzic

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GLOSSARY

ABARE	Australian Bureau of Agricultural and Resource Economics
ACCC	Australian Competition and Consumer Commission
ACEEE	American Council for an Energy Efficient Economy
AEEMA	Australian Electrical and Electronics Manufacturers Association
AGO	Australian Greenhouse Office
ANZMEC	Australian and New Zealand Minerals and Energy Council
ANZMEC	Australian and New Zealand Minerals and Energy Council
APEC	Asia-Pacific Economic Cooperation
AS	Australian Standard
BAU	Business As Usual
BEE	Bureau of Energy Efficiency (India)
BIL	Basic Insulation Level
BOM	Bill of Materials
CEE	Consortium for Energy Efficiency (USA)
CENELEC	Comité Européen de Normalisation Electrotechnique
	European Committee for Electrotechnical Standardization
CLASP	Collaborative Labelling and Appliance Standards Program
CO2-e	CO2 (Carbon Dioxide) equivalent
COAG	Council of Australian Governments
COAG	Council of Australian Governments
CRHiSi	Cold Rolled High Silicon magnetic steel
CRHiSiDR	Cold Rolled High Silicon Domain Refined steel

DISR	Department of Industry, Science and Resources
DOE	Department of Energy (US)
DTCEM	Distribution Transformer Cost Evaluation Model (USA)
EC	Council of the European Union
ECI	European Copper Institute
EES	Energy Efficient Strategies
EPA	Environmental Protection Administration (Taiwan)
ESAA	Electricity Supply Association of Australia
EU	European Union
FCR	Fixed Charge Rate
GATT	General Agreement on Tariffs and Trade
GST	Goods and Service Tax
GWA	George Wilkenfeld and Associates
GWh	Giga-Watt-hour
GWP	Global warming potential
HE	High efficiency (eg meeting the criteria designated in AS2374).
HSE	High starting efficiency: one of the projection scenarios
HTS	High Temperature Superconducting
HV	High Voltage
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronic Engineers (USA)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
kV	kilo-Volt: measure of voltage at input and output sides of transformer

kVA	kilo-Volt-Ampere: measure of capacity of transformer
kWh	kilo-Watt-hour: measure of energy
LCC	Life Cycle Cost
LE	Leonardo Energy
LF	Load Factor
LL	Load Losses
LLF	Loss Load Factor
LSE	Low starting efficiency: one of the projection scenarios
LTS	Low Temperature Superconducting
LV	Low Voltage
MEPS	Minimum Energy Performance Standards
MR	Media Release
MSE	Medium starting efficiency: one of the projection scenarios
MV	Medium Voltage
MVA	Mega-Volt-Ampere
MWh	Mega Watt-hour
NAEEEC	National Appliance and Equipment Energy Efficiency Committee
NAEEEP	National Appliance and Equipment Energy Efficiency Program
NATA	National Accreditation Testing Authority
NEM	National Electricity Market
NEMA	National Electricity Manufacturers Association (US)
NGGI	National Greenhouse Gas Inventory
NGS	National Greenhouse Strategy
NGS	National Greenhouse Strategy

NLL	No Load Losses
NPV	Net present value
NPV	Net Present Value
OEE	Office of Energy Efficiency (Canada)
ONAN	Oil Natural Air natural (cooling method)
p.u.	per unit
PV	Present Value
RIS	Regulatory Impact Statement
TDR	Test Discount Rate
TOC	Total Operating Cost
TTMRA	Trans-Tasman Mutual Recognition Agreement
TWh	Tera-Watt-hour
UNFCCC	United Nations Framework Convention on Climate Change
UNSW	University of New South Wales
V	Volt
VA	Volt-Ampere

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1. INTRODUCTION

1.1. Distribution Transformer – Key Power System Component

Electrical power systems utilise several voltage levels. By the time electrical energy is received at most consumers' connection points (at 415 V for three phase supply and at 240 V for single phase supply), it has been usually transformed through up to five voltage levels: initially being stepped up to 500 kV by the generator transformer, then down to 220 or 110 kV via a terminal substation transformer, then down to 66 - 33 kV at a bulk-supply point, further down to 22 - 11 kV in a zone substation and finally at a local distribution substation to a level acceptable by the Low Voltage (LV) networks - 415 V. The last of these voltage transformations is being performed in one of the key components of the electrical power system - a distribution power transformer.

Majority of the consumers of electrical energy are connected at this LV level (all residential and bulk of smaller industrial and commercial customers). Some larger customers, such as factories, mines, large office buildings or hospitals are connected to the electrical networks at 11 - 33 kV (or even at higher sub-transmission and transmission voltages 66 - 500 kV). These High Voltage (HV) customers can operate some of their specialised equipment at higher voltages, however, they still have to employ their own (non-utility owned) distribution transformers to provide supply for their local general LV loads. Distribution transformer is also used, albeit to a much lesser extent, to enable connection of embedded generators to the distribution networks.

Distribution transformers can be identified by voltage and rating (capacity). The voltage is most commonly specified as a pair of input/output values (e.g. 11/0.415 kV). The rating of a transformer indicates the amount of power it can transfer between its two sets of terminals. For example, a transformer with a rated capacity of 500 kVA is designed to continuously transfer its full load of 500 kVA under standard operating conditions (as defined in the AS 2374.1: 1997).

By convention, the electrical power system comprises of the "transmission" and the "distribution" networks. However, the voltage levels allocated to each type of network slightly differ between Australian electrical utilities. Generally, transmission transformers operate in the voltage range from 66 to 500 kV and within range of ratings from 3 MVA to few hundreds MVA. These transformers are sometimes called "power transformers", although this term, according to AS 2374.1, encompasses "distribution transformers" as well. The commonly used term "distribution transformer" as defined in Australian Standard AS 2374.1 (Power Transformers) describes group of power transformers, which operate in the voltage range up to 33 kV and have ratings 10 – 2,500 kVA. It is estimated that there are about 600,000 distribution transformers owned by Australian electrical distribution and transmission utilities. The bulk of these transformers are owned by the electrical distribution companies which operate LV networks (415 V) and Medium Voltage (MV) networks (generally 11 - 33 kV, although some distribution companies own some assets at higher voltages). Number of distribution transformers installed in electrical distribution networks is estimated to grow at approximately 1.5% per annum, GWA (2002).

Strong growth of the Australian economy in the last 10 years suggests that the current stock of non-utility owned transformers (estimated at 115,000 in 2005) increases at a rate of 2.5% per annum, ABARE (2004).

Although all power transformers have a very high efficiency - the largest power transformers are arguably the most efficient machines devised by humankind - amount of energy power transformers transfer and the number of them installed in the power system means that the amount of energy which they dissipate is, without a doubt, massive. The large power transformers have a very high efficiency (in excess of 99.75% at full-load), since in a transformer costing \$5 - \$10 million it is cost-effective to reduce the losses to the minimum manageable level. However, as the full-load can be in order of few hundreds of MVA the small relative losses of 0.25% can still be significant in absolute terms. At the other end of the scale small distribution transformers are less efficient; overall operating efficiency is somewhere around 96.8%, GWA (2002), but due to their large number it is very important to aim for the highest efficiency that can be practicably achieved. The lost electricity in Australia in 2000 is estimated at 5,865 GWh, which is nearly 6 million tonnes of carbon dioxide equivalent (CO_2-e) or approximately 66% of the emissions associated with the operation of all domestic refrigerators and freezers in Australia GWA (2002).

1.2. Research Problem

1.2.1. General Aims of Research

The environmental issues, efficient use of energy and quality of supply have become closely interrelated over the last few decades. Consequently, major policy issues for governments of developed countries to face over the first 10 to 20 years of the 21st century would be to find a compromise between the steady increase in energy demands and the need to undertake effective measures to protect the environment.

The problems associated with satisfying both, constantly increasing energy demands and accompanying environmental constraints could be partially solved by improvements in energy efficiency. Distribution power transformers are considered to be relatively efficient electrical machines, however still roughly 2% of the total world electricity production is lost due to distribution transformers inefficiencies.

There are numerous reasons, which prevent distribution transformers in Australia from being standardised and catalogued products. The most obvious ones are huge differences between regional utilities and network operators are constrained by the required voltage ratios, tapping ranges, maximum losses, no-load voltages, short-circuit impedances, limiting dimensions, accessories and service conditions. The compatibility with existing apparatus often imposes additional restrictions on the selection of distribution transformers.

This research is focused on the improvement of assessment methodologies and utilisation practices for distribution power transformers. In summary, the general aim of this research is twofold:

Firstly, this research explores the potential design improvements and increased efficiencies for distribution power transformers offered for sale in the Australian market. It analyses the existing design and manufacturing technologies and general trends in the context of the Australian market and suggests courses of action for industry, regulatory bodies and the end users. These actions could help to ensure that those technologies are part of the global solution for complex environmental issues. To some extent this research is directed towards a rational risk management and technical methodology to allow Australian electrical distribution utilities and other interested parties to deal cost-effectively with recent and future developments of distribution transformer technologies while maintaining globally accepted commitments in regard to inevitable climate changes.

Secondly, this research aspires to contribute to those global environmental commitments by developing new approach for evaluation, assessment and utilisation of distribution power transformers.

1.2.2. Specific Aims of Research

The specific aims of this research are:

- To overview current distribution power transformers technologies used in Australia and compare them with modern world practices, trends and developments;
- To analyse current Australian practices for evaluation, selection and utilisation of distribution power transformers;
- To provide a general overview of high-efficiency distribution transformers;
- To develop a new comprehensive methodology for assessment of distribution power transformers which will promote high efficiency transformers;
- To propose a new classification of distribution power transformers based on transformer performances and suitability for particular application and service conditions.

This research explores the potential design improvements and increased efficiencies for distribution transformers analysing the existing design and manufacturing technologies, relevant international regulatory and technological developments and general trends in the context of the Australian market. It suggests courses of action for industry, regulatory bodies and the end users, which could help to ensure that those actions are part of the global solution for complex environmental issues. In addition, this research develops a new approach for evaluation, assessment and utilisation of distribution power transformers and as such, to some extent, is directed towards a rational risk management and technical methodology to allow Australian electrical utilities and other interested parties to deal cost-effectively with recent and future developments of distribution transformer technologies.

This research is a contribution towards development of new procedures and methodologies, which will provide guidelines and recommendations to improve distribution transformers' performances and increase compatibility of needs and capabilities of various stakeholders: end users, standards' setting bodies, regulators, research organisations, equipment manufacturers, designers and consultants. The new methodology will assist electrical distribution utilities and industrial / commercial users of distribution transformers to select the optimal rating of distribution transformers for particular service conditions and future load growths. The optimising criteria will also include assessment of energy losses where a rigorous financial analysis will be applied to analyse the long-term consequences of the purchasing decision (i.e. the Total Operating Cost - TOC, cost of saved energy, return on investment, potential reduction in greenhouse gases emission, etc.).

1.3. Research Context

1.3.1. New Challenges for Australian Electrical Utilities

Electrical distribution companies are major users of distribution transformers. To a large extent they also govern the employment of distribution transformers by other users (e.g. industrial and commercial users).

In the last 10 years deregulation of the Australian electricity supply industry has introduced a new competitive environment for the electrical distribution companies. Some players in this competitive arena (e.g. foreign investors, retail companies, large customers) are trying very aggressively to keep abreast of advancements in relevant technologies and to take advantage of the changes following introduction of the National Electricity Market (NEM). However, most Australian electrical distribution utilities are still predictable and very slow to transform, because the electrical distribution system they control resists the changes and "prefers" to operate in a static environment. The electrical professionals in those utilities have not been driven by the basic competitive requirements, as the essential day-to-day operation of the distribution system has been perceived as much more important than the global business itself.

The electricity supply industry is being reshaped into a fiercely competitive marketplace. The objective of introducing competition into these markets is to make them more efficient. In addition to the reduction of the total real running costs of their assets, electrical utilities are increasingly required to provide more reliable supply and keep a high level of quality of power supplied. Electrical equipment has an operating life of 25 - 40 years and purchasing equipment with optimal long term returns on investments is sometimes in contradiction with immediate financial expectations from shareholders.

On the other hand, the most economical solutions are often in contradiction with the best possible technical practices and/or locally approved long-established and approved methods. The possibilities for expansion, new market opportunities and challenges from competitors have emerged. The role of the electrical distribution company has changed with new competitive positioning of customers, new partnership opportunities, new stakeholders, more demanding shareholders and continuously increasing power demands on the ageing distribution system assets. The reposition of the electrical distribution businesses is a necessity and this is possible through re-evaluation of previous practices, introduction of more customer-oriented procedures and policies, overcoming of non-competitive strategies, adoption of modern competitive assessment techniques and increased effectiveness.

1.3.2. Distribution Transformer Assessment Techniques

Most Australian electrical distribution utilities claim that they purchase distribution transformers using some type of loss evaluation procedure. These purchasing practices have been established over the past 25 years, as the utilities have apparently become aware of the range and the value of distribution transformer losses. On the other hand, very few industrial and commercial customers include evaluation of distribution transformer losses in the purchasing process. Their selection of distribution transformers is mostly driven by the low initial investment. Consequently, they usually select a distribution transformer with relatively high losses and suitably low efficiency. The current Australian practices for purchasing industrial and commercial distribution transformers in addition to favouring "initial cost effective" transformers with higher electrical losses also include over-sizing distribution transformers by 25 to 50% to allow for future capacity needs.

A careful analysis of the tenders (and limited available information on the follow-up activities) for distribution transformers issued by major Australian distribution companies in the last ten years reveal that there is declining motivation for these utilities to rigorously apply assessment of lifetime operating costs into their purchasing policies.

The recent changes in structure of the electricity supply industry in Australia have greatly reduced the ability of distribution companies to minimise their operating costs. According to distributors themselves and their regulators, "the state-based regulation of distributor charges appears to be favouring first cost concerns above lifetime operating cost". Unfortunately, most consumers are neither aware of the consequences of this practice nor in a position to directly influence it. It appears that as a consequence "the costs of electrical distribution services, and the emissions of greenhouse gases, are projected to be higher than would be the case if operators of electricity distribution transformers were to base investment decisions on lifetime operating costs" GWA (2002).

It should be mentioned that the electrical distribution companies also oversize their distribution transformers and the estimate is that more than 30 % of all distribution transformers are oversized by at least 25%. In the last 10 to 15 years the practices of Australian distribution utilities for selection of distribution transformers have been simplified and reduced to the following two steps:

- checking the compliance of the offered transformers against the basic technical details outlined in the tendering documents;
- simple capitalisation of transformer losses.

The second step (if it were applied at all) has been further simplified by applying basically the same formula for the assessment of total operating costs for all distribution transformers under all service and loading conditions.

A number of Australian distribution companies have used the loss capitalisation formula, which has been taken from the Australian Electronic and Electrical Manufacturers' Association/ Electricity Supply Association of Australia specification for pole mounting distribution transformers (AEEMA/ESAA, 1998). This formula has been applied for all types of oil-immersed distribution transformers: pole-mounted, ground-mounted (indoor and outdoor), as well as for special applications. This loss capitalisation method did not recognise transformer overload capabilities and did not allow for improved transformer designs. Moreover, it was completely unacceptable for large distribution transformers (1,000 -2,500 kVA), which have a very different ratio between no load and load losses in comparison with smaller pole mounted transformers. This research presents a critical analysis of this loss capitalisation method and recommends new solutions for specific applications of distribution transformers in different distribution networks. This research covers three-phase, oil-immersed ONAN cooled distribution transformers rated 150 - 2,500 kVA designed for distribution networks 11 - 33 kV. It excludes designs and solutions, which are outside the range of technologies, materials and production methods currently used by major manufacturers in Australia. Full list of excluded materials and technologies is presented in Chapter 8. The developed assessment techniques could be easily extended to other technologies, types and families of distribution transformers (dry type transformers, single-phase transformers, etc.) and would compliment assessment of related electrical equipment (high voltage switchgear and kiosk substations).

1.3.3. Energy Efficiency

The expected large increases in energy demand and the need to undertake effective measures to protect the environment could be partially solved by improvements in energy efficiency of electrical equipment. With the recent focus on the environmental costs associated with use of electrical energy, the efficiency of electrical equipment (including distribution transformers) has come under the spotlight. Distribution transformers are considered to be "highly efficient devices", but still roughly 2% of the total world electricity production is lost due to distribution transformers inefficiencies. Australian commitments to limit greenhouse gas emission and to actively contribute to the global effort to protect our environment are closely related to the significantly deregulated Australian energy market reform. Consideration of transformer efficiency is critical to reduction of the load impact on the distribution network and to the total owning cost of the purchaser. In addition, as a major part of Australian electricity is generated in coal-burning power plants, the decrease of electrical losses in distribution transformers will be a significant contribution towards reduction of emitted greenhouse gasses. Optimised distribution transformers (cost-effective and highly efficient designs and appropriately improved utilisation, loading and maintenance techniques) would provide numerous global benefits to the wider public as well as local benefits to electrical distribution companies, their customers and other users of distribution transformers (increased reliability of supply, improved competitiveness through more efficient electrical distribution networks, energy efficient transformers will reduce needs for new generation capacities and reduced investments in electrical distribution and transmission networks and most importantly - reduction of greenhouse gas emissions).

1.3.4. Significant Events in Australian Distribution Transformer Market

Two recent events, which have had significant effect on development of Australian market for distribution power transformers are:

- conclusion of the Federal court proceedings against major Australian transformer manufacturers involved in the power transformer and distribution transformer cartels in April 2004;
- introduction of the mandatory Minimum Energy Performance Standards (MEPS) requirements for distribution transformers in Australia in October 2004.

Both of these events have been described in more details in Chapter 2.

1.4. Research Methods

This research includes the following five methodological sequences:

- literature review;
- data collection and analysis of Australian market for distribution transformers;
- analysis of distribution transformer technologies and designs;
- analysis of present assessment procedures and proposal for development of improved assessment methodologies;
- simulations and testing.

1.4.1. Literature Review

In addition to author's unremitting long-term professional interests in publications about distribution transformers, this stage includes a 6 years long process of reviewing relevant

Australian and international publications (over 600 scientific papers, reports, studies, policies, standards, proposals, fact sheets, media releases, catalogues, brochures and books) covering numerous changes in the market, regulatory framework and policies as well as developments in technologies and designs.

1.4.2. Data Collection and Analysis of Australian Market for Distribution Transformers

The main sources of research material are various government departments and agencies (including reports prepared by various stakeholders and consultants), internal documentation obtained from distribution utilities, manufacturers' catalogues and technical information, conference proceedings, the internet and personal communication and market information obtained on confidential basis.

1.4.3. Analysis of Australian Distribution Transformers Technologies and Designs

The scope of research was limited to three phase oil-immersed distribution transformers rated 150 to 2,500 kVA. For this range of products all major Australian manufacturers use very similar conventional technologies, manufacturing methods and materials. These technologies were optimised over the last 15 years with significant input and technical support from large European transformer manufacturers. However, there are some unique technological advancements specific for particular Australian manufacturers:

- introduction of oblong type core for larger transformers by Schneider Electric (Australia);
- Wilson Transformer Company utilises rectangular core for smaller distribution transformers;

- GE (Alstom) is developing a very compact large kiosk transformer.

The preliminary analysis of the most common designs and technologies for distribution transformers has been performed using publicly available data. This analysis required development of few simple software applications (e.g. simplified transformer design package, costing calculations, etc.). The more serious analysis included assessment of specific technical data and was related to particularly selected products. At this stage some of new and emerging technologies for distribution transformers were assessed. As none of them is commercially available in Australia, designs based on those technologies were excluded from further considerations. More details are given in Chapter 8.

Most information about actual assessment methods and practices were not published or readily available. The author has utilised his extensive professional contacts within Australian "transformer" circles including his membership in the CIGRÉ, Australian Panel AP2 (Power Transformers). This part of the research includes also some limited field activities.

1.4.4. Analysis of Present Assessment Procedures and Proposal for Development of Improved Assessment Methodologies

This part of the research program includes the following activities:

- analysis of previous and current assessment methodologies;
- development of a comprehensive methodology for assessment of distribution transformers based on life cycle cost analysis;
- analysis of recently introduced MEPS for distribution transformers.

The diversity and complexity of factors involved in this stage has emphasised the need for development of new algorithms to bridge the gap between economic and engineering analysis tools. This stage assessed impact of environmental policies and commitments and required use of rigorous financial analysis, decision programming; risk analysis, assessment of asset management techniques and total operating cost analysis.

1.4.5. Simulations and Testing

The proposed methodology was tested on few selected products (including discontinued and newly developed distribution power transformers). It included assessment of utilisation methods for a very efficient distribution transformer, immediately before implementation of MEPS in Australia. The methodology was also compared against international practices. This stage includes verification of the newly developed methodology based on an extensive testing program of a new line of distribution transformers developed for a major Australian electrical distribution company.

1.5. Proposed Framework for Development of Assessment Methodology

The above presented research methods could be transferred to this subsequent framework for development of assessment methodology:

- research of distribution transformer market in Australia;
- engineering analysis (analysis of design methods for distribution transformers under consideration and development of simple costing calculations);
- analysis of Life Cycle Cost (LCC) and Total Operating Cost (TOC) methods;
- critical analysis of MEPS for distribution transformers in Australia.

As this research occurred in the same period when significant changes were introduced in the Australian regulatory environment (i.e. introduction of MEPS in the context of distribution transformers), the original idea of this research project to propose the efficiency levels for distribution transformers has been replaced with a critical analysis of the imposed MEPS. The following chart graphically presents various stages and methods applied in this research project. It is based on a flow diagram of analyses for distribution transformers energy conservation standards DOE *Framework* (2000).

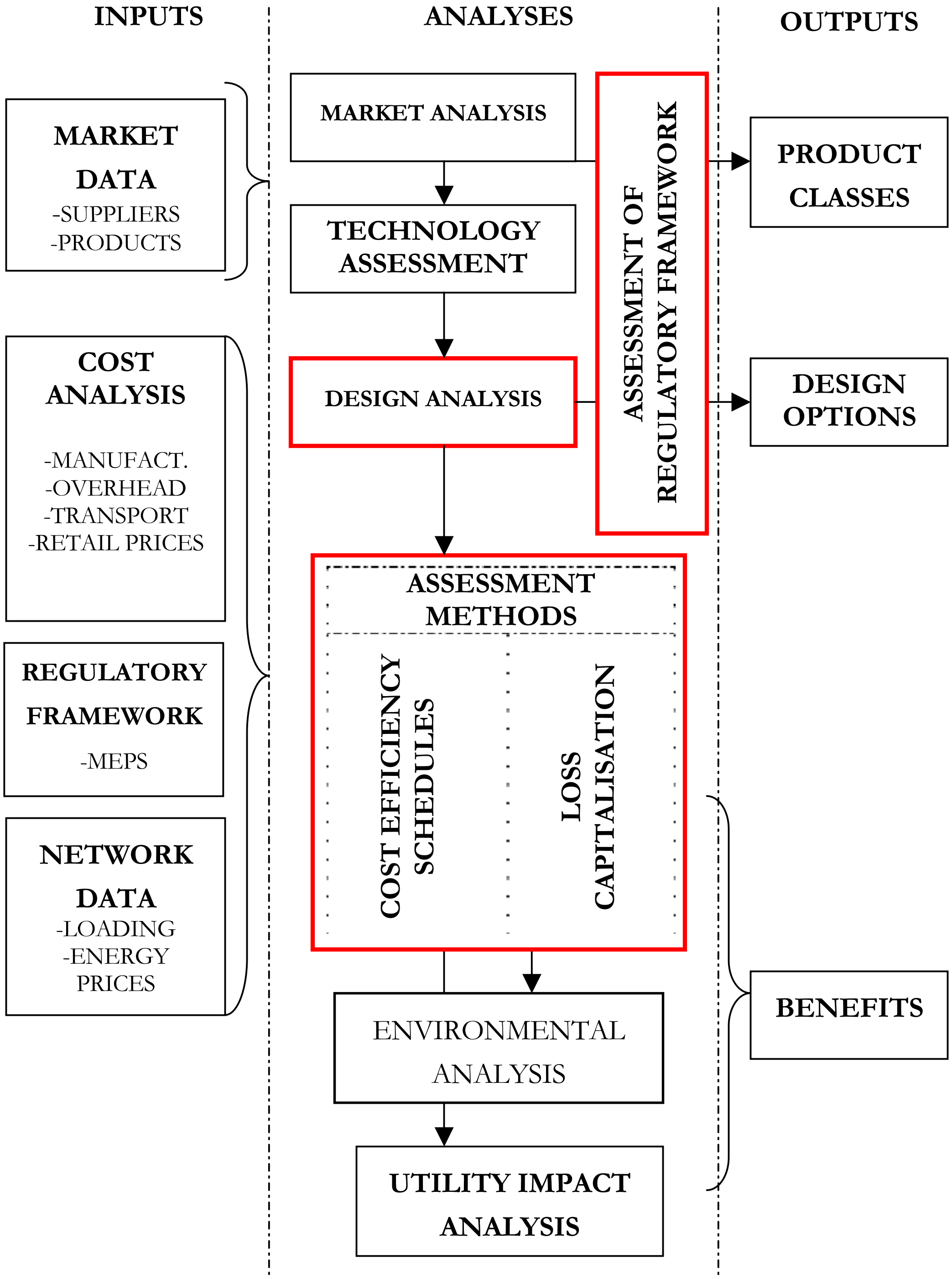

FIGURE 1 - DEVELOPMENT STAGES, INPUTS, ANALYSES AND OUTPUTS FOR THIS RESEARCH PROJECT

1.6. Outline of the Thesis

Chapter 1: this introductory chapter includes general description of the distribution transformer and its role in the power system. It sets the scene for the research thesis describing the scope of this research and its general and specific aims, unfolding the context of the investigation, highlighting the interrelations between the energy markets, energy efficiency and relevant equipment selection practices in electrical distribution companies. This chapter also describes research, the applied research methodologies and presents the outline of the thesis.

Chapter 2 describes in more details the recent events in the Australian market for distribution power transformers:

- conclusion of the Federal court proceedings against major Australian transformer manufacturers involved in the power transformer and distribution transformer cartels (in April 2004);
- introduction of the mandatory Minimum Energy Performance Standards (MEPS) requirements for distribution transformers offered for sale in Australia (in October 2004).

In addition, this chapter includes comprehensive review of relevant literature.

Chapter 3: this chapter describes the current status of Australian distribution transformer market focusing on identification of major stakeholders and review of recent events relevant for the industry. In addition, this chapter briefly describes the changes in the regulatory regime for distribution transformers (i.e. from October 2004, distribution transformers manufactured in or imported into Australia must comply with Minimum Energy Performance Standards requirements as defined in AS 2374.1.2-2003.). A special attention is given to comparison of utility and non-utility owners of distribution transformers and their respective purchasing strategies for distribution transformers.

Chapter 4 deals with the first step in developing new assessment methodology - development of cost-efficiency schedules. It involves performing an engineering analysis on the existing and proposed design options including assessment of corresponding efficiency levels. The main purpose of the engineering analysis is to identify the relationship between distribution transformer costs and energy efficiency levels. Various approaches to development of cost efficiency schedules are discussed. In addition this chapter discusses distribution transformer losses as well as technology and design variations relevant for reduction of losses. A comprehensive analysis of costing model, including a detailed case study is also presented. Finally, a simple assessment methodology is presented based on the following steps:

- classification of distribution transformers into kVA rating groups;
- selection of a representative rating in each group;
- development of cost efficiency schedule for the representative kVA rating;
- application of scaling factors to estimate relevant performances/parameters for non-representative kVA ratings.

Chapter 5: the second major step in development of assessment methodology is discussed in this chapter. It is related to the existing and proposed loss capitalisation techniques for distribution transformers. The increasingly competitive electricity market puts Australian utilities under greater pressure to operate their networks more efficiently, to maximize reliability of supply and to reduce the total costs of their assets. These goals could be achieved by investments in predictive maintenance, improvement of asset management methodologies and introduction of effective investment strategies. The need to respond to sometimes conflicting messages from various stakeholders makes design of electrical distribution systems and selection of relevant equipment more complex. The most common method for assessment and selection of distribution transformers currently used in Australia is a simple capitalisation of transformer losses. A number of utilities currently use one set of capitalisation factors for the evaluation of the total operating costs for all distribution transformers under various service and loading conditions.

This chapter analyses that method and recommends its extension by the introduction of new evaluation factors based on life cycle cost concepts and on expected service and loading conditions.

Chapter 6 investigates background assumptions and methods used in developing recently introduced MEPS for distribution transformers. The author was involved in early consultation processes related to development of draft MEPS recommendations. In addition, this chapter includes an update on current status of international efficiency standards and recommendations for distribution transformers.

Chapter 7: in the last two decades the Australian market has shown an increasing demand for packaged substations with three phase distribution power transformers installed in metallic enclosures. The local electrical utilities and transformer manufacturers have developed many different designs based on unique specifications and distinctive combination of construction features. Highly restrictive local environmental and urban planning regulations have resulted in development of very compact packaged substations with extremely arduous service conditions for built-in transformers. The limited footprints and ever increasing transformer ratings have resulted in reducing the ratio between the physical dimensions of the installed transformer and its rated power. This chapter investigates utilisation of Australian oil-immersed, ONAN cooled and hermetically sealed distribution transformers rated 150 – 2,500 kVA, highlighting their distinctive features: unique design, loading capability, reliability performances and safety features. The chapter includes results of an extensive tests conducted in a major Australian facility for manufacturing and refurbishment of distribution transformers. It included assessment of utilisation methods for a very efficient distribution transformer, immediately before implementation of MEPS in Australia. The methodology was also compared against practices in Europe (where very similar standards for distribution transformers apply). This stage included verification of the newly developed methodology based on an extensive testing program of a new line of distribution transformers developed for a major Australian electrical distribution company.

Chapter 8 summarises conclusions and recommendations from this research. It briefly outlines the basic steps in developing new assessment methodology for distribution transformers. This chapter also discuses emerging technologies for distribution transformers and recommends areas for further research.

Chapter 9: a list of publications and presentations made during the course of this project is included in this chapter.

2. LITERATURE SURVEY

Literature survey included a 6 years long process of following relevant consultation processes in Australia and USA, consequent development of regulatory framework and policies as well as analysis of initial results of implemented efficiency standards (in Australia).

This extensive process included reviewing of over 600 relevant Australian and international scientific papers, reports, studies, policies, standards, proposals, fact sheets, media releases, catalogues, brochures and books, following dynamic changes in the Australian market, much slower changes in the regulatory framework and policies and very slow developments in distribution transformers technologies and designs.

2.1. Development of Regulatory Framework in Australia

There are limited publications covering development of mandatory Minimum Energy Performance Standards (MEPS) for Australian Transformers. The MEPS development process (for distribution transformers in Australia) is presented in Chapter 6, together with excerpts from major publications prepared by NAEEEC (1999-2001), NAEEP (1999-2005), Ellis (2001) and GWA (2002). Some of the key documents have been summarised below and in Appendix 3.

NAEEEC introduced MEPS for certain distribution transformers on 1 October 2004. Details are contained in the MEPS profile and Regulatory Impact Statement and in AS 2374.1.2-2003.

The following reports have been released for distribution transformers:

- MEPS Technical Report – Distribution Transformers, detailed technical report by Mark Ellis & Associates gives data on market, overseas programs, emissions, test procedures and program options (Ellis, 2000);
- MEPS Profile – Distribution Transformers: proposed MEPS levels for a range of distribution transformers which operate on 11k and 22 kV systems from 10 kVA to 2,500 kVA NAEEEC (2001):
- Regulatory Impact Statement: MEPS for Electricity Distribution Transformers, Report 2001/18 GWA (2002).

MEPS – Analysis of Potential for Minimum Energy Performance Standards for Distribution Transformers (Ellis, 2001), is the report prepared for the Australian Greenhouse Office by Mark Ellis & Associates with the assistance of Associate Professor Trevor Blackburn (UNSW). The report gives data on market, overseas programs, emissions, test procedures and program options. It concentrates on MEPS for distribution transformers, which operate on 11 and 22 kV systems from 10 - 2,500 kVA; includes liquid filled and dry type.

MEPS Profile – Distribution Transformers NAEEEC (2001) proposes MEPS levels for a range of distribution transformers, which operate on 11 and 22 kV systems from 10 - 2,500 kVA; includes liquid filled and dry type. This document sets out the timetable for public consultation in the development of the new MEPS levels.

Regulatory Impact Statement: Minimum Energy Performance Standards and Alternative Strategies for Electricity Distribution Transformers is the report prepared by George

Wilkenfeld and Associates GWA (2002) for the AGO. This document recommended to introduce mandatory minimum energy performance standards for all electricity distribution transformers of up to 2,500 kVA capacity, falling within the scope of a proposed new part of Australia Standard AS2374.1.2 2001: Power Transformers: Minimum Energy Performance Standards for distribution transformers.

Appendix 2 includes a summary of relevant Australian Standards for distribution transformers.

2.2. Development of International Efficiency Programs

This research has focused on the Australian market for distribution transformers; however, a particular attention has been given to the US program for development of Minimum Energy Performance Standards for distribution transformers. This thesis includes extensive referencing to and quoting of the relevant Department of Energy (US) documents.

In addition, Ellis (2001) and Leonardo Energy (LE, 2005) have analysed international efficiency standards for distribution transformers and development of regulatory framework in the USA, Canada, Mexico, Europe, India, China, Japan, Taiwan and New Zealand.

Leonardo Energy (LE) is a program managed by European Copper Institute (ECI) involving over 100 partners in various projects related to electrical energy. LE promotes best practice in electrical engineering and energy regulation focusing on quality of supply, electrical safety and sustainable electrical energy. LE (2005) highlights that "the costs and profits of network companies in a liberalized electricity market are in most countries limited by regulation or regulated tariffs. This may inhibit investments in energy efficiency measures, for instance high efficiency transformers. The risk is that companies are more focussed on short term cost savings and fail to invest in systems that would save more in the long run. If the correct regulatory framework is developed, investments in improving the efficiency of a network can also be stimulated under market regulation". The document focuses on barriers for investment in high efficiency products and recommends possible remedial measures.

2.3. Transformer Design Issues and Assessment Techniques

Transformer design issues relevant to this research are discussed in Feinberg (1979), Lenasi (1981), Harrison (1988), Franklin (1993), McConnel (2001) and Ling (2003). These publications deal with theoretical approaches to calculation of distribution transformer losses, as well as with some more practical aspects such as scaling of relevant parameters, costing principles, etc.

In addition, works of WEC (1982), Howe (1999), McConnel (2000) and Nadel (2001) discuss development of emerging and alternative technologies for distribution transformers, which may contribute to increase of efficiency of distribution transformers. More details on these opportunities are presented in Chapter 8.

2.4. Power Transformer Issues

Although the scope of work for this research includes only oil-immersed distribution transformers, there is a huge body of literature covering large power transformers, which is to some extent applicable to distribution transformers and as such relevant for this research. In particular, CIGRÉ publication on economical aspects of management of power transformers CIGRÉ (2003) is very useful. It includes scaling factors for power transformers, which provided a valuable benchmark values for this research.

3. DISTRIBUTION TRANSFORMER MARKET IN AUSTRALIA

3.1. Stakeholders

In the context of distribution transformers, their assessment techniques and utilisation modes, the following Australian stakeholders have been identified:

- distribution utilities as major owners and operators of distribution transformers;
- private purchasers of distribution transformers;
- suppliers and their associations (local and overseas manufacturers, importers, Australian Electrical and Electronic Manufacturers Association - AEEMA);
- consumers and the wider public;
- state based regulatory authorities;
- Australian Greenhouse Office (AGO) and its agencies;
- Energy Supply Association of Australia - ESAA.

In Australia most of distribution transformers are owned by the distribution utilities. These electrical distribution utilities are still natural monopolies and, as such, are financially regulated by the Australian Competition and Consumer Commission (ACCC) and the state-based regulators. The regulators administer some of the high level operational issues of these distribution monopolies (i.e. reliability of supply, power quality, access to the network, tariffs, etc.) and control the process where the permissible costs incurred by utilities are passed through to consumers. The general function of this process is to ensure that a quality electricity supply is provided reliably and at minimum cost to the public.

Ellis (2001) has compared regulatory regimes in Australia and few other countries he has found that "*there is evidence that cost effective investment in transformer efficiency is not occurring in countries such as Canada, the US and parts of Europe, and that the regulatory regimes existing at that time were not providing sufficient motivation to ensure investment in efficiency*."

It appeared that also in Australia the costs of distribution losses were simply passed through to the customers and there was no financial incentive for distribution utilities to reduce network losses (e.g. there was no return on investment in more efficient transformers).

In summary, the major causes for inability of these and other similar regulatory regimes to encourage use of efficient distribution transformers were:

- the fact that there is a huge competition for regulated capital (needed for network augmentations and refurbishments due to continuous load increases and the ageing network assets);
- the treatment of losses in the electrical distribution networks.

In recognition of these market failures, some countries (including Canada in 2002 and Australia in 2004) have introduced specific regulation to improve transformer efficiencies. These events are described in more details in Section 3.4 and Chapter 6.

3.2. Suppliers

The major manufacturers of distribution transformers in Australia are:

- ABB Transmission and Distribution Ltd;
- Alstom Australia Ltd (recently acquired by Areva engineering group);
- AW Tyree Transformers Pty Ltd;

- Schneider Electric (Australia) Pty Ltd;
- Wilson Transformer Company Pty Ltd.

In addition, there are 18 smaller manufacturers; most of them are low volume producers participating only in smaller and highly specialised areas of the market.

Distribution transformers enjoy free trade status in the international markets and there are several importers of distribution transformers in Australia. Some of the major manufacturers also import products from their international electrical engineering associates to supplement their offer to the Australian market. It is estimated that approximately 17% of the transformers sold each year in Australia are imported (Ellis, 2001).

It should be mentioned that there is a strong market for refurbishment of distribution transformers (winding inspections and re-clamping, oil replacement and re-conditioning of insulation system, replacement of gaskets and accessories, repainting, etc). The value of this market is estimated at $5 million per annum. As some utilities are driving their assets harder it seems that this market will continue to grow. According to GWA (2002) "there appears to be little economic scope for increasing the energy efficiency of units during the refurbishment process".

3.3. Price Fixing Arrangements in Australian Transformer Market

In April 2004, the court proceedings against major Australian transformer manufacturers involved in the power transformer and distribution transformer cartels were finalised. Penalties of $35 million were ordered against ABB Power Transformers Pty Ltd (in liquidation), ABB Transmission and Distribution Pty Ltd, Alstom Australia Pty Ltd, Wilson Transformers Company Pty Ltd, AW Tyree Transformers Pty Ltd and Schneider Electric (Australia) Pty Limited for their involvement in price-fixing and market-sharing contraventions of the Trade Practices Act 1974 after Justice Arthur Emmett in the Federal Court, Sydney declared their actions unlawful MR (2004). The court also imposed penalties totalling $1 million against the company executives involved in the cartels. The penalties handed down against companies and senior executives involved in the power transformer and distribution transformer cartels are the highest penalties recorded in Australia. "the size of the penalties indicates the seriousness of the contraventions", said Mr Graeme Samuel, Australian Competition and Consumer Commission Chairman. "These breaches were long-running arrangements in significant markets" MR (2004). The orders were made as part of two important sets of proceedings brought over allegations of an extensive cartel between the principal firms in the transformer industry, involving large power transformers and smaller distribution transformers.

During *Distribution Transformer Proceedings*, the court found that that there was extensive market-sharing and price-fixing cartel conduct in the market for distribution transformers in period from 1993 until 1999. This market in Australia is estimated to be worth approximately $150 million per annum. The ACCC argued that the level of penalty ordered by the court should reflect a number of factors, including, the seriousness and covert nature of the unlawful conduct, the number of separate contraventions, the amount of commerce affected by the arrangements, the size of the companies and the level of management involved MR (2004).

The customers affected by these illegal arrangements included many of the largest electricity transmission and distribution utilities across Australia. "Although these conspiracies were directed at the tender processes for power and distribution transformers, it is the Australian consumer who has ultimately paid the price", said Mr Samuel MR (2004). It is important to highlight the fact that in these proceedings ABB, Schneider Electric (Australia), Wilson Transformer Company, Alstom Australia and AW Tyree Transformers admitted their involvement in the unlawful conduct and cooperated with the ACCC during the investigation process.

The initial allegations brought against major transformer manufacturers in 2000 and consequent investigations, court proceedings and finally the imposed penalties were closely watched and intensively discussed in the Australian "transformer industry" circles.

These events have had two-fold impact on this research:

- Access to relevant information has become extremely difficult. In the past, the Australian transformer industry has been suspicious to requests for technical information and obtaining commercial data was very difficult. Although the above events have enabled a reasonable access to most technical data, commercial information has become virtually inaccessible.
- These events and the subsequent changes in the distribution transformer market have highlighted the need to develop a simple and efficient method for assessment of distribution transformers, using limited publicly available data and relevant tender (technical) information.

The most interesting and quite controversial outcome of the above events is the alleged increase in the prices of distribution transformers in Australia over the last 5 years. Although the rising copper, oil and in particular steel prices could be blamed for this increase to some extent (and probably in long term), some of the major Australian distribution utilities "complained" (even though in private conversations only) about an apparent sharp increase in the average distribution transformers prices following the opening of the investigations in 2000. The popular joke in transformer industry around that time was "that the cartel principles have obviously worked very well and the cartel participants were busily (and co-operatively) working on developing a new strategy to compensate for the incoming penalties".

Other issues related to the cartel investigations was a significant increase in delivery times, incapability of transformer manufacturers to service equipment provided by other suppliers and inability to provide complete tender offers for large customers using cartel participants as sub-contractors. Although the market-sharing and price-fixing behaviour is unlawful and as such absolutely unacceptable, it appears that during 90's when the transformer market in Australia was continuously growing (without any significant increase in manufacturing capacities) the cartel principles have to some extent successfully controlled the increasing demand for distribution transformers in the brisk pre - 2000 Olympics Australian economy.

3.4. Introduction of MEPS for Distribution Transformers

From October 2004, distribution transformers manufactured in or imported into Australia must comply with Minimum Energy Performance Standards (MEPS) requirements. These requirements are set out in AS 2374.1.2-2003: Power Transformers, Minimum Energy Performance Standard (MEPS) requirements for distribution transformers (AS 2374.1.2-2003).

The scope of transformer MEPS covers oil-immersed and dry-type distribution transformers with power ratings from 10 - 2,500 kVA designed for use in 11 and 22 kV electrical distribution networks. The intention of MEPS is to increase energy efficiency by eliminating low efficiency transformers from the market. The standard also defines minimum efficiency levels for “High Power Efficiency Transformers” - distribution transformers that meet more stringent performance levels than MEPS (also specified in AS2374.1.2:2003) are allowed to be promoted as “High Power Efficiency Transformers”.

The Summary of MEPS Requirements sets out the regulatory testing, registration and checking requirements:

- test procedures for transformers used to determine compliance with MEPS for distribution transformers are listed in the following two regulatory Australian Standards AS2374.1-1997 Power Transformers and AS2735-1984 Dry Type Power Transformers. As the scope of this research includes only oil-immersed distribution transformers, the further discussions will exclude the considerations relevant for dry-type distribution transformers. Transformers within the scope of MEPS are required to have on their rating plate a statement that indicates compliance with AS 2374.1.2. The Minimum Energy Performance Standards are set out as power efficiency levels at 50% of rated load in AS 2374.1.2 when tested in accordance with AS 2374.1. The Australian standard AS 2374.1: Power transformers Part 1: General, specifies the technical requirements for single and three-phase power transformers, including auto transformers, but excludes single-phase transformers rated less than 1 kVA, three-phase transformers rated less than 5 kVA. It also excludes certain special transformers such as instrument, starting, testing and welding transformers as well as transformers for static converters and those mounted on rolling stock. This standard (AS 2374.1) is based on and has been reproduced from IEC 60076-1:1993. However this Australian standard is not equivalent to the IEC standard as it includes some Australian variations such as commonly used power ratings and preferred methods of cooling, connections in general use, and details regarding connection designation.

- product registration – the regulated products offered for sale after 1 October 2004 must be registered with a State regulator unless the supplier can prove that they were manufactured or imported prior to this date. There is provision in the standard to lodge registration for transformers or families of transformers with comparable and similar specifications and performance characteristics.
- regular checks - independent NATA accredited laboratories are conducting checks of MEPS registered products to ensure that all products offered for sale perform in compliance with MEPS requirements or higher requirements for "High Power Efficiency Transformers" (if applicable).

More details about introduction of mandatory MEPS requirements for Australian distribution transformers are given in Chapter 6 and Appendix 3.

3.4.1. Preliminary MEPS Testing Results

The preliminary checking tests conducted before introduction of MEPS confirmed that majority of distribution transformers on the Australian market at that time (2003) were reasonably efficient MEPS *Fact Sheet* (2004). The preliminary tests were conducted on five typical products from four manufacturers, ranging between 50 to 500 kVA and included dry type and oil immersed distribution transformers.

All tested transformers met mandatory energy efficiency MEPS levels and two transformers also met the higher standards defined for "High Power Efficiency Transformers". The tests also confirmed that manufacturers of distribution transformers have excellent in-house testing facilities as the results from manufacturers tests were within -0.01 to +0.04% of results produced by the independent NATA laboratory MEPS *Fact Sheet* (2004).

3.5. Structure of Australian Market

Ellis (2000) provided an analysis of the distribution transformer market in Australia in 2000 as follows:

TABLE - 1 AUSTRALIAN DISTRIBUTION TRANSFORMER MARKET (ELLIS, 2000)

	Installed MVA			**Number of Units**		
Ownership	**Single Phase**	**Three Phase**	**Total**	**Single Phase**	**Three Phase**	**Total**
Utility	6,000	73,000	79,000	160,000	328,000	488,000
Private	1,000	13,000	14,000	14,000	72,000	86,000
Total	7,000	86,000	93,000	174,000	400,000	574,000

Assuming that the annual sales are 19,100 units (3,100 MVA), the distribution utilities own 83% of the transformer stock and that 70% of the total stock are three-phase transformers, the estimate for the market in 2005 would be as presented in Table 2.

TABLE 2 - ESTIMATE OF AUSTRALIAN DISTRIBUTION TRANSFORMER MARKET IN 2005

Ownership	Installed MVA			Number of Units		
	Single Phase	**Three Phase**	**Total**	**Single Phase**	**Three Phase**	**Total**
Utility	6,440	87,000	93,440	185,850	388,650	574,500
Private	1,060	14,000	15,060	15,000	80,000	95,000
Total	7,500	101,000	108,500	200,850	468,650	669,500

The majority (86%) of distribution transformers installed in Australian distribution networks are liquid-filled. Table 3 presents the segment of the Australian market considered in this research project (oil-immersed, ONAN cooled three phase distribution transformers rated up to 2,500 kVA):

TABLE 3 - PART OF AUSTRALIAN DISTRIBUTION TRANSFORMER MARKET INVESTIGATED IN THIS PROJECT (ESTIMATE FOR 2005)

Ownership	Installed MVA			Number of Units		
	Oil Filled	**Dry Type**	**Total**	**Oil Filled**	**Dry Type**	**Total**
Utility	69,000	19,000	88,000	343,039	45,611	388,650
Private	5,000	8,000	13,000	50,000	30,000	80,000
Total	74,000	27,000	101,000	393,039	75,611	468,650

The annual sales of 19,100 units (3,100 MVA) correspond to a total annual value of the distribution transformer market in Australia of $150 million. The average price of $48/kVA applies for smaller and single phase units as the price per kVA for larger three phase distribution transformers is around $25 - 30/kVA. This sales estimate is consistent with data from the US, which has recorded annual sales of 3.25% of the total stock USEPAa (1998) for a similar level of economic activity.

The non-utility owned (private) distribution market in Australia is estimated to total about 660 MVA. As the non-utility owners tend to purchase somewhat larger and less efficient (and consequently less expensive) units, the estimate for average price is $ 30/kVA. This gives a value of about $20 million for the private market GWA (2002).

Finally, the value of imported distribution transformers is estimated at approximately $17 million per annum. This is approximately 11% of total estimated annual sales by value (Ellis, 2001). It seems that majority of these imports are dry type transformers for non-utility users.

3.6. Typical Product Structure

Typically, the major manufacturers in Australia offer two types of distribution transformers (for the same rating) in order to satisfy the specific market needs:

- basic low efficiency ("industrial") models designed for the private market;
- optimised ("utility") models (where some sort of loss capitalisation formula has been applier and/or designs were optimised to meet specific requirements regrading dimensions and accessories) mostly for electrical distribution utilities;

Some manufacturers also offer highly efficient premium models for a limited range of ratings (usually 400 - 1,500 kVA).

The "industrial" distribution transformers have on average 10% higher losses and are approximately 5 - 10% less expensive than similar "utility" transformers, whilst the premium models are 15 - 25% more expensive than the "utility" models.

More details about specific distribution transformers products are given in Appendix 1.

3.7. Issues for Utility Market

In mid 1990's the Australian vertically integrated state-government owned electricity entities have been restructured into four main components:

- generators;
- transmission companies;
- distribution companies;
- electricity retailers.

A new wholesale National Electricity Market (NEM) was established in the eastern states (Victoria, New South Wales, South Australia, ACT and Queensland) and the some of the publicly owned electricity assets (generators and distribution networks) were sold to the private sector.

Transmission companies remained in public ownership in all states except Victoria, where assets were sold but the Victorian government retained a tight control over planning and some operational aspects of the transmission network.

Out of 16 distribution companies - 7 of them are currently privately owned. These natural monopolies are subject to economic regulation, covering capital investments, tariffs, access to the network principles, and some of operational issues (network reliability and power quality). GWA (2002) states that most of the utility distribution transformers currently in use were installed before re-structuring, when distribution transformer selection process was based on principles of cost recovery and optimised capital allocation. That old model considered the value of reduced losses in the distribution system as those "could be realised through savings in the transmission network, a reduction in demand for generation and the ability to accommodate more of the seemingly inevitable growth in user demand before requiring additional investment" GWA (2002).

Examples of loss capitalisation calculations based on that model are given in Chapter 5. However, it appears that in the post-restructuring period when distribution businesses became solely responsible for operation of their networks, the focus has shifted towards competition for capital and accountability for losses has diminished.

3.8. Issues for Non-Utility Market

Private owners of transformers face slightly different challenges. Developers of large industrial and commercial estates who install "industrial" distribution transformers in those developments mostly rely on contractors to deliver a full package (MV connection cables, distribution transformers and electrical switchboards). They normally do not have incentive to install energy efficient transformers as it is difficult to recover this additional investment (most developments will be sold or let and the tenants will pay for the ongoing running cost). Although some of the private developers will continue to own the installed distribution transformers (e.g. owners of industrial estates, mines, manufacturing premises, hospitals, etc.) and mostly have the engineering expertise to assess the value of losses, most of them still favour less expensive (and less efficient transformers) relying on the lowest initial cost principle.

3.9. Conclusions on Market Survey

Restructuring of the Australian electricity industry has removed incentives for electrical distribution companies to include analysis of long-term losses of equipment in the purchasing decisions.

It seems that "low initial cost" method was much more attractive than higher investments in more efficient equipment, which will reduce long term operational losses and minimise the total life cycle costs. Following privatisation of electrical distribution networks in Victoria, some major manufacturers recorded increase in sale of high loss (low efficiency) distribution transformers to the distribution utility market.

Similarly, most developers who purchase distribution transformers for private use in large industrial and commercial complexes favour low cost inefficient distribution transformers, as they are not concerned with lifetime operating costs.

Likewise, many of organisations (mines, large factories, etc.) which own and operate their private distribution transformers perceive transformer losses as a small part of the total operating costs, unwilling or unable to understand long term benefits of more efficient equipment.

Consequently, the cost of additional electrical losses are ultimately being passed on the society (consumers paying higher price for electricity and other products in whose production electricity has been used and emissions of greenhouse gases are higher than should be).

4. DISTRIBUTION TRANSFORMER ENGINEERING ANALYSIS – TECHNOLOGY ASSESSMENT AND DESIGN ISSUES

4.1. Cost Efficiency Schedules

The first step in developing new assessment methodology is to perform an engineering analysis on the existing and proposed design options including assessment of corresponding efficiency levels. The main purpose of the engineering analysis is to identify the relationship between distribution transformer costs and energy efficiency levels. This is often referred to as a cost-efficiency schedule DOE *Framework* (2000). Cost-efficiency schedules are necessary for development of further economic analyses and Life Cycle Cost (LCC) methodologies which consider time value of money. A critical issue in this engineering analysis is availability and accuracy of relevant technical information and use of specially developed engineering analysis tools.

There are three basic evaluation approaches for developing cost efficiency schedules DOE *Framework* (2000):

- efficiency level approach;
- design option approach;
- reverse engineering approach.

The *efficiency level approach* is focused on calculating relative cost of improving efficiency of distribution transformers. It includes two steps:

- selection of a number of transformer efficiency levels for a range of (existing) distribution transformers;
- estimate of the total or incremental manufacturing cost of transformers that would

achieve the specified efficiency levels.

This approach requires very good estimation technique for the manufacturing costs. A full application of this method relies on manufacturers to provide an accurate representation of the costs related to particular level of improved efficiency. Most Australian distribution transformer manufacturers who were involved in this research project preferred this method as it is time efficient, does not require development of detailed designs and keeps the number of items of information requested of manufacturers to a minimum. However, this method has some serious disadvantages. Firstly, as design data are not known, it is not possible to verify the accuracy of the information received from the manufacturers. Secondly, lack of design information prevents conduction of any serious sensitivity analysis. Consequently, a big issue with this method is uncertainty about the costs of distribution transformer efficiency improvements. The author has applied this method in early stage of the research. The obtained data provided first rough estimates for costs related to increase in distribution transformer efficiencies and formed a basis for further research stages.

The *design options approach* is based on methodologies to determine the incremental costs of improving design options. This approach includes the following steps:

- selection of distribution transformer technology for alternative transformer designs (e.g. a new improved core design, such as oblong core, or a new material option for a relevant component);
- manufacturers provide estimated costs for distribution transformers built with these design options.

This approach requires significant involvement and commitment of manufacturers in the research project. It is believed, that this method is internally used by manufacturers as a basis for development of new products. Unfortunately, Australian manufacturers have shown very little enthusiasm for external application of this method as it requires a significant commitment from design resources and would disclose possible technological advancements (or shortcomings). Although this method provides excellent coordination between technological and economic sides of efficiency improvements, it is perfect for new technologies and is not really suitable for the existing range of products. Another interesting limitation factor for application of this method is the possibility that manufacturers may have knowledge of how to produce a highly efficient and cost-effective transformer that exceeds the design option selected by the author. For example, manufacturers may be able to develop a new set of designs that would consider a more comprehensive range of design options and include various combinations of core materials, core designs, cross-sections and dimensions, insulation materials and windings, which are superior to the design option selected by the author. This approach required the author to be able to model the efficiency improvements resulting from the considered design options using expert software packages. As these software packages are confidential, in-house developed business tools, manufacturers were not prepared to make theses software packages available for external use. Due to the above reasons the *design options approach* has been confirmed as inappropriate for this research. A variant of this model has been presented in this chapter.

Finally, there is the *reverse engineering approach* where manufacturing costs are derived from bills of materials. The author has selected this approach (also known as the cost assessment approach) as the most suitable method for assessment of existing distribution transformers. It is the most detailed method that calculates the actual manufacturing cost for a range of existing products. Although a full application of this method is very costly and time consuming, it was suitable for this research as it was applied on a very limited number of representative designs. This method has supplemented the initial results obtained by the efficiency level approach. A similar method was assessed by the US Department of Energy DOE *Framework* (2000); however, it is not clear how this approach would allow bridging from a small number of designs to the substantial number of designs in use in the present (USA) marketplace".

The reverse engineering approach requires significant amount of data. It consists of qualitative and quantitative efforts based primarily on publicly available information. Some of cost-efficiency information is compiled using distribution transformer retail prices and their existing efficiencies. However, the most critical input to this engineering analysis are data from distribution transformer manufacturers and design experts. As information coming from these sources is not complete (mostly due to commercial issues related to the current tenders), a considerable quantity of substitute information is also required to enable estimate of cost efficiency, where current market information is not available.

It should be noted that the recent USA practices in selecting a suitable approach for cost analysis of distribution transformers are still being debated. For example, in DOE *ANOPR – FNR* (2004), the USA DOE analyses suitability of the above approaches for cost analysis of distribution transformers and reports that: "there was no clear consensus among the respondents at the November 2000 framework document workshop regarding the most appropriate approach to pursue in the engineering analysis".

National Electricity Manufacturers Association (NEMA) preferred the efficiency level approach. In their opinion, this is the superior method as both the design-option and cost-assessment approaches require the estimation of manufacturing costs by non-experts. The American Council for an Energy Efficient Economy (ACEEE) suggested that the DOE utilise the cost assessment approach, as it has proven more accurate and reliable in prior assessments. The US DOE recommended the "modified design-option approach" as the most suitable approach for assessment of a large number of different distribution transformer designs. The software-design approach is based on market dynamics, where manufacturers compete for the tender award using their customised software to design distribution transformers which meet customer requirements. The DOE used specially developed software to produce a database which included hundreds of distribution transformer designs. The design software calculates the incremental costs of improving efficiency by changing design or changing the combination of materials.

4.2. Distribution Transformer Losses

The scope of work for this research is limited to oil immersed distribution transformers and relevant modern manufacturing technologies available in Australia. An oil immersed distribution transformer is a static electrical machine consisting of three major components:

- an active part consisting of a magnetically permeable core and a set of windings (insulated low resistance conductors wound around the core);
- an insulation and cooling system - insulation paper and mineral oil or a synthetic cooling liquid surrounding the active part;
- a transformer container (tank), connection terminals and accessories.

The distribution transformer changes the alternating current from a primary voltage to a secondary voltage. For the most common step-down distribution transformers in Australia the primary voltage is usually 11, 22 or 33 kV (HV side) and the secondary voltage is 415 - 433 V (LV side). Distribution transformer transforms the voltage through an alternating magnetic field in the core, which is created by the primary winding. The magnetic field induces the secondary voltage in the secondary winding. The change in voltage is made possible through the different number of turns in the primary and the secondary windings.

Distribution transformers are very efficient devices as their losses are generally very small, in order of a few percent of the total power transferred through the transformer windings. The transformer losses include two types of losses:

- no-load losses (core or iron losses);
- load losses (winding or copper losses).

No load losses are constant energy losses, which occur as soon as distribution transformer is energised (even if the load is not connected). No load losses result in generation of heat in the core. These losses consist of two major components:

- hysteresis losses caused by the magnetic reluctance of the core;
- eddy current losses due to currents induced in the core by the magnetic field.

The load losses occur in both the primary and secondary windings. They are consequences of the electrical resistance in the windings. The load losses increase with the square of the load connected to the transformer. In principle, increases in transformer efficiencies are oriented towards design options, engineering practices and manufacturing techniques related to reduction of transformer losses associated with these two assemblies: the core and the windings.

Generally, reduction of distribution transformer losses is a trade-off issue against higher manufacturing costs, i.e. more economical design means higher losses and lower losses are associated with a more expensive distribution transformer.

4.3. Technology Assessment

Technology assessment for distribution transformers under consideration is limited to assessment of the active parts of typical Australian distribution transformers. For comparison purposes, some consideration is also given to alternative design options available in the USA and Europe.

Conductor materials presently used in windings for distribution transformer applications include aluminium and copper. In a very limited number of cases, aluminium and copper alloys have also been applied. Conductors for distribution transformers are utilised in form of standard size wires and foils.

The following summary includes comparison of aluminium and copper used in an identical distribution transformer application:

- copper has a higher electrical conductivity and about 40% lower resistive losses;
- aluminium has lower eddy current losses due to higher resistance;
- aluminium has lower mechanical strength, but it is easier to form and work with;
- aluminium is also less expensive than copper;
- there are low load loss designs which utilise aluminium, however due to larger conductor cross sectional area a required bigger distribution transformer core, these designs have higher no load losses.

There are number of distribution transformer design options which utilise both copper and aluminium. In such cases, copper wire is normally applied in the high voltage (HV) windings and aluminium foil, at lower current density, in the low voltage (LV) windings.

In addition to foils and wires as the most commonly used forms of distribution transformer conductors, some larger distribution transformers, where very high efficiency is required, utilise bundled, transposed, and stranded conductors to further reduce eddy current loss component.

Distribution transformers utilise the following *core materials*:

- high-silicon magnetic steels, both non-oriented hot rolled and oriented cold rolled;
- domain-refined grain oriented, high-silicon magnetic steels;
- amorphous magnetic steels (currently used for wound core designs in the USA).

Distribution transformer core losses have been significantly reduced by introduction of high-silicon, cold rolled transformer steels. The commercially available cold rolled, high-silicon transformer steels are nominally designated as M2, M3, M4, M5 and M6.

In the past, distribution transformer cores utilised high loss, hot-rolled, thick-laminated, non-oriented, low-silicon magnetic steels. Today, distribution transformers almost exclusively use cold rolled, low-loss steels that contain 2-3% silicon (as well as very small percentage of other chemical elements). These core materials have much thinner and better insulated laminations. Laser-scribed transformer core steels are domain refined, offering even better performances. All of the above distribution transformer core materials can be applied at different magnetic flux levels and within a range of lamination thicknesses. In addition there are different core configurations (e.g. wound and stacked core arrangements).

There is very limited number of applications of amorphous materials in distribution transformer cores as this material is not presently viable for stacked core configurations. More details on amorphous metal cores are given in Chapter 8.

4.4. Design Variations

For a given set of “normal” constraints defined by the distribution transformer kVA rating, Basic Insulation Level (BIL), voltage rating, total impedance, temperature rise, weight, physical size and overload capabilities, there is still a large set of design variables that have to be taken into account in distribution transformer engineering analysis. Variations of design variables and construction techniques normally applied in distribution transformer engineering analysis include the following design options:

- variation of current density (g - A/mm^2);
- variation of flux density (B - Tesla);
- alteration of volts per turn (V/turn);
- modification of geometric shape and construction techniques, including location of voltage spacers, frame and coil dimensions, placement and number of cooling ducts, insulating materials, core types, etc.).

Table 4 presents array of design factors for a typical distribution transformer:

TABLE 4 - DISTRIBUTION TRANSFORMER DESIGN VARIATIONS

Conductor Material	Copper
	Aluminium
Conductor Type	Foil
	Wire
	Special construction
Core Material	Cold Rolled High Silicon (CRHiSi) magnetic steel
	Cold Rolled High Silicon Domain Refined (CRHiSiDR) steel
Core Construction	Core cutting
	Core stacking
	Core joints (lapping or butting)
	Core type (shell form or core form)
Winding Construction	LV-HV arrangement
	Coil winding pattern
	Cooling channels (number and location)
	Insulation system (material and arrangement)
Transformer construction	Shape
	Placement of accessories (e.g. internal fuses or switchgear)
	Bushing arrangements
	Frame and winding dimensions
	Placement of voltage spacers
Electrical Variations	Current density (g - A/mm^2)
	Flux density (B - Tesla)
	Volts per turn (V/turn)

For a given efficiency level (the total losses are constant) the no load losses and load losses are inversely related, as increase in no load losses generally means decrease in load losses and vice versa. Consequently, a specified efficiency level of a distribution transformer can be achieved with a relatively large number of different combinations of load losses and no load losses. These combinations are achievable due to variations in electrical factors (current density, flux density, volts per turn), choice of different materials for core and windings and variations in construction techniques for the core and the windings assemblies (optimisation of geometric configuration and relevant electrical and thermal parameters).

A general overview of the loss reduction options based on the above discussions is presented in Table 5 DOA *Framework* (2000).

TABLE 5 - GENERAL LOSS REDUCTION OPTIONS

Loss Reduction Options		**No Load Losses**	**Load Losses**	**Effect on Price**
Decrease No Load Losses	Use lower loss core material	Lower	No Change	Higher
	Decrease flux density (increase core Cross Sectional Area - CSA)	Lower	Higher	Higher
	Decrease flux density (decrease V/turn)	Lower	Higher	Lower
	Decrease length of flux path (decrease conductor CSA)	Lower	Higher	Higher
Decrease Load Losses	Use lower loss conductor material	No Change	Lower	Higher
	Decrease current density (increase conductor CSA)	Higher	Lower	Higher
	Decrease lengths of current path (decrease core CSA)	Higher	Lower	Lower
	Decrease length of current path (increase V/turn)	Higher	Lower	Higher

Figure 2 presents losses and efficiencies (at different loading levels and power factor 0.95 lagging) for a typical 1,500 kVA oil immersed distribution transformer.

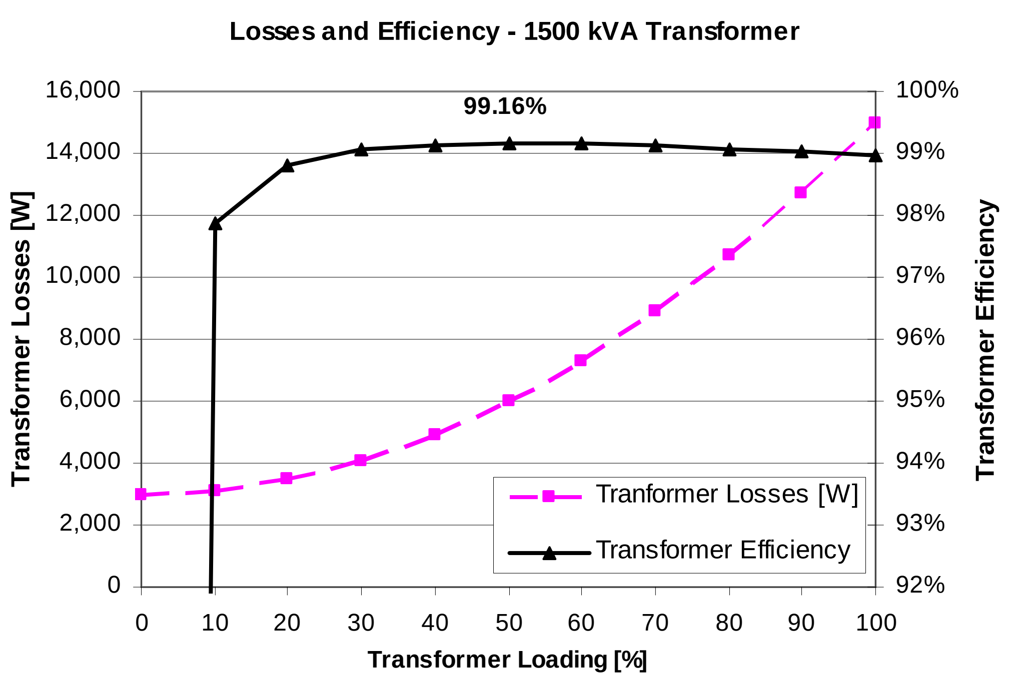

FIGURE 2 - LOSSES AND EFFICIENCY OF A TYPICAL 1,500 KVA DISTRIBUTION TRANSFORMER

4.5. Distribution Transformer Costing Model

The main purpose of the engineering analysis is to identify the relationship between distribution transformer costs and energy efficiency levels. This research has initially applied the efficiency level approach in the distribution transformer engineering analysis. This method calculates relative costs of improving efficiency of the existing distribution transformers. A simple methodology has been developed to calculate the total and/or incremental manufacturing cost for distribution transformers within a selected range of efficiency levels. This methodology is based on an iterative process where a range of different design solutions (based on range of materials, constructual features, load losses and no-load losses) is being optimised by minimising the total costs. These costs comprise of the selling price (sum of manufacturing, overhead, mark-up and shipment costs) and the estimated cost of losses (capitalised losses for the designed transformer life). A more comprehensive analysis of the total costs is presented in the later sections of this chapter.

4.5.1. Direct Manufacturing Costs

Design techniques for distribution transformers currently used by major Australian manufacturers are based on highly customised in-house developed software packages. The results of routine electrical and mechanical calculation performed by software are hundreds (and in some cases thousands) of solutions which, would satisfy the electrical and other input requirements. The whole design process is actually being reduced to selecting an economically optimised product (from manufacturer's point of view) from that huge pool of solutions. The cost calculation module, which is included in the design software package, calculates both direct manufacturing costs as well as other add-on costs (overhead, mark-up and shipment costs). A theoretical analysis of technique behind a typical costing module based on Lenasi (1981) is presented.

Input data for cost calculations are grouped into two sets:

- external input parameters provided by the customer (tender data, such as kVA rating, range of losses, cost of losses, expected service conditions, desired transformer life, accessories and note about compliance of the product with relevant standards - in most cases this note clarifies requested specific performances over and above the Australian Standard requirements);
- internal parameters defined be the design and manufacturing processes and material prices.

Figure 3 presents a cross-section area of a typical three-phase core-type distribution transformer. LV parameters are defined by index “1” and HV parameters are defined by index “2”, whilst index “3” refers to distances between two windings. Transformer kVA rating defined by LV parameters is:

$$P_{nom} = 3 \times U_{ph1} \times I_{ph1} \tag*{[1]}$$

Equation [1] could be developed into the following relation:

$$P_{nom} = A_1 \times a \times b \times B \times g \times D^2 \tag*{[2]}$$

where, A_1 is a constant which includes frequency, space factor for transformer core, space factor for LV windings and a connection factor (dependant on the type of winding connections; i.e. star, delta or “interconnected star”).

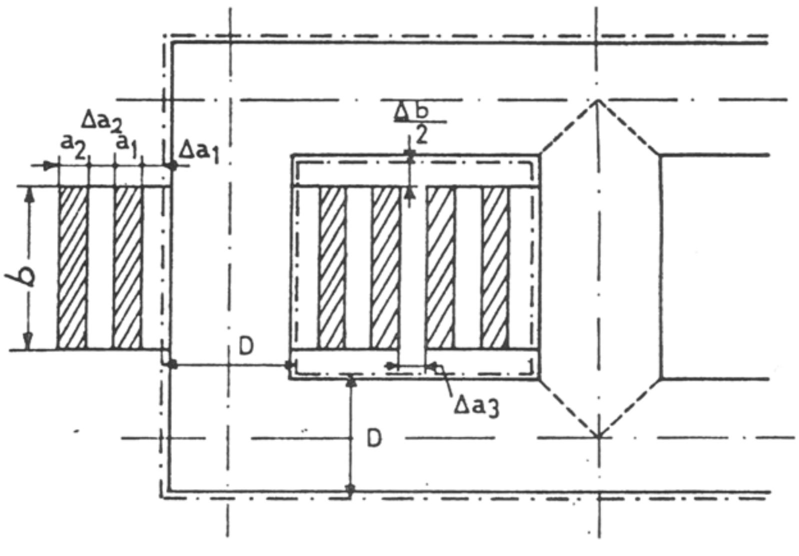

FIGURE 3 - TYPICAL THREE-PHASE CORE-TYPE DISTRIBUTION TRANSFORMER

Equation [2] is the starting point in the cost optimisation process of a distribution transformer. It includes five independent variables:

- width of LV winding - a
- electrical hight of windings - b
- magnetic flux density - B
- current density in LV winding - g
- core diameter - D.

Transformer rating P_{nom} does not change in the cost optimisation process.

The cost of the active part C, includes cost of the core C_{Fe} and cost of the conductors C_{Cu}, (assuming that winding material is copper).

$$C = C_{Fe} + C_{Cu} \tag{3}$$

The cost of the core is a function of its dimensions (i.e. size of the winding window and the core diameter):

$$C_{Fe} = \left(A_2 \times b + A_3 \times a + A_4\right) \times D^2 + A_5 \times D^3 \tag{4}$$

where the constants A_2 to A_5 include cost of the core steel, core space factor and specific mass of steel laminations; winding space factor and connection factor; ratio of current densities in LV and HV windings and selected insulation distance between (i.e. related to the particular Basic Insulation Level - BIL).

Similarly, the cost of windings is

$$C_{Cu} = \left(A_6 \times D + A_7 \times a + A_8\right) \times a \times b \tag{5}$$

The constants $A_{6,}$ A_7 and A_8 are related to the above factors as well as the cost of conductor material and the specific mass of the conductor material.

The cost optimisation problem is related to minimisation of the total cost C in Equation 3.

This could be described by additional three conditions, which define required load losses P_{SC}, no load losses P_{NLL} and short circuit voltage u_{SC} (Equations [6], [7] and [8]).

The load losses at 75^{0}C could be calculated as:

$$P_{SC} = \left(A_9 \times D + A_{10} \times a + A_{11}\right) \times a \times b \times g^2 \qquad [6]$$

The constants A_9 to A_{11} include factors related to additional stray losses, which could also be separately calculated or estimated based on previous similar designs.

The no load losses could be presented as:

$$P_{NLL} = \left(A_{12} + A_{13} \times B + A_{14} \times B^2\right) \times \frac{C_{Fe}}{k_{Fe}} \qquad [7]$$

where k_{Fe} is the cost of the core material (\$/kg). The first part of Equation [7] represents specific no load losses as a parabolic function of magnetic flux density *(B)*. The constants A_{12} to A_{14} are closely related to features of the core material and quality of the core manufacturing processes.

Requirements for short circuit voltage u_{SC} could be converted into requirements for inductive reactance u_{XN} (as the resistive component of u_{SC} has already been defined by load loss requirements).

$$u_{XN} = \frac{A_1 \times a \times g}{B \times D^2}\left(A_{15} \times D + A_{16} \times a \times D + A_{17} \times a + A_{18} \times a^2 + A_{19}\right) \qquad [8]$$

The above constants include number of sensitive design factors, such as the factor for "interconnected star" connection and the Rogowski factor (which is a function of winding dimensions (*a* and *b*) and also could be defined as a constant for a range of design options).

Equation [3] could be written as

$$C = C(a, b, D) \tag{9}$$

and the additional conditions in Equations [2], [6], [7] and [8] could be expressed as a set of non-linear algebraic Equations:

$$\begin{aligned} \Phi_1 &= P_{nom}(a, b, g, B, D) - P_{nom} = 0 \\ \Phi_2 &= P_{SC}(a, b, g, D) - P_{sc} = 0 \\ \Phi_3 &= P_{NLL}(a, b, B, D) - P_{NLL} = 0 \\ \Phi_4 &= u_{XN}(a, g, B, D) - u_{XN} = 0 \end{aligned} \tag{10}$$

In principle, the minimum of the function *C,* under conditions [10], could be solved using Lagrange method. However, this method has some practical problems, as the matrix Equation contains mixed differentials. There is a possibility that the errors are not easily detectable and that the matrix (9x9) does not always converge.

Another, undesirable outcome of this theoretical approach is a possibility that the full theoretical solution might hide dependency of the total cost *C* on the core diameter *D*. Consequently, a modified approach is proposed, where the cost minimisation problem is reduced from nine variables to five variables (*a, b, g, B* and *D*) and the four additional conditions become constants (P_{nom}, P_{SC}, P_{NLL} and u_{XN}). If the core diameter *D* is chosen to be a major variable the minimisation problem is reduced to finding solution for system [10] for a range of discrete values for the core diameter *D*. It should be noted that if another variable is chosen to be a discrete independent variable (e.g. flux density *B*) the system does not always provide technically acceptable solutions. The modified system of Equations [10] could be solved using Newton-Raphson iterative method providing a set of minimum costs for a range of technically acceptable designs.

If X is a column-vector consisting of *a, b, g* and *B,* the iterative method is as follows:

$$X_{k+1} = X_k - \Phi'^{-1}_k \times \Phi_k \qquad [11]$$

The inverse matrix Φ'^{-1} is (4x4). The system [11] quickly converges in all cases. The initial value for the core diameter D_0 is selected on the basis of verified similar designs:

$$D_0 = d_0 \times \sqrt[4]{P_{nom}} \qquad [12]$$

Iterations in system [11] are terminated when the error *R* reaches value:

$$R = \sum_{1}^{4} \Phi_{ir}^2 \leq \varepsilon_1 \qquad [13]$$

where Φ_{ir} represents relative difference from respective nominal values. The initial conditions a_0, b_0, g_0 and B_0, together with D_0 would provide the initial cost C_0. If the core diameter is increased in steps

$$\Delta D_0 = \Delta d_0 \times \sqrt[4]{P_{nom}} \qquad [14]$$

a new set of costs C_i is calculated. When $C_{j+1} > C_j$, the value for ΔD_n is reduced and multiplied by (-1):

$$\Delta D_{n+1} = -\Delta D_n / n \qquad [15]$$

In such a way, the iterations calculate the costs which oscillate around the absolute minimum until

$$D_k \leq \varepsilon_2 \times \sqrt[4]{P_{nom}} \qquad [16]$$

The constants ε_1 and ε_2 are predetermined acceptable iteration errors.

It should be noted that the calculated minimum manufacturing costs do not always present a satisfactory solution if the selected constants (e.g. for stray losses, space factors, etc) significantly vary from actual values. Consequently, if a high accuracy is required, this method is only recommended for engineering analysis based on efficiency level approach, e.g. optimisation of existing distribution transformer designs. In such cases, the initial values for constants used in calculations could be determined from tests and measurements on actual products which undergo optimisation procedure.

In addition to engineering analysis, this method is widely used in research and development of large power transformers where interdependencies between various variables are investigated. This cost calculation method is particularly suitable for preparation of tenders and it could be used for development of stand-alone transformer design applications.

It is possible to extend this method to the following applications:

- distribution transformers with multiple coils per winding;
- single phase transformers;
- distribution transformers which utilise both aluminium and copper as conductor materials (e.g. aluminium foil in LV winding and rectangular or round copper wire in HV winding);
- different configurations of magnetic circuits (i.e. round, rectangular and oblong transformer cores);
- calculation of minimum costs for the whole transformer (including non-active components, such as cooling and insulation systems).

If transformer employs different conductor materials in LV and HV windings, a new independent variable (ratio of current densities in LV and HV windings) should be introduced.

An interesting application of this method is in cost optimisation of distribution transformers with rectangular and oblong cross section of the core. In this case, instead of one variable core diameter *D*, two variables (width and length for rectangular cross sections and diameter and length for oblong cross sections are needed). There are two cost calculation methods available for this case:

- a slow, but reliable method largely based on principles previously described in this section;
- a very attractive and efficient method of "fast slope" which is also applicable for distribution transformers with two materials; a drawback of this method is possibility to be trapped in a local minimum, however if an existing design is being optimised, this limitation becomes much less important.

4.5.2. Costing Structure

The total distribution costs are calculated using a model presented in Figure 4. A standard method of cost accounting to determine the costs associated with manufacturing includes production and non-production costs. These are combined to determine the full cost of a product. The estimates of the costs listed in Figure 4 were obtained from Australian manufacturers, based on average material and labour prices in period 2002-2004. This analytical method included the profit margin associated with the product. That margin is generally added to the full cost of product. In consultation with manufacturers about the input costs of materials, the calculation method was developed in such a way that it reflected the final marked-up sales price (i.e. not just the manufacturer's direct costs). The final cost included all handling factors, scrap factors and all overhead costs.

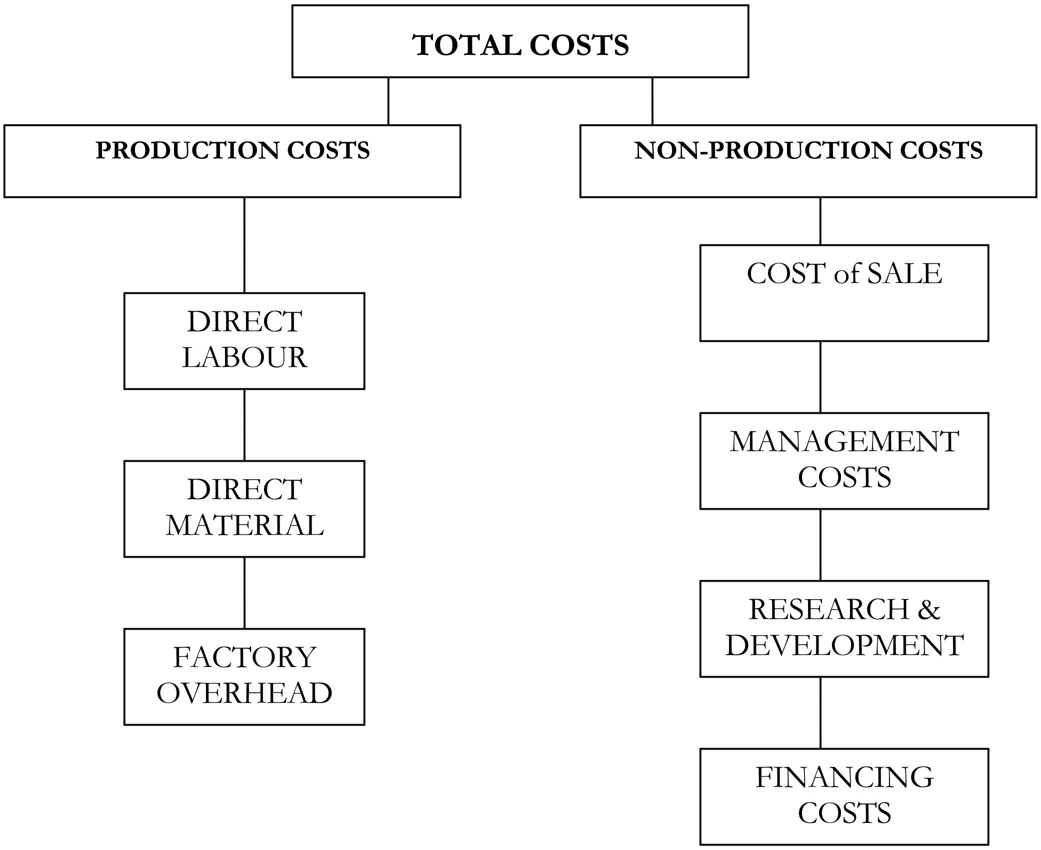

FIGURE 4 - FULL COST OF DISTRIBUTION TRANSFORMER

4.6. Engineering Analysis – Case Study

The presented case study explores relationships between costs and energy efficiency for a range of typical 1,500 kVA oil-immersed distribution transformers (11/0.433 kV) developed for Australian utility market. The analysis includes existing and proposed (optimised) design solutions as presented in Table 6:

TABLE 6 – 1,500 KVA TRANSFORMER - DESIGN OPTIONS UNDER CONSIDERATION

Design Options	No Load Losses [W]	Load Losses [W]	Total Losses [W]	Efficiency at 50% Load	Total price*
Option 1	1,950	10,840	12,790	99.38%	$27,390
Option 2	2,280	11,234	13,514	99.33%	$27,100
Option 3	1,870	9,950	11,820	99.42%	$28,900
Option 4	2,400	11,380	13,780	99.31%	$27,145
Option 5	1,890	12,100	13,990	99.35%	$27,123
Option 6	1,950	8,960	10,910	99.44%	$29,310
Option 7	2,120	12,700	14,820	99.30%	$25,999
Option 8	2,200	10,200	12,400	99.37%	$27,291

*) The total selling price does not include the Goods and Services Tax (GST).

4.6.1. Typical Technical Data

Tables 7 and 8 present design information and an extract from Bill of Materials (BOM) for design Option 2. This transformer utilises M3 core steel and Aluminium conductors (Aluminium foil for LV winding and aluminium rectangular wire for HV windings). It has relatively high no load losses of 2,280 W. Better quality “95 grade” magnetic core steel would reduce the core losses by approximately 25%, however this steel is 30% more expensive. The load losses of 11,234 W are approximately at an average level for this selected group of design lines.

For the purpose of this analysis the above design options do not include any accessories, which would normally be specified by end users (depending on service conditions and tender requirements).

Table 7 – Design data for 1,500 kVA transformer - Option 2

DESIGN DATA

RATING	1,500	kVA		50	Hz		3	phase		
HV	11,000	V	D		conn	HV AMPS			79	
LV	433	V	y		conn	LV AMPS			2,000	
Core Diameter	249 mm	1,515 kg	Limb area		435 mm^2					
Leg Height	678 mm		Limb Flux		1.7271 T	No Load Loss			2,280	Watts
Leg Pitch	510 mm		Yoke Flux		1.7271 T	Load Loss			11,234	Watts
Diameter	249 mm		Sound Level		66.92 dB	Ez			5.86%	
Steel	95 Grade					TOTAL LOSS:			13,514	Watts

MAX Tap	10	%			Length		1,580	mm		
MIN Tap	7.5	%			Width		560	mm		
In Steps Of	2.5	%			Height		1,502	mm		
NO Of Tap Pos	8				Oil		1,650	litres		
LV Turns	15	15	Layers		HV Turns		726		23	Layers
MATERIAL	Al	Foil			MATERIAL		Al	2x Sec Wire		
Size	640	x	2.2		SIZE		9.5	x		2.36
Weight	161	kg			Weight		359	kg		
Current Density	1.42	A/mm^2			Current Den		1.01	A/mm^2		
Conductor Insulation	0	mm			Cond. Ins		0.2	mm		
Ducts	2	off	3 mm		Ducts		1	off		3 mm

Gradient	10	°C			Gradient		11	°C		
HV Rise	61.8	°C			HV Rise		62.5	°C		
Mean Oil Rise	50	°C								
Eddy	2.1				Eddy		7.1			

Dual Insul.		LV ID	255 mm					HV ID		361.4 mm
Inter Layer Insulation	0.3 mm	AD	640 mm			0.1 mm		AD		636 mm
		RD	45.2 mm					RD		71.8 mm
		WEIGHT	161.3 kg					Weight		358.9 kg
eo	16.7	V/turn				V stress			1,055	V/layer-layer

							FULL		.5 or .67	0.33
Connection Factor	3.86048		Inter layer Ins				1		2	3
alpha	0.96346		Paper per Layer				2		0	0
Core Build Factor	25.78598		Impulse Layer				2		0	0

Risers	88.5x	9.5			MATERIAL	Al		79.8 kg		2.4 A/mm^2
Busbars	80x	10			MATERIAL	Cu		21.3 kg		2.5 A/mm^2
Flexibles	70x	0.3		32	Leaves			5.4 kg		3.0 A/mm^2

Bush Stems					DELTA LEADS				2.6	
Bush Palms					TAPCH LEADS				2.6	
Bush Leads	4									

Table 8 – Bill of Materials for 1,500 kVA transformer - Option 2

COSTING

CORE		Quantity	Unit Price	Subtotal
Core Steel	kg	1,515	$3.48	$5,272
Scrap Factor	8%	121.2	$3.48	$422
Core Clamps	each	1	$450.00	$450
				$6,144
WINDINGS				$0
LV Cond. + 6%	kg	161	$6.50	$1,109
HV Cond. + 2.5 %	kg	359	$8.00	$2,944
S/F Bars	set	1	$75.00	$75
Insulation	set	1	$515.00	$515
				$4,643
TANK				
Tank	each	1	$1,290.00	$1,290
Radiators	each	45	$8.00	$360
Paint	each	1	$75.00	$75
Oil	l	1,650	$0.77	$1,271
				$2,996
ACCESSORIES				
Tapchanger	each	1	$250.00	$250
LV Bushings	set	1	$450.00	$450
HV Bushings	set	1	$105.00	$105
Wheels/Skids	set	0	$350.00	$0
Expl'n Vent	each	1	$75.00	$75
Wind. Thermometer	each	0	$1,890.00	$0
Marshalling Box	each	0	$350.00	$0
Rad. Isol. Valve	each	1	$150.00	$150
Misc. Material				$150
				$1,180
Total Material				**$14,963**

LABOUR				
Core	hours	18	$28.00	$504
Windings	hours	30	$28.00	$840
Tanking	hours	30	$28.00	$840
Fabrication	hours	65	$28.00	$1,820
Accessories	hours	0	$28.00	$0
Total Labour		**143**		**$4,004**

Material		$14,963	56.3%
Labour		$4,004	15.1%
Manufacturing		**$18,967**	71.4%
Overhead	12%	**$2,276**	8.6%
Delivery			0.0%
Gross Margin	25%	**$5,311**	20.0%
TOTAL PRICE		**$26,553**	

Figure 5 presents costing structure for Option 2 distribution transformer.

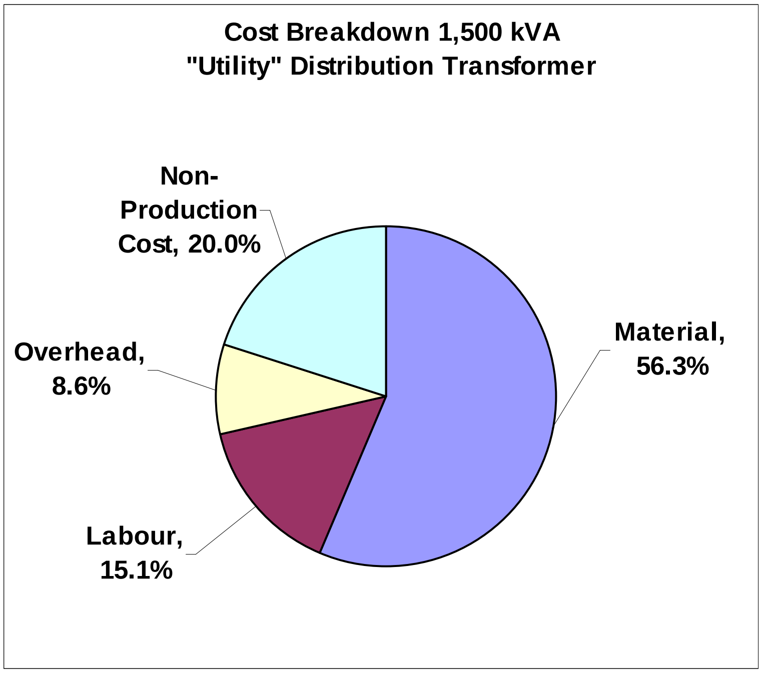

FIGURE 5 - COSTING STRUCTURE FOR 1,500 KVA "UTILITY" DISTRIBUTION TRANSFORMER - OPTION 2

4.7. Cost Efficiency Schedules

The main purpose of the engineering analysis is to identify the relationship between distribution transformer costs and energy efficiency levels, which is often referred to as a cost-efficiency schedule. Figure 6 shows such a relationship for the above design options for a limited range of typical 1,500 kVA distribution "utility" transformers. The presented cost efficiency schedule includes the total selling price. This is the preferred assessment approach from customer's point of view as this analysis often includes assessment of distribution transformers from different manufacturers. However, from manufacturer's point of view an alternative method, which includes only production costs (direct material, direct labour and factory overheads), could be seen as more appropriate for cost-efficiency assessment. In this case impact of non-production (fixed) costs is relatively easy assessable and a full focus on production costs only could help manufacturers to define possible course of action in improving design solutions (e.g. to identify which costs would sharply increase for a marginal increase in efficiency).

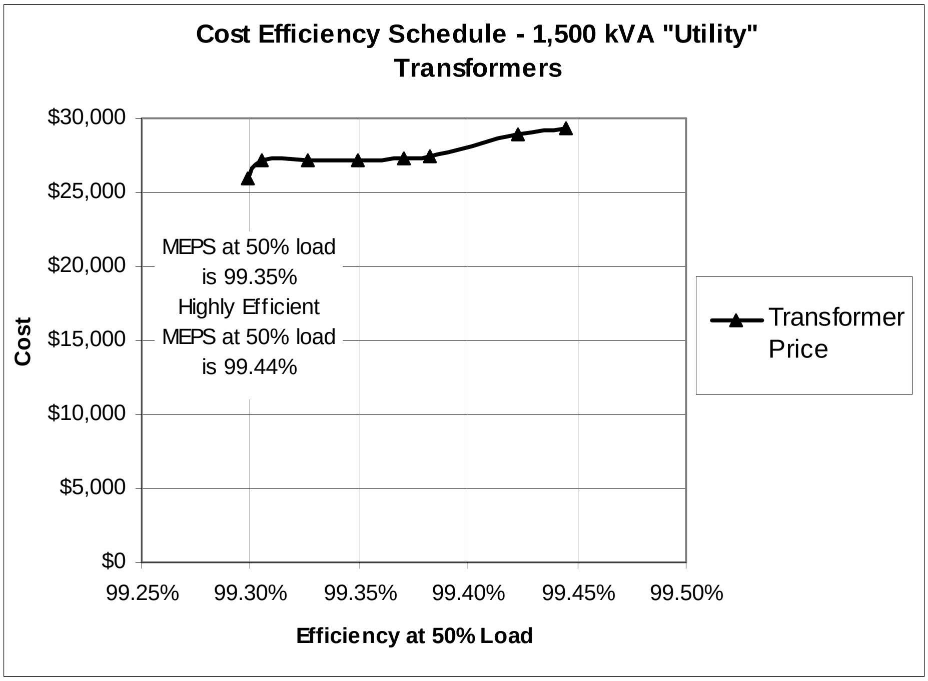

FIGURE 6 - COST EFFICIENCY SCHEDULE FOR A RANGE OF 1,500 KVA “UTILITY” DISTRIBUTION TRANSFORMERS

Figure 7 presents another version of the cost efficiency schedule where in addition to the distribution transformers’ prices, the Total Operating Costs (TOC) are included. The TOC in Figure 7 are calculated by summing the transformer prices and relevant costs of losses (based on unit costs of $1.80/W for Load Losses and $6.30/W for No Load Losses). The TOC will be discussed in more details in Chapter 6.

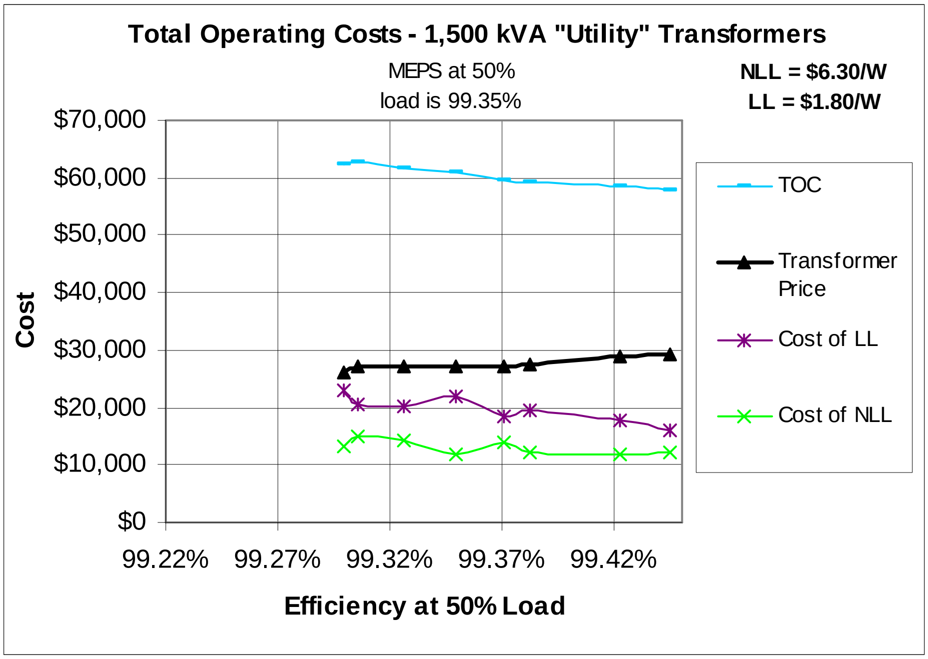

FIGURE 7 - TOTAL OPERATING COSTS FOR A RANGE OF 1,500 KVA “UTILITY” DISTRIBUTION TRANSFORMERS

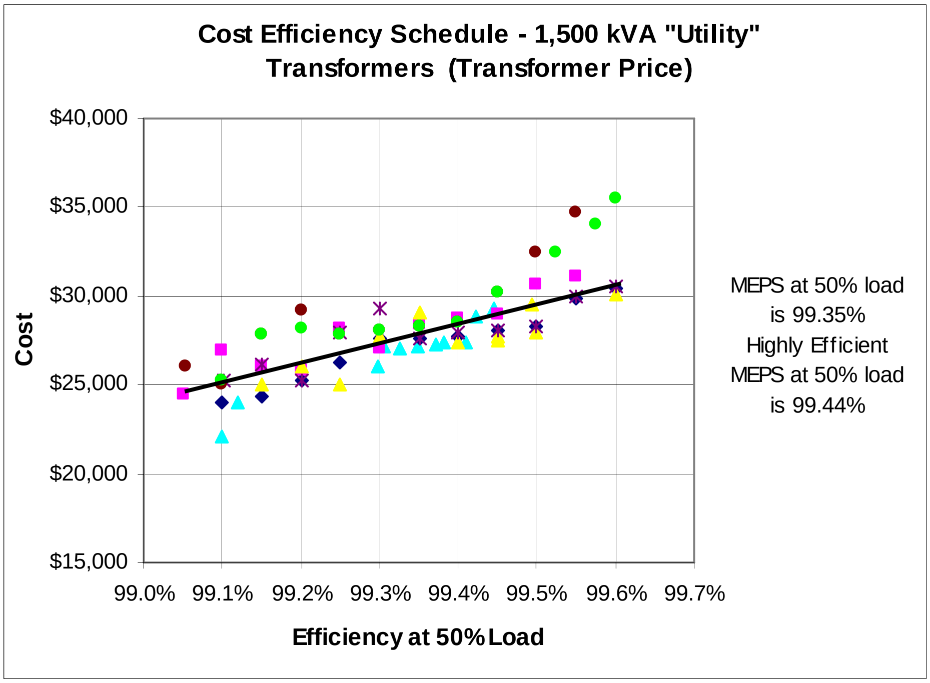

FIGURE 8 - TYPICAL COST EFFICIENCY SCHEDULE FOR A FULL DESIGN RANGE OF 1,500 KVA “UTILITY” DISTRIBUTION TRANSFORMERS

Figure 8 presents a cost efficiency schedule for a range of 1,500 kVA distribution transformers. This schedule was created during the design optimisation process where hundreds of designs are being produced. The solid line represents a trend-line based on a polynomial function of second order.

4.8. Simple Assessment Methodology

A simplistic approach to assessment of distribution transformers would start with this scatter plot, where all available (or offered) design options are classified into three categories:

- Category 1 - designs high above the trend line (prices/costs higher than average for a given efficiency level);
- Category 2 - designs on or very close to the trend line (average prices/costs);
- Category 3 - designs below the trend line (prices/costs lower than average).

The next step in the assessment process involves investigations related to number of design options in each category and relative impact of design options farthest from the trend-line on the trend-line itself.

Although, an obvious choice for a distribution transformer design would be one of more designs from Category 3 (in this category, for a given efficiency level or efficiency range, the costs/prices are below the average), it is recommended to thoroughly review these designs to ensure that the offered design solutions are compatible with specified requirements (i.e. to exclude non-standard dimensions, components and materials). It is reasonable to expect that the chosen designs for relatively low efficiency requirements are from Category 3 and the optimal designs for high efficiency requirements are from

Category 2. A comparative analysis of plotted cost efficiency schedules for design solutions from different manufacturers would be very useful in the initial assessment of their respective offers.

The above cost efficiency analysis could be applied for a full range of distribution transformers under consideration (e.g. for discrete ratings in the range 15 – 2,500 kVA). The range of ratings could be the full range from the tender or the range of ratings already employed by the user. As this analysis is a very laborious and time consuming task a simplified approach is proposed as follows:

- distribution transformers are classified in the kVA rating groups;
- a representative rating for each group is chosen;
- each representative rating is fully assessed on number of parameters;
- remaining kVA ratings in each group are assessed applying an appropriate scaling factor to the relevant parameters of the representative rating.

4.8.1. Rating Groups and Representative kVA Ratings

The scope of work for this research includes oil immersed distribution transformers (three-phase) in the range 150 – 2,500 kVA. There are several possible classifications and groupings for distribution transformers in this range based on size (small, medium, large, very large), application (pole mounted, ground mounted, pad-mounted/enclosed, indoor), service conditions, loading, etc.

The proposed kVA rating groups and representative respective kVA ratings for pad-mounted distribution transformers are presented in Table 9.

TABLE 9 - RATING GROUPS AND REPRESENTATIVE KVA RATINGS

Rating Group	Rating Range	Representative Design
Group 1	300 kVA – 630 kVA	500 kVA
Group 2	750 kVA – 1,000 kVA	1,000 kVA
Group 3	1,250 kVA – 2,000 kVA	1,500 kVA

The selection for rating range is based on obvious similarities in engineering design and construction principles (including some electrical parameters such as impedance and current density, transformer dimensions, thermal performances, commonly used winding materials and size of enclosures).

The chosen representative designs are most commonly used kVA ratings in Australia and after applying appropriate scaling factors these representatives should reasonably well correspond to less common ratings (200, 400, 800, 2000 and 2,500 kVA) and some unusual ratings in Australia (315, 630, 1,250, 1,600, 1,750 and 2,250 kVA)

It has to be noted that "very large" distribution transformers (e.g. 2,500 kVA and above) require specially developed assessment techniques. Although these distribution transformers are manufactured on the same principles as smaller distribution transformers, these non-standard products are produced in very limited numbers and for special applications and service conditions. As they are at the extreme end of the rating range, these distribution transformers do not fit very well into "scaling factor techniques".

4.8.2. Scaling Factors

As discussed in the previous section, the simplified assessment methodology is based on selecting representative kVA ratings within rating groups, and extrapolating the results of the engineering analysis from the representative units within their respective kVA rating groups.

The scaling factors are based on mathematical relationships that exist between the kVA ratings and the physical size, cost, and performance of distribution transformers within the same kVA rating group. For example, the fact is that larger transformers are more efficient, i.e. they have lower percentage losses than smaller units with similar other electrical characteristics (voltage, BIL, etc.). The "size-electrical performance" relationships come from Equations which describe fundamental correlations between transformer's basic parameters (CIGRÉ, 2003 and TSD, 2004).

It is well known that for the fixed kVA rating and frequency of distribution transformer, the product of its conductor current density, core flux density, core cross-sectional area, and total conductor cross-sectional area is also constant.

For a distribution transformer with a fixed frequency, magnetic flux density, current density, and BIL rating any change in the kVA rating is possible only if the core cross-section and the core window area change. Consequently, increase in the kVA rating is proportional to increases of height, width, and depth of the core and windings. Analysis of this scaling relationship, which is presented in Appendix 4, confirms that there are non-linear interactions between distribution transformer kVA ratings and its dimensions:

- Transformers linear dimensions vary as the ratio of kVA ratings to the ¼ power;
- Cross sectional areas vary as the ratios of kVA ratings to the ½ power;
- Volumes vary as the ratio of the kVA ratings to the ¾ power.

The last of the above relationships (between kVA ratings and volumes) which is characterised by the power of ¾ or 0.75 is responsible for the well-known "0.75 scaling rule" theory (CIGRÉ, 2003). Table 10 presents the most commonly used scaling relationships in distribution transformers. The respective values for scaling factors in columns "Relative to kVA rating" and "Relative to length L" show clearly the ¼ power relationship between kVA rating and a reference linear dimension - length.

TABLE 10 - SCALING RATIOS FOR DISTRIBUTION TRANSFORMERS

Quantity	Relative to kVA rating	Relative to length L
Rating	-	$(\text{Length})^{4}$
Weight	$(\text{kVA rating})^{3/4}$	$(\text{Length})^{3}$
Cost	$(\text{kVA rating})^{3/4}$	$(\text{Length})^{3}$
Length	$(\text{kVA rating})^{1/4}$	-
Width	$(\text{kVA rating})^{1/4}$	-
Height	$(\text{kVA rating})^{1/4}$	-
Total Losses	$(\text{kVA rating})^{3/4}$	$(\text{Length})^{3}$
No-load losses	$(\text{kVA rating})^{3/4}$	$(\text{Length})^{3}$
Exciting Current	$(\text{kVA rating})^{3/4}$	$(\text{Length})^{3}$
% Total loss	$(\text{kVA rating})^{-1/4}$	$(\text{Length})^{-1}$
% No-load loss	$(\text{kVA rating})^{-1/4}$	$(\text{Length})^{-1}$
% Exciting Current	$(\text{kVA rating})^{-1/4}$	$(\text{Length})^{-1}$
% R	$(\text{kVA rating})^{-1/4}$	$(\text{Length})^{-1}$
%X	$(\text{kVA rating})^{1/4}$	(Length)
Volts/turn	$(\text{kVA rating})^{1/2}$	$(\text{Length})^{2}$

The ¾ scaling rule can be used to estimate the losses of all transformers in a kVA rating group based on the losses of a representative unit. Application of this rule requires that the transformers are of the same type and they have the same voltage, core material, core flux density and conductor current density. In that case, theoretically, the physical proportions, the eddy losses proportions and the insulation space factors of all transformers in particular kVA rating group are all essentially constant (within a reasonably narrow range of kVA ratings).

In practice, however, for some design groups (especially pad mounted distribution transformers) sometime is very difficult to keep the above proportions constant and consequently, there are deviations from the ¾ scaling rule. The most common inconsistency is the scaling factor for the cost. CIGRÉ (2003) notes a scaling factor of 0.5 - 0.6 for power transformers:

$$Cost_2 = Cost_1 \left(\frac{kVA_2}{kVA_1} \right)^{0.5-0.6} \qquad [17]$$

The author has analysed hundreds of designs for distribution transformers for pad mounted substations and the most appropriate scaling factor for costs is 0.65-0.70.

More detailed analysis of distribution transformers' scaling factors is presented in Appendix 4.

5. CAPITALISATION OF DISTRIBUTION TRANSFORMER LOSSES

5.1. Background

Australian electrical utilities are under continuing pressure to operate their networks more efficiently and to reduce the total real running costs of their assets. Those ultimate goals could be achieved by investments in predictive maintenance, development of analytical asset management methodologies and introduction of effective investment strategies based on life cycle concepts. Although the current trends towards investments in products and services rather than system capacity will help utilities to compete in new deregulated electricity markets, there is an urgent need for long-term capital investments in high-quality equipment to ensure the reliable and cost effective supply of electricity. The most economical solutions are often in contradiction with the best possible technical practices and/or locally approved traditional methods. There are additional requirements: i.e. the need to meet environmental commitments such as managing emissions of greenhouse gases in conformance with various global and local environmental regulations. Consequently, the selection of some electrical equipment and design of electrical distribution systems has become more complex.

This chapter deals with current practices of Australian electrical utilities in selecting electrical distribution transformers. The distribution transformer is the most important single piece of electrical equipment installed in electrical distribution networks with a large impact on the network's overall cost, efficiency and reliability. Selection and acquisition of distribution transformers which are optimised for particular distribution network, utility's investment strategy, network's maintenance policies and local service and loading conditions will provide definite benefits (improved financial and technical performance) for both utilities and their customers.

There are numerous reasons, which prevent distribution transformers in Australia from being standardized and catalogued products. The most obvious ones are significant differences between regional utilities in required voltage ratios, tapping ranges, loss factors, short circuit impedances, dimensions, accessories and most importantly loading and service conditions. The compatibility with existing apparatus often imposes additional restrictions on design and selection of distribution transformers. For example, requirements to meet particular bushing arrangement to match existing switchgear and layout of connecting cables could significantly affect the final price and thus shifting the focus from relevant (but in this case financially less important) technical performances. In the last 20 years the Australian practices for the selection of distribution transformers have been simplified and reduced to two steps:

- compliance with basic technical details outlined in the tendering documents;
- capitalisation of transformer losses.

The second step has been further simplified by applying one formula and one set of evaluation coefficients for the assessment of total operating costs for all distribution transformers under all service and loading conditions. A number of Australian electrical utilities currently use the loss capitalisation formula, which has been taken from the AEEMA/ESAA specification for polemounting distribution transformers (AEEMA/ESAA, 1998). This chapter presents the critical analysis of that method and recommends its extension by introduction of various additional evaluation factors. The presented material deals with oil-immersed ONAN cooled distribution transformers 150 –

2,500 kVA, rated up to 33 kV and could be easily extended to other types of distribution transformers.

5.2. Loss Capitalisation Formulae

In the mid 1970's the sharply increased cost of electrical energy forced Australian electrical utilities to recognize the critical importance of the cost of electrical losses. The electrical utilities developed various methods for the evaluation of electrical losses (Howe, 1993). Unfortunately, some of those methods have not been later updated to fully implement modern life cycle concept methodologies. Disaggregation of vertically structured electrical utilities and their subsequent partial privatisation has significantly affected the balance of technical and economic considerations in their transformer purchase decisions. In order to reduce short-term capital constraints and to meet shareholders expectations, preferences had been given to distribution transformers with lower initial capital costs (and intrinsically with higher losses).

The most widely used method for the evaluation of distribution transformers in Australia is the Total Operating Cost (*TOC*) method. The TOC method proposes that in purchasing of any item of plant or equipment the following two costs have to be considered:

- the initial capital cost (*FC*);
- the operating cost (cost of losses).

$$TOC = FC + K_{NLL} * NLL + K_{LL} * LL \quad [18]$$

where

K_{NLL} is No-Load Loss evaluation factor [\$/W], K_{LL} is Load Loss evaluation factor [\$/W], NLL is No-Load Loss at nominal voltage [W] and LL is Load Loss at 75^0C [W].

As a general rule, transformers with lower losses use more and/or better materials for their construction and thus cost more. The evaluation process becomes essentially a comparison between two types of transformer designs: high loss / low cost design versus low loss / high cost designs.

It is extremely important that the absolute values of loss evaluation factors K_{NLL} and K_{LL} are calculated accurately. They could significantly influence the minimum of the TOC function as all gains in relatively low capital costs could be marginalized by extremely high running costs (as a consequence of unrealistically high loss evaluation factors) and vice versa. Unfortunately, the tools required to determine the loss evaluation factors are quite complex and some Australian utilities use less rigorous methods or adapt coefficients already developed for similar applications. For example, there is a widely adopted practice in using loss evaluation factors from AEEMA/ESAA (1998) specification for polemounting distribution transformers for assessment of all distribution transformers.

5.2.1. Determination of Loss Evaluation Factors

The ESAA/AEEMA (1998) proposes the following values for loss evaluation factors for distribution transformers of 100 kVA and above: K_{NLL} = \$6.30/W and K_{LL} = \$1.80/W. Unfortunately, the ESAA/AEEMA (1998) does not provide information about methods used in determining these coefficients and the applied loading considerations.

The calculation of loss evaluation factors depends on the type of transformer being considered, its size and service and loading conditions. In addition to the inflation rate, interest rate and cost of capital there is a need to consider changes of above factors during the expected transformer life (25-30 years). Finally, there are slight differences in assessing a distribution transformer operated by an industrial/commercial owner and a distribution transformer operated by an electrical utility. The latter is more complex because of daily and seasonal load variations and possibilities of a load growth. The unpredictability of the deregulated electricity market adds more uncertainties in the process of transformer loss capitalisation. The performances of distribution companies in energy trading and abilities in predicting future trends could significantly influence the calculation of loss evaluation coefficients.

The loss evaluation factors K_{NLL} and K_{LL} widely used by Australian electrical utilities could be reconstructed from the following Equations:

$$K_{NLL} = f * \left(p + 8760 * q\right) \qquad [18]$$

$$K_{LL} = f * D^2 * (p + 8760 * q * LLF) \qquad [19]$$

and based on the following assumptions:

f is capitalisation factor:

$$f = \frac{(1+r)^n - 1}{r(r+1))^n} \qquad [20]$$

where r is the interest rate (6.25%), t is the expected transformer life (25years). The demand factor D is the ratio between the maximum demand and the transformer rated power (0.85).

The load factor LF is the ratio of the average transformer load to its maximum demand

(0.30). The annualised charge per kW of maximum demand (*p*) is estimated at $102/kW and the energy cost *q* is $0.05/kWh.

The loss load factor *LLF* could be calculated as follows:

$$LLF = aLF + bLF^{2} \tag{21}$$

where coefficients *a* and *b* depend on the relative contribution from load losses and no load losses (normally for distribution transformers, these coefficients are as follows:

$$a = 0.3 - 0.5, b = 1 - a \tag{22}$$

Relationship between loss load factor LLF and load factor LF is graphically presented in Figure 9 (Franklin, 1993). It includes boundary curves where either *a* or *b* is 0 and a typical curve for *a=0.3* and *b=0.7*.

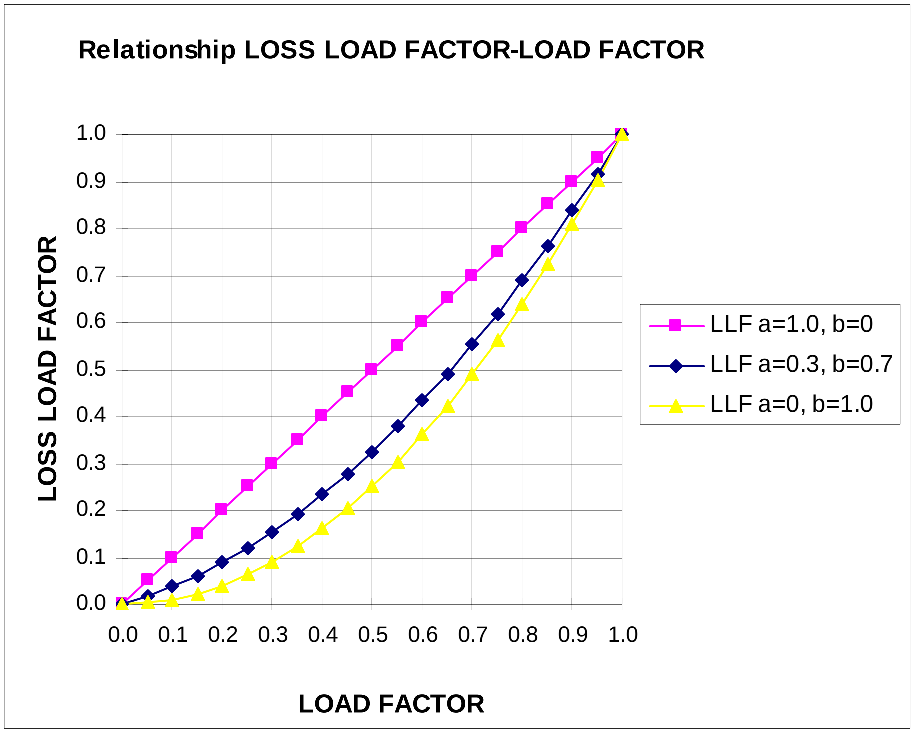

FIGURE 9 - RELATIONSHIP BETWEEN LOSS LOAD FACTOR *LLF* AND LOAD FACTOR *LF*

Applying the above relations and assumptions: K_{NLL} = \$6.30/W and K_{LL} = \$1.80/W. Table 11 presents the approximate range and the most commonly used values for loss evaluation factors K_{NLL} and K_{LL}. A more detailed assessment of AEEMA/ESAA loss evaluation factors is given in Appendix 5.

TABLE 11- TYPICAL LOSS EVALUATION FACTORS (IN 2000 A$)

Country	**K_{NLL} [A\$/W]**		**K_{LL} [A\$/W]**	
	Range	**Nominal**	**Range**	**Nominal**
India		**5.80**		**1.00**
Vietnam	8.00-10.50	**9.00**	1.00-4.00	**2.50**
China		**7.50**		**2.50**
Thailand		**6.00**		**3.00**
Indonesia		**5.00**		**3.00**
Philippines		**15.00**		**6.00**
USA	4.50-7.50	**6.00**	1.50-3.50	**2.00**
Germany	7.00-10.00	**10.00**	1.50-8.00	**4.00**
UK	5.50-10.00	**7.50**	1.00-2.00	**1.50**
Australia	5.00-7.20	**6.30**	1.20-2.50	**1.80**

5.2.2. Impact of Load Factor on Loss Evaluation Factors

Equation [21] will utilise coefficients $a=0.5$ and $b=0.5$ if the daily loading diagram is similar to that as shown in Figure10. The load is shown as percentage of the transformer rated power. This loading diagram could be adequate for a typical application with a lightly loaded pole mounted transformer. However, where a complex loading pattern is required (including daily and seasonal peaks, short overloads, etc.) a slightly modified approach should be used.

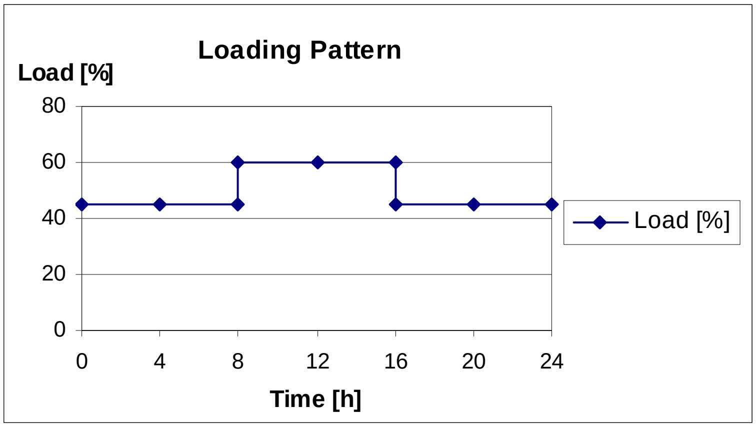

FIGURE 10 - SAMPLE DAILY LOADING DIAGRAM

Figure 11 shows variations in the load factor *LF* and the loss evaluation factor K_{LL} when non-peak load has been changed over a range from 10% of the transformer rated power to the full maximum demand equal to 120% of the transformer rated power.

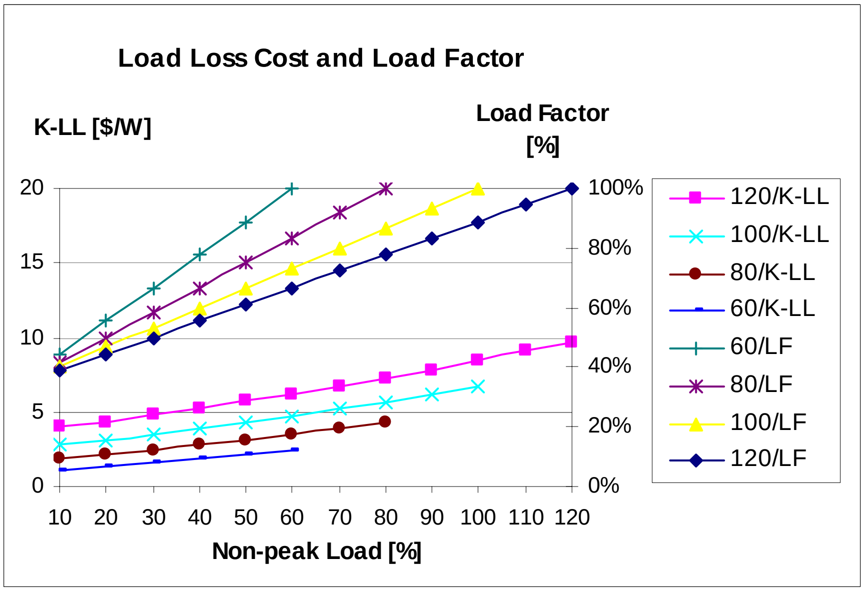

FIGURE 11- FACTOR K_{LL} AND LOAD FACTOR L_F AS FUNCTIONS OF NON-PEAK LOAD AND MAXIMUM DEMAND

The curves in Figure 11 are calculated using daily load patterns similar to that shown in Figure 10 (8 hours non-peak load + 8 hours maximum demand + 8 hours non-peak load), with maximum demands equal to 60, 80, 100 and 120 % of the transformer rated power. The no load loss factor K_{NLL} is in all cases \$6.30/W.

However, the load loss evaluation coefficient K_{LL} could be anywhere between \$1.10 and 9.70/W. It appears that the practice of applying \$1.80/W for coefficient K_{LL} across the board for all applications and loading conditions is a very rough approximation.

5.2.3. Impact of Annualised Charges of Maximum Demand on Loss Evaluation Factors

The impact of annualised charges per kW of maximum demand on loss evaluation factors is presented in Figure 12.

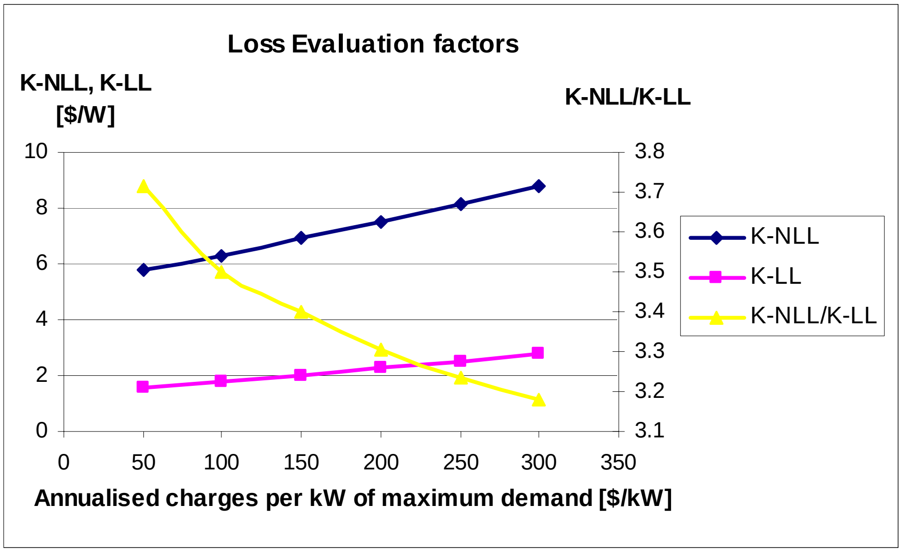

FIGURE 12 - FACTORS K_{NLL} AND K_{LL} AS FUNCTIONS OF ANNUALIZED CHARGES PER KW OF MAXIMUM DEMAND

As annualised charges per kW of maximum demand increase, both factors K_{NLL} and K_{LL} increase, however the ratio K_{NLL}/K_{LL} decreases. These charges are unique to particular utility and could vary significantly ($100 - 500/kW). Utilities with largely urban, fully established networks, which are characterized by short, medium to heavily loaded distribution lines and highly concentrated loads could calculate the value for annualised charges per kW of maximum demand very accurately.

On the contrary, when semi-urban and rural networks are analysed (where large investments in distribution and transmission projects are required), the annualised charges per kW of maximum demand are much more uncertain and usually are 25 - 40% higher than in urban networks.

5.3. Practical Considerations in Distribution Transformer Design

Once both loss evaluation factors are accurately determined, they will be included in tender documents so transformer manufacturers could use them in design optimisation process. Alternatively the loss evaluation factors could be used to evaluate the total operating costs (TOC) for the existing transformers.

5.3.1. The Loss Ratio

The objectives of the transformer designer are to meet purchaser's expectations regarding the lowest possible TOC. However, there are important additional requirements (e.g. need to meet expected profit margins using standard manufacturing techniques and materials). It has already been shown MIT (1943) that for the maximum theoretical operating economy (only costs of losses considered), the ratio of the no-load loss evaluation factor to the load loss evaluation factor should be equal to the ratio of full load losses to no- load losses per effective demand:

$$\frac{K_{NLL}}{K_{LL}} = \frac{LL}{NLL} \qquad [23]$$

A simple analysis of Equations [18] and [23] will ultimately lead to the well-known condition for the highest possible transformer efficiency when

$$NLL = LL \qquad [24]$$

Figure 13 shows combination of Equations [18] and [19] with Equation [23]. If the load factor LF increases (the load loss will also increase), the most economical ratio of load losses to no load losses decreases. Consequently, Figure 13 would suggest that lightly loaded pole-mounted transformers should have a relatively higher ratio LL/NLL, contrary to heavily loaded kiosk substation transformers, which will provide better total economy with lower ratio LL/NLL.

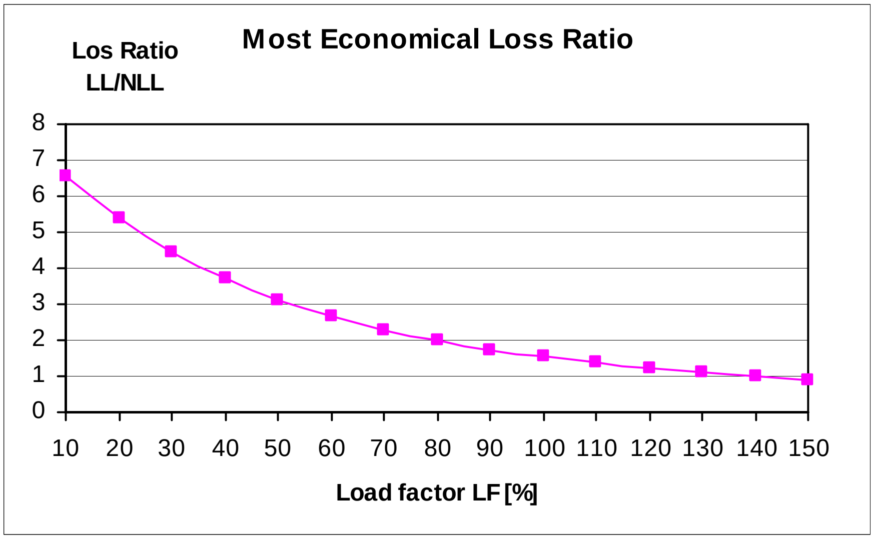

FIGURE 13 - THE MOST ECONOMICAL LOSS RATIO AS A FUNCTION OF THE LOAD FACTOR LF

A detailed analysis performed on some distribution transformers recently designed for Australian utility market, shows that reasonable deviations from the theoretical optimum loss ratio (+/- 15% tolerance band for the loss ratio) could provide very competitive solutions. Those designs will fit well into optimal technological processes an they will satisfy all technical requirements. These designs represent the most practical solutions from the manufacturer's point of view and as such they are very important because of implications on the final selling price.

5.3.2. The Loss Product

The designer controls the price of a transformer since the production cost *PC* relates to the no-load losses *NLL* and load losses *LL* as:

$$PC = X/(NLL * LL) \qquad [25]$$

where X is a coefficient which depends on particular transformer size and type. It is obvious that lower transformer losses will increase its production cost *PC* and ultimately the selling price. It is possible to calculate the optimal product of transformer losses using methods developed in (MIT, 1943):

$$NLL \times LL = Y \sqrt[3]{\frac{1}{K_{NLL} K_{LL}}} \qquad [26]$$

The factor Y could be expressed as a function of fixed annual cost *FC*:

$$Y = const. \times \sqrt[3]{FC^2} \qquad [27]$$

Some typical representative design data for three sets of designs of a 1,000 kVA distribution transformer are shown in Table 12.

TABLE 12 - TYPICAL DESIGN DATA FOR 1,000 KVA TRANSFORMERS

	Design A	**Design B**	**Design C**
Price *FC* [$]	18,000	25,000	19,500
***NLL* [W]**	2,500	1,200	1,800
***LL* [W]**	15,500	13,000	14,000
LL/NLL	6.2	10.8	7.8
K_{NLL} [$/W]	8.00	8.00	8.00
K_{LL} [$/W]	1.40	1.40	1.40
K_{NLL}/K_{LL}	5.7	5.7	5.7
X	641	390	504
***TOC* [$]**	59,700	52,800	53,500

These designs are very different and consequently the coefficient X is not constant. The above method (determination of the desirable loss product for given costs) should be used for the analysis of designs, which belong to the same set of designs (e.g. set of designs very similar to design B), with very small differences in prices. The minimum TOC method indicates that design B is the optimal solution. It is the highest priced option, but having the lowest losses still provides the lowest lifetime cost.

There are usually at least 2 or 3 designs, which come very close to the lowest TOC. Some utilities apply the range of 100-105 % of the minimal TOC increasing the number of possible choices and ultimately trying to purchase the transformer with the lowest initial costs within that range. This method, which is called the Band of Equivalence, has been used by some North American utilities. Although this method could help to reduce initial capital investments and preserve capital in the short term, a rigorous analysis could prove that this method does not include an appropriate risk assessment. Some studies estimate that over 80% of all buyers apply the Band of Equivalence or similar approximation method ICF (1998). Occasionally, the same method is used to select transformers with the lowest losses (usually more expensive transformers). In this case and in the case where the transformer with the lowest TOC is extremely expensive, an additional method called the Test Discount Rate (TDR) could be used to justify the initial higher investments. For example, the purchasing price for design B is $5,500 higher than for design C and the saving in TOC is only $700. It is recommended to review the initial data (especially loading diagrams), as minor changes in loading patterns, and consequently different loss evaluation factors will probably justify the selection of the transformer with slightly higher TOC (but which costs $5,500 less). The application of the Test Discount Rate is a common practice in the UK

5.4. Life Cycle Cost Method for Assessment of Distribution Transformers

The Life Cycle Cost method for assessment of distribution transformers developed by the USA Department of Energy DOE *LCC* (2002) is based on the following steps:

- selection of design under consideration and selection of loss evaluation coefficients and load profile and price profile for particular application;
- calculation of cost of losses;
- projection of losses and costs in future, selection of discount rate and calculation of present value of future cost of losses;
- reporting on LCC savings, payback, equivalent loss evaluation factors and presentation of results for "average" scenario.

The aim of LCC analysis is to evaluate the economic impact of any potential energy efficiency standard, including changes in operating expenses (usually decreased) and changes in purchase price (usually increased). DOE analyses the net effect of transformer costs over transformer service life. The LCC includes the installed cost (purchase price plus installation cost), operating expenses (energy and maintenance costs) calculated over the lifetime of the distribution transformer taking into account a selected discount rate. "The LCC is decreased (net savings) if the savings in reduced operating expenses from a more efficient transformer more than compensate for the increased installed cost", DOE *LCC* (2002).

"Transformer design, efficiency and economics are characterized by a large degree of diversity which is represented in the LCC by distributions. There are many possible transformer designs with different loss and efficiency characteristics. In the US, there are over 3,000 retail utilities each of which may experience different costs and economic conditions. As part of a distribution system with varying load factors, system loads and electricity costs, each individual transformer experiences different loads which vary over time. Each of these elements affects the economics of improving transformer efficiency. The LCC model captures these effects by utilizing probability distributions instead of point values as inputs. The LCC uses several data sets as its source for these distributions. Potential transformer designs are represented by a distribution of over 2,000 potential designs from the engineering analysis. Utility economics are represented by a sample of over 50 utilities. Hourly loads are represented by over 2,300 transformer load profiles based on simulations from actual system loads. Losses are valued (weighted) by hourly marginal generation costs, plus transmission and distribution cost adders. These hourly loads and costs manifest themselves in the spreadsheet as hourly load and price curves for each representative transformer for three day-types: weekdays, weekends, and peak days. As many of the inputs to the LCC are distributions rather than point values, the LCC results are also distributions, created by running the LCC model 10,000 times using a Monte-Carlo simulation tool", DOE *LCC* (2002).

5.5. Comparison of TOC and LCC

Capitalisation of losses is a widely accepted method for assessment of distribution transformers in Australia. However, the current Australian practice is somewhat too simple and a better understanding of applied factors and methods is needed. The huge regional differences in energy costs, system capacity costs, loading patterns and cost of capital will produce quite different loss evaluation factors for different utilities. The distribution transformers in Australia have already been considered to be highly customized products and applying one set of coefficients for different supply authorities, which operate under different circumstances, cannot be easily justified. The loss evaluation coefficients developed for pole mounted transformers can not be simply applied to assessment of large distribution transformers. The assessment methods applied in Australia do not recognize transformer overload capabilities and do not allow for improved transformer designs (i.e. increased reliability). Further research should prove that the cost of periodic maintenance and condition assessment (if any) shall be included in the assessment process. In addition, the cost associated with transformer failures, based on known failure rate for particular design should be added to the transformer price. The correct assessment method should be based on a more rigorous financial analysis, which will consider all other costs related to the transformer (i.e. forecasting costs, stock management, disposal costs, etc). The prediction of future cost of capital and loading cycles should be more rigorous. The impact of service conditions should be included.

The reference temperature for load losses is 75^0C, and the initial results of research about impacts of lower reference temperatures on TOC indicate that the reference temperature

75^{0}C puts some limitations on transformer designs. The lower temperature limits will promote optimised low loss transformers and dual name plate rating. The same approach could be applied to the kiosk substation distribution transformers, in which full rating inside the kiosk enclosure has been a unique Australian feature.

The impact of possible load growth and diversity factor for load losses for transformers operating in parallel or close to each other should be accommodated in the assessment method. As loading cycles and costs of energy and power vary between "industrial" and "utility" distribution transformers it is worthwhile to encourage the use of different loss evaluation coefficients.

An important non-cost factor has not been included in the above discussions. This is an additional factor to the TOC and takes into account the overload capability and failure rate of a particular transformer design, compliance with non-critical technical requirements, past performance of a particular manufacturer, delivery time, additional technical services offered (increased warranty, stocking, transformer inventory management, forecasting, product improvements and updates etc).

5.5.1. Difference between LCC and TOC Methods DOE LCC (2002)

The LCC analysis is used to calculate the total cost to purchasers of a transformer over its lifetime, including first cost and operating costs. The DOE uses the LCC analysis as part of its consideration of economic justification for energy efficiency standards. The TOC analysis considers first cost and operating costs and is used by some utilities to optimise their investments in new transformers. LCC is calculated from:

$$LCC = IC + \sum_{n=1}^{LIFETIME} \left(OC_n / 1 + DR \right)^n \qquad [28]$$

where *IC* is the initial installed cost, OC_n is the operating cost in year *n* (including value of losses and maintenance costs) and *DR* is the discount rate.

The Total Operating Cost (*TOC*) is calculated in Equation [18] and includes the capital cost and cost of losses.

The LCC and TOC methods are very similar and in some cases TOC and LCC methodologies do not produce significantly different answers.

These two methodologies, however, are often used in different contexts. The LCC analysis used by the DOE evaluates costs and benefits before taxes and analyses economics in real inflation-adjusted dollars. The TOC analysis, used by many US and Australian utilities, considers after-tax revenues and costs as well as nominal prices and discount rates IEEE (2001).

The LCC model developed by DOE annualises capacity costs by applying a capital recovery factor, which is based on the real discount rate. The capital recovery factor multiplied by the unit capacity cost gives the annualised unit cost of capacity. This annualised capacity cost is then applied to the annual capacity requirement and included in the cost stream that is evaluated for the LCC analysis DOE *LCC* (2002).

"The TOC analysis method uses a combination of levelised cost components to calculate loss evaluation coefficients. The TOC uses a methodology common in utility rate-making to calculate revenue requirements through the use of a Fixed Charge Rate (FCR). The FCR includes mark-up for taxes and other expenses to assure that revenue streams set on the basis of the FCR will maintain the value of the company. For a TOC calculation, the capacity costs are multiplied by a fixed charge rate and then divided by the fixed charge rate when calculating loss evaluation coefficients. The result is an answer that depends on the capacity cost, but which is insensitive to the fixed charge rate.

The LCC calculates forecasted annual costs, aggregates them into the annual operating costs, and calculates the present value of the annual cost stream. This method uses a simple capital recovery factor and assumes that there is no net impact from taxes and other utility expenses that are not explicitly accounted for in the analysis.

With recent changes brought about by the restructuring of the electricity industry, in which utilities obtain electricity from wholesale markets at the margin, the generation capacity costs are implicit in the correlations between peak prices and loads. The TOC methodology currently does not have a mechanism for incorporating these economic effects. The LCC methodology used by DOE with its hourly load profiles does capture the impact of peak wholesale market prices on the operating costs of transformer losses by including the impact of peak wholesale prices on the economic value of load losses DOE *LCC* (2002).

6. INTRODUCTION OF MANDATORY MEPS FOR DISTRIBUTION TRANSFORMERS IN AUSTRALIA

6.1. Background

6.1.1. *Regulatory Framework for MEPS*

Energy consumed by various equipment and appliances is a major source of greenhouse emissions. The most effective (and widely used) measure to reduce greenhouse emissions attributable to equipment and appliances is application of Codes and performance standards. Under the 1998 National Greenhouse Strategy, responsibility for the Australian Appliance and Equipment Energy Efficiency Program resides with Australian and New Zealand Minerals and Energy Council (ANZMEC). ANZMEC comprises the Minister of State from each Australian jurisdiction and New Zealand responsible for energy matters. This program provides "an important stimulus for the development of world-class energy efficient products. Benefits can flow through to the general community in the form of monetary savings from lower operating costs and increased employment levels resulting from Australian industry's ability to exploit potential export markets", (NAEEP, 2001a). Minimum Energy Performance Standards (MEPS) is a government regulatory program included in the state and territory laws that excludes from the market products, which do not meet the minimum energy performance levels. The National Appliance and Equipment Energy Efficiency Committee (NAEEEC) is a regulatory body that includes energy efficiency officials and regulators that implement the MEPS program and range of supporting measures in Australia and New Zealand. This body is also responsible for provision of relevant information for consideration by the ANZMEC. ANZMEC has authorised NAEEEC to develop and publish plans for MEPS for any industrial or commercial equipment identified as a significant contributor to the growth in energy demand or greenhouse gas emissions. These plans represent "a transparent way for government agencies to explore community and stakeholder support (for both mandatory and voluntary measures) to reduce greenhouse gas emissions produced by these types of equipment" (NAEEP, 2001a). The MEPS development process includes feasibility assessment (technical, economic cost-benefit analyses and available supervisory measures) and wide public consultations before any final decision is made.

6.1.2. Why Are Distribution Transformers Being Considered For MEPS

Distribution Transformers are being considered for MEPS due to the following:

- there is a large number of distribution transformers and due to the fact that almost all power generated in Australia passes through distribution transformers means even small improvements in transformer efficiency can result in significant savings of energy and in greenhouse gases reduction;
- electricity distribution transformers have a very long life (estimates range from average of 25 years to as much as 50 years for lightly loaded distribution transformers);
- the cost of transmission and distribution losses are passed on to consumers and the electricity utilities who are responsible for purchasing most of the transformers are not motivated to invest in more efficient distribution transformers;
- there is no market incentive for private purchasers of distribution transformers

(around 15% of the market) to purchase efficient distribution transformers as they easily include increased energy cost of inefficient distribution transformers into their total operating expenses (these costs are included into final cost of their products and services);

- "cumulative savings by 2015 resulting from the introduction of MEPS in 2005 are estimated to be at least 346,000 tons of carbon dioxide equivalent (CO_2-e) and could be as high as 950,000 tons CO_2-e" NAEEP (2001a).

6.1.3. The Original MEPS Program

In 1994 NAEEEC commenced investigations about potential benefits of mandating MEPS for distribution transformers. In 2000 a Steering Group including representatives from the industry and the Government was established with aims to advance the investigations.

The original program proposed to regulate liquid type distribution transformers with power ratings from 10 - 2,500 kVA and an input voltage of more than 5 kV and dry type transformers from 15 - 2,500 kVA. The NAEEEC developed a multi-staged public consultation process aiming to introduce nationally consistent standards for distribution transformers around July 2003. The aim was to increase the energy efficiency of distribution transformers by:

- mandating MEPS within relevant state and territory legislation commencing in July 2003 that match the relevant Canadian standards for distribution transformers (CAN/CSA-C802.1 and CAN/CSA-C802.2, 2001);
- exploring stakeholder support for developing higher energy performance standards

for products to be marketed as “high efficiency” distribution transformers, possibly at a level that matches US standards for distribution transformers, which were to come into force by July 2003;

- helping stakeholders to promote high efficiency products to the Australian marketplace.

6.2. Development of MEPS Methodology for Australian Distribution Transformers.

Development of MEPS for distribution transformers requires appropriate test procedures for measuring energy consumption as well as data on the efficiency and other relevant market intelligence. GWA (2002) provided a brief analysis of two main approaches to develop MEPS methodology and to establish appropriate MEPS levels:

- the statistical approach;
- the engineering approach.

The statistical approach is focused on a specific market at a specific time. It includes setting a standard efficiency levels based on available statistical energy efficiency data and energy costs. “The results of such an analysis are both time dependent and country-dependent, and reflect the particular costs and energy efficiency characteristics of the range of models available at a specific time in a particular market” GWA (2002).

The engineering analysis approach involves selection of a representative model. Such a “baseline” model normally incorporates the characteristics and technological features typical of a group of products under investigation. Alternative design options and combinations of options are then assessed, using the “baseline” model as a starting point.

A variation of this approach is used in this research, as this method has a number of advantages over the statistical approach and its variants GWA (2002):

- "it explicitly analyses the relationships between energy consumption, product price and capacity or level of energy service, and so allows estimates to be made on the effects of changing those relationships. In the statistical approach the existing relationships are considered to hold;
- there is no need to consider the number of existing models which meet the criteria found to be most cost-effective. This is not important provided the industry has a capacity to produce complying models within a specified time, without unacceptable adjustment costs (which are separately analysed);
- the approach is less sensitive to time and place, since it concentrates on product design and manufacture rather than market structure. However, it is still market dependent to the extent that the "baseline" models selected for analysis are typical of the market in question".

It should be noted, however, that this engineering method is time-consuming, resource-intensive and data-intensive and requires access to proprietary design information from manufacturers and/or detailed knowledge of design and manufacturing principles).

Development of Australian MEPS levels for distribution transformers is based on global Australian strategy for development of MEPS, which is endorsed by ANZMEC in 1999. This strategy relies heavily on MEPS methodologies developed in other markets (based on engineering and/or statistical approaches). This strategy is outlined in "National Appliance and Equipment Energy Efficiency Program: Future Directions 2002-04" NAEEEP (2001):

"In 1999 ANZMEC agreed that Australia would match the best MEPS levels of our trading partners after taking account of test method differences and other differences (eg climate, marketing and consumer preference variations). This new policy represented a radical change of direction from the previous Australian practice of debating the technical possibilities of MEPS levels with all stakeholders. The new policy covered any product regulated by mandatory labelling or MEPS programs in other developed countries."

In summary, this strategy defines the following steps in considering new MEPS, or revisions to existing MEPS, for any given product GWA (2002):

- "establish what MEPS levels, if any, apply in the countries with which there is significant Australian trade;
- take account of test method differences and other differences (eg climate, marketing and consumer preference variations), and adjust MEPS levels accordingly;
- subject the adjusted MEPS levels to cost-benefit, greenhouse reduction and other appropriate analyses (working with key stakeholder representatives);
- formally consult with stakeholders;
- if the adjusted MEPS levels pass the appropriate tests, adopt them".

It should be noted, however, that ANZMEC approach does not limit application of MEPS only to products, which were assessed in the other markets and it does not exclude application of cost-effectiveness criteria GWA (2002).

6.3. Regulatory Impact Statement GWA (2002)

The Council of Australian Governments (COAG) requires that the proposal such as MEPS for distribution transformers must be subject to a Regulatory Impact Statement (RIS). The RIS estimates the benefits, costs and other impacts of the proposal. It also assesses the likelihood of the proposal meeting its major objectives: "The purpose of preparing a Regulatory Impact Statement is to draw conclusions on whether regulation is necessary, and if so, on what would be the most efficient regulatory approach. Completion of a RIS should ensure that new or amended regulatory proposals are subject to proper analysis and scrutiny as to their necessity, efficiency and net impact on community welfare. Governments should then be able to make well-based decisions. The process emphasises the importance of identifying the effects on groups who will be affected by changes in the regulatory environment, and consideration of alternatives to the proposed regulation. Impact assessment is a two step process: first, identifying the need for regulation; and second, quantifying the potential benefits and costs of different methods of regulation. In demonstrating the need for the regulation, the RIS should show that an economic or social problem exists, define an objective for regulatory intervention, and show that alternative mechanisms for achieving the stated objective are not practicable or more efficient" COAG (1997).

The RIS for MEPS for distribution transformers GWA (2002) has considered the following options:

- "status quo - business as usual (BAU);
- the proposed regulation (mandatory MEPS) which adopts all the requirements contained in Draft Australia Standard 2374;

- an alternative regulation which only adopts those parts of the Standard that are essential to satisfy regulatory energy objectives (targeted regulatory MEPS);
- voluntary MEPS, where minimum energy efficiency levels for distribution transformers would be made publicly available, and industry is encouraged, but not compelled to adhere to the proposed levels;
- another regulatory option involving a levy imposed upon inefficient equipment to fund programs to redress the greenhouse impact of equipment energy use;
- a levy on electricity reflecting the impact it has on greenhouse gas emissions" GWA (2002).

6.3.1. Estimated Greenhouse Gas Reductions

According to GWA (2000): "Distribution transformers in the Australian electricity system account for around 25% of transmission and distribution losses, equivalent to 5,450 GWh or approximately 5,400,000 tons CO_2-e (based on data for 1998). Electricity consumption is predicted to grow steadily and distribution losses may slightly increase as a result of the change to lower nominal voltage of 230 V as proposed by AS 60038–2000. These factors are likely to outweigh the estimated decrease in the greenhouse intensity of electricity, so that by 2015 losses due to distribution transformers are estimated to be at least 6,000,000 tons CO_2-e. Discussions with the industry suggest that the large majority of pre MEPS distribution transformers complied with the proposed MEPS. The area where most benefits have arisen was the private ownership market where the least efficient products are typically installed. This tends to be the largest market for dry-type transformers where lower efficiency levels are found.

Based on available information concerning the stock and performance of Australian distribution transformers, the proposed MEPS level in 2005 would reduce greenhouse emissions by approximately 32,000 tons CO_2-e per annum, with a successively larger impact in subsequent years. Cumulative savings from MEPS in the years to 2010 and to 2015 are estimated to be 185,000 tons CO_2-e and 346,000 tons CO_2-e, respectively. If the trend continues towards the purchase of lower efficiency transformers in Australia, greenhouse savings as a result of MEPS in 2015 would be between 650,000 tons CO_2-e to 950,000 tons CO_2-e."

6.3.2. Estimated Economic Implications - Original MEPS Program

"Since Australian manufacturers can supply a wide range of high efficiency transformers, MEPS should not unjustifiably disadvantage any single supplier. The MEPS itself is not a trade barrier. There is, however, a capital cost premium for efficiency in transformers reflecting increased material costs and, in some cases, handling costs. For example, industry claim that the approximate cost difference between the "low loss" transformers and the "industrial" range is in the region of 10 - 20%.

Without regulation, the increasing pressure on purchasers to reduce capital costs is likely to result in a growth of inefficient transformers sold on a "first-cost" basis by importers. This would have ramifications for Australian manufacturers as well as broader economic and greenhouse impacts" GWA (2002).

6.3.3. Cost-Benefit Analysis for MEPS Program

The benefits from the MEPS for distribution transformers are calculated as the Net Present Value (NPV) at 10% discount rate of the projected reduction in electricity losses. Greenhouse gas emission savings have not been valued.

The cost arising from MEPS for distribution transformers is the NPV of the projected increase in the price of transformers due to increased efficiency. The RIS states that introduction of MEPS would not introduce any additional program costs, "since transformer energy efficiency testing is already common and the administrative infrastructure for MEPS already exists" GWA (2002).

In addition, the RIS concludes that "the benefit/cost ratios range from 1.0 to 1.2 for utility-owned transformers, where the value of losses is related to the wholesale price of energy, and 3.3 to 4.0 for privately owned transformers, which face much higher marginal electricity prices and for which the value of electricity saved is consequently higher. The projections represent a price/efficiency ratio of 0.5. For private transformers, MEPS remain cost effective up to ratios of 1.8", GWA (2002).

6.3.4. Other RIS Considerations GWA (2002)

The RIS also considered the following issues:

- supplier and trade issues - distribution transformers are manufactured and freely traded in all developed countries in the Asia Pacific region. Introduction of MEPS levels is not likely to significantly change the number of suppliers, nor the price competition between them;
- market failure - introduction of mandatory "MEPS option would address market

failure in the private transformer market, and the increasing risk of market failure in the utility transformer market, by enforcing investment in more efficient products so that the total life cycle cost of transformers to users would be lower than otherwise";

- information failure - "mandatory MEPS option would be to introduce consistency in declarations of transformer energy efficiency and in the designation of "high efficiency" models. The introduction of MEPS would put reliable data on the energy efficiency of every transformer model in the public domain for the first time;
- product quality - MEPS are not expected to have any negative effect on product quality or function. Actually, increase in transformer efficiency "should lead to lower heat gain in operation, and hence lower failure rates and higher overall network reliability";
- world's best practice - "Canada and Mexico have MEPS for transformers, and the European Union and the USA are considering implementing them. The proposed MEPS levels are based on and equivalent to, the most stringent currently in place (those for Canada, which took effect in January 2002) and so are consistent with the principle adopted by ANZMEC - matching but not exceeding the most stringent MEPS levels in force elsewhere. The proposed criteria for designating transformers as "high efficiency" are roughly equivalent to the MEPS levels under consideration for the EU and the USA, and as such are an indicator of the likely direction of world's best practice".

6.4. Proposed MEPS Levels for Distribution Transformers

6.4.1. Summary of MEPS for Distribution Transformers

From 1 October 2004, most distribution transformers rated between 10 and 2,500 kVA that are designed for 11 and 22 kV networks are required to meet minimum energy performance standards (MEPS) in order to be sold in Australia. Mandatory energy performance levels are contained in the Australian Standard AS2374.1.2:2003 Power Transformers - Minimum Energy Performance Standard (MEPS) Requirements For Distribution Transformers, and apply to single and three phase, dry type and oil immersed transformers. After 1 October 2004, distribution transformers that meet more stringent performance levels than MEPS (also specified in AS2374.1.2) are allowed to be promoted as "High Efficiency Power Transformers". Appendix 2 provides more details about the Australian Standard AS2374.1.2 and lists special distribution transformers, which are not subject to MEPS. The values for MEPS are given in Appendix 3. These MEPS are expressed as efficiency levels at 50% of nominal load. The test methods which should be used to determine compliance with MEPS for distribution transformers are defined in AS2374.1-1997 Power Transformers and AS2735-1984 Dry Type Power Transformers.

Distribution transformers, as regulated products, offered for sale after 1 October 2004 must be registered with a State regulator. The distribution transformers, which were registered with Australian Greenhouse Office (Energy Efficiency) by January 2005, are presented in Appendix 1.

The Australian program and regulation for energy efficiency in distribution transformers is being followed by New Zealand regulators.

6.4.2. Summary of RIS Conclusions

The RIS concluded that the mandatory MEPS option is "likely to be effective in meeting its stated objectives:

- the mandatory MEPS option can deliver a better rate of improvement for energy efficiency of transformers in Australia than market forces. MEPS can demonstrably improve the energy efficiency of appliances and equipment, particularly where the purchaser is able to pass on inefficient running costs to third parties;
- none of the alternatives examined appear as effective in meeting all objectives, some would be completely ineffective with regard to some of the objectives, and some options appear to be far more difficult or costly to implement;
- the projected monetary benefits of the mandatory MEPS option appear to exceed the projected costs by a ratio of about 1.4 to 1, without assigning monetary value to the reductions in CO_2 emissions that are likely to occur (possibly as high as 870,000 tones CO_2-e per annum by 2010);
- the benefit/cost ratio for privately-owned transformers is significantly higher than for utility-owned transformers".

6.5. Comparison of Australian and US cost benefit approaches to MEPS

McMahon (2004) compared US and Australian approaches to analysis of costs and benefits of minimum energy performance standards (MEPS). In his report, prepared for the Australian Greenhouse Office and the Collaborative Labelling and Appliance Standards Program (CLASP), McMahon analysed some other appliances in the presented case studies, however, the findings are also relevant for distribution transformers MEPS. The report also suggests improvements for the approach taken in Australia

The MEPS in Australia and USA are subject to distinctive and specific constraints as the overall purposes of the programs are different:

- the purpose of the Australian program is to reduce greenhouse gas emissions;
- the purpose of the US program is to increase energy efficiency.

The market structures are different:

- Australia imports significantly large share of its distribution transformers (especially dry-types);
- most of the USA distribution transformers are produced locally.

The policy contexts are again different:

- Australia adopts the MEPS already in place elsewhere (i.e. Canadian Standards for distribution transformers);
- the US regulatory bodies are "conducting pioneering engineering-economic studies to identify maximum energy efficiency levels that are technologically feasible and economically justified".

The approaches to determining the relationship of price to energy efficiency also differ:

- the Australian approach is based on the current market data;
- the US approach uses prospective estimates.

The report recommends that both approaches be refined by including "retrospective analysis of impacts of MEPS on appliance and equipment prices".

The capitalisation of losses (Total Operating Costs and Life-Cycle Cost) methods are similar (more details about these two methods are given in Chapter 5):

- Australia uses average values, and this method could be improved if more data were available.
- the US approach uses statistical surveys that permit a more detailed analysis, based on full distributions (rather than average values).

The methods for the national cost - benefits analyses methods are very similar, however the methods would benefit by introduction of additional sensitivity analyses.

In addition, consideration should be given to lower discount rates, which "could lead to more stringent MEPS in some cases".

The technology and market assessments are similar and no changes are recommended for either approach.

Both the Australian and the US analyses impacts on industry, competition, and trade are quite detailed and the report does not recommend any changes.

In conclusion, "Australia's analysis approach could be expected to have less analytical detail and still result in MEPS levels that are appropriate for their policy and market context. In practice, the analysis required to meet these different objectives is quite similar. To date, Australia's cost-benefit analysis has served the goals and philosophies of the program well and been highly effective in successfully identifying MEPS that are significantly reducing greenhouse gas emissions while providing economic benefits to consumers. In some cases, however, the experience of the USA - using more extensive data sets and more detailed analysis - suggests possible improvements to Australia's cost-benefit analysis".

It seems that recommended changes “would increase the depth of analysis, require additional data collection and analysis, and incur associated costs and time. The recommended changes are likely to have incremental rather than dramatic impacts on the substance and implications of the analysis as currently conducted” McMahon (2004).

6.6. International Energy Efficiency Standards and Programs for Distribution Transformers

6.6.1. Liberalisation of the Electricity Market

LE (2005) analyses main barriers (and recommends possible remedial measures) for electrical utilities’ investments into high efficiency equipment in a liberalized electricity market:

- “most regulatory models rely on a partial redistribution of savings to consumers. This discourages companies from making investments for efficiency improvements, since cost reduction from the investment are shared with the consumers. It would be advisable to allow some carryover of measurable efficiency gains, so that investing in energy efficiency becomes more attractive for the network companies;
- capital-intensive investments are very sensitive to future changes in the regulatory regime. This discourages investments in efficiency improvements. Special incentives should be given to promote capital-intensive energy efficiency measures (in a stable regulatory system);
- the regulatory framework tends to concentrate on cost savings in the short term. Such an approach does not encourage companies to take the life cycle costs of

equipment into account. There should be incentive for network operators to take LCC into account;

- energy losses are calculated without consideration of external costs. The true cost of network losses should be taken into account".

The following summary of efficiency standards and status of MEPS programs and activities in different countries to address the tendency of both utilities and non-utilities to purchase distribution transformers of lower efficiency than is cost-effective from a lifecycle perspective is compiled from Ellis (2001) and LE (2005).

6.6.2. China

The mandatory minimum efficiency standards for power transformers (the "S9" standard) were introduced in 1999. This standard, approved by the State Bureau of Quality and Technology Supervision, covers both distribution and power transformers. It limits the maximum load losses and no-load losses for oil immersed types ranging from 30 to 31,500 kVA as well as for dry types in the range from 30to 10,000 kVA. Introduction of the S9 standard has significantly improved efficiency of power transformers in this market.

6.6.3. Europe

Distribution transformers in the European Union are covered by: world-wide standards (e.g. ISO, IEC), European standards and regulations (e.g. EN, Harmonization Documents) and various national standards (e.g. BSI, DIN, UNE, OTEL, etc).

CELEC has defined efficiency standards for three phase distribution transformers in the range from 50 to 2,500 kVA, 50Hz and up to 36 kV. The standard HD428 defines three categories for load losses (*C, A* and *B* - value of losses in ascending order) and no-load losses (*C', B'* and *A'* - value of losses in ascending order). A similar standard (HD538) stipulates the load losses and no-load losses of dry type transformers. Distribution transformers built to HD428 and HD538 have a limited number of preferred values for rated power (50, 100, 160, 250, 400, 630, 1,000, 1,600 and 2,500 kVA), however, the intermediate values are also allowed. A separate HD is under consideration for pole-mounted transformers. Loss values for transformers are usually declared as maximum values with a specified tolerance. Higher losses may incur a financial compensation for exceeding the loss limit and the losses lower than the guaranteed may be subject to a bonus awarded to the manufacturer (this would normally apply for larger transformers).

HD428 therefore allows customers to choose between three levels of no-load losses and three levels of load losses. In principle, there are 9 possible combinations, ranging from the lowest efficiency, (*BA'*) to the highest, (*CC'*). These efficiency ranges are extremely wide. The minimum efficiency in the highest category (*CC'*) is still far below the efficiency of the best in class and far below the *5-star* transformer defined by the Indian standards.

CENELEC is currently defining new efficiency categories with lower losses. In 1999, a *Thermie* project of the European Union assessed the total energy losses in distribution transformers. The savings potential in the 15 countries of the EU was estimated to be 22 TWh. The standards are not as yet mandatory, and a mandatory minimum efficiency standard for distribution transformers is not expected to be introduced in the near future. "This is very disappointing, given the availability of world-class transformer technology in Europe" LE (2005).

6.6.4. Taiwan

"Since 1992, an eco-label program called *GreenMark* has been run by the Environmental Protection Administration (EPA) and currently covers over 50 products. For conforming products, the *GreenMark* logo label may be used on product packaging, brochures or on the products themselves. It is intended that distribution transformers will be covered by this program although the energy performance criteria have not yet been determined" Ellis (2001).

6.6.5. India

"In India, the Bureau of Energy Efficiency (BEE) has developed a "*5-star*" classification scheme for distribution transformers in the range from 25 to 200 kVA. The scheme is a co-operative venture between public and private organizations that issues rules and recommendations under the statutory powers vested with it.

The *5-star* program stipulates a lower and a higher limit for the total losses in transformers, at 50% load. The scheme recommends replacing transformers with higher star rated units. The *5-star* unit represents world-class technology, while *3-star* is recommended as a minimum, and already followed by many utilities. India historically has a rather poor performance in transformer energy efficiency, but this *5-star* program could become an important driver for change" LE (2005).

6.6.6. Japan

"In Japan, transformers are a part of the *Toprunner Program,* which either defines the efficiency for various categories of a product type, or uses a formula to calculate minimum efficiency. This program, which covers 18 different categories of appliances, has some major differences compared to other Minimum Energy Performance programs. The minimum standard is not based on the average efficiency level of products currently available, but on the highest efficiency level achievable. However, the program does not impose this level immediately, but sets a target date by which this efficiency level must be reached. A manufacturer's product range must, on average, meet the requirement. It is not applied to individual products. Labelling of the products is mandatory. A green label signifies a product that meets the minimum standard, while other products receive an orange label" LE (2005).

6.6.7. Mexico

As in Australia, the Mexican standard includes voluntary and mandatory elements. The Mexican standard, NOM-002-SEDE-1999 defines minimum energy performance standards and maximum load losses and no-load losses for transformers in the range from 5 to 500 kVA. The standard also defines the compulsory test procedure for determining efficiency performance. The efficiency levels are less stringent than those proposed for Canada and the US. The regulation makes allowances for smaller manufacturers, who may appeal for an exception during transitionary period before meeting the requirements.

6.6.8. USA

"The energy savings potential in the USA from switching to high efficient transformers is high. In 1997, the National Laboratory of Oak Ridge estimated it to be 141 TWh.

Utilities purchase over 1 million new units each year, and it is estimated that if the average efficiency of utility transformers was improved by one-tenth of one percent, greenhouse emissions reductions of 1,800,000 tones CO_2-e per annum would be achieved over a 30 year period. The US has currently has a number of voluntary initiatives designed to increase the efficiency of distribution transformers USEPA (1998b).

- the National Electrical Manufacturers Association (NEMA) created the TP1 standard - Guide for Determining Energy Efficiency for Distribution Transformers (TP-1-1996), and a standard test method for the measurement of energy consumption in transformers (TP-2). The TP1 standard defines a minimum efficiency for dry and oil-filled type transformers in the range from 10 to 2,500 kVA and it is likely to become the mandatory minimum efficiency level in the near future;
- secondly, distribution transformers also are part of the broader *EnergyStar* labelling program. *EnergyStar* is a voluntary program that encourages the participating utilities to calculate the total cost of ownership of their transformers and to buy the type if it is cost-effective to do. *EnergyStar* is based on TP1 because EPA was looking to set an easy standard that did not cause protracted arguments, so it may be tightened in the future;
- the third program in the US, set up by the Consortium for Energy Efficiency (CEE), aims to increase the awareness of the potential of efficient transformers in industry. It consists of a campaign to measure the efficiency of industrial transformers and to stimulate year period. As a result, in the Energy Star transformer program, participating utilities agree to perform an analysis of total

> transformer operating costs, using a standard methodology, and to buy transformers that meet *EnergyStar* guidelines when it is cost-effective to do so. The program provides technical assistance to partners to ensure that transformers are not oversized, and has developed a Distribution Transformer Cost Evaluation Model (DTCEM) to provide a standard methodology for the evaluation of multiple transformer bids. To compliment this tool, the program also labels transformers, which conform to its targets USEPA (1998a).

The US Department of Energy (DOE) Federal Energy Management Program encourages government procurement of energy efficient distribution transformers. The DOE is currently proceeding with industry-wide consultation and the development of test procedures with a view to the adoption of Minimum Energy Performance Standards (MEPS) for transformers. No firm implementation commitment has been made as yet, however test standards under consideration include the ANSI/IEEE standards (C57.12.90-1993 and C57.12.91-1995) and the NEMA standard (TP-2 1998)" LE (2005) and Ellis (2001).

6.6.9. Canada

"In Canada the Office of Energy Efficiency (OEE) of Natural Resources Canada (NR-Can) has amended Canada's Energy Efficiency Regulations (the Regulations) to require Canadian dealers to comply with minimum energy performance standards for dry-type transformers imported or shipped across state borders for sale or lease in Canada.

The standards are harmonized with NEMA TP-1 and TP-2 standards. Amendment 6 to

Canada's Energy Efficiency Regulations was published in 2003. The regulation of dry-type transformers is included in this amendment with a completion date of January 1, 2005. This requires all dry-type transformers manufactured after this date to meet the minimum energy performance standards.

As far as oil transformers are concerned Canada has conducted analysis of MEPS implementation potential and found that the great majority of Canadian oil distribution transformers already comply with NEMA TP-1 so the standard would almost have no influence on the market. The yearly MEPS standard impact would only be 0.98 GWh for liquid filled transformers compared to saving potential at 132 GWh expected for dry-type transformers. Also *EnergyStar* products are very actively promoted in Canada" LE (2005).

6.7. Critical Review of MEPS for Distribution Transformers

It should be highlighted that under the incentive of the National Greenhouse Strategy (NGS) and due to the strong support from all of the parties involved, the establishment of the MEPS for Australian distribution transformers passed relatively smoothly. However, there were some issues of concern which are listed below:

- the MEPS development processes are relatively long and once the performance levels are established (in a consultative environment) it will be very difficult to review and change them. Carrying out a new consultation process requires significant resources. Because of that, minimum efficiency standards are rarely adjusted to the economics of the market or to new technology developments. This inflexibility of MEPS regulation should be taken into account through introduction of much more rigorous assessment methodologies;

- “mandatory Minimum Energy Performance Standards (MEPS) have the advantage that they achieve immediate effect. Experience from MEPS for other products shows that from the moment of adopting such standards, the efficiency of the average new products increases. MEPS success has also been proven internationally, with China as the most striking example. However, minimum standards will in most cases be set as a compromise between the requirements of all parties involved. As a consequence, standards are normally not set high enough to achieve the full economic and environmental benefits” LE (2005).
- although the Regulatory Impact Statement (RIS) prepared by GWA (2002) concluded that introduction of MEPS does not favour any particular supplier, it should be noted that this is true only in a short time-frame. New entrants into the market will have better opportunities to invest into improved high efficiency designs (e.g. investment into better technology, more attractive long term contracts with suppliers of high quality components, etc.). If the MEPS levels were raised in near future it may be more difficult to comply with such higher standard, as this would require substantial redesign and as a consequence greater capital cost and there would need to apply a more strict cost benefit analysis than has been done to date EEA (2003).
- there have been some arguments EEA (2003) that “singling out of one small part of a network’s total asset base for an alternative regulatory energy performance standard seems inconsistent and of very limited value given the level of savings that could be achieved”. According to EEA (2003) the electrical utilities take into

account all equipment performance efficiencies as part of their long-term investment considerations. Consequently, the need for the implementation of MEPS needs to be clearly fitted into an electricity regulatory framework, rather than being solely driven by concerns over reduction of greenhouse gasses. EEA's refusal to adopt such an implementation of MEPS was due to their concerns about apparent "piecemeal coverage of electricity industry assets outside of the economic / performance regulatory structure";

- discussions with some of key utilities in New Zealand indicate that the industry already has higher efficiency levels for distribution transformers (through voluntary self-regulation) than those proposed by the MEPS and to mandate a lesser standard than what is being used would be a retrograde step;
- the reports used as a basis for development of MEPS for distribution transformers in Australia do not discuss rigorously data about the efficiency of the pre-MEPS models. It seems that for a large part of distribution transformer population the improvement in efficiency is measured in points of a percent. As the whole concept is based on 50% loading (and not the actual load, which the distribution transformer will experience), it is suggested that "a substantial expansion of this work would be required to rigorously demonstrate that the MEPS standard would be appropriate" EEA (2003);
- the MEPS alternatives (presented in GWA (2002) and LE (2005)) include labelling and voluntary schemes. "Labelling is an effective way of bringing transparency to the market. A clear definition of efficiency, a transparent measurement procedure and a labelling system should be the start of every mandatory or voluntary

program to increase transformer efficiency. Voluntary schemes do not have the disadvantages of a mandatory minimum standard. The targets can often be set at a more ambitious level and reviewing them is less difficult and time consuming. Consequently, it is a much more flexible system. The main difficulty to overcome in voluntary programs is reaching a reasonable degree of participation often taking few years. The goal of a voluntary program should be to make the incentives and the image so important that it becomes difficult for companies to ignore. High image value, a meaningful brand presence, and a strong policy context for instance make the Japanese *Toprunner* program a good example of an effective scheme", LE (2005);

- it seems that the Australian market is generally comfortable with MEPS levels, however, there were strong views (expressed during the consultation process) that the method of calculating Australian MEPS was somewhat deficient. In particular, strong reliance on Canadian MEPS and simple increase of Canadian MEPS to take account of the different system frequency between North America (60 Hz) and Australia (50 Hz) was too simplistic. In addition, it is not clear if the applied methodology considered difference in definition of kVA rating between the two standards. As the North American and Australian electrical distribution systems are quite different (e.g. predominantly single phase supply and a large number of smaller less efficient distribution transformers in North America versus mostly three phase supply through larger more efficient distribution transformers in Australia), the percentage of the lost energy due to distribution transformer inefficiencies is much smaller in Australia;

- the MEPS as mandatory "minimum" standards do not allow for tolerances in transformer losses. This has introduced additional commercial risks for manufacturers;
- the MEPS does not take into account fact that some utilities require kiosk transformers to be fully rated in the enclosure. Such units have much higher rating outside of enclosure (and would be subject to higher efficiency requirements).
- MEPS requires much more extensive testing regime. The cost of these additional tests will have to be borne by the manufacturers who will no doubt pass it on in the final product costs. The RIS GWA (2002) does not include these costs into cost-benefit analysis. The costs for additional tests are estimated to be $2,000 - 3,000 per unit/model, and the customized small series product lines might be significantly affected by these additional costs.

In conclusion, it is recommended that the MEPS for distribution transformers are refined by including:

- more rigorous analysis of MEPS levels;
- retrospective analysis of impacts of MEPS on distribution transformer prices. This analysis should consider two separate components leading to price impact: changes in manufacturing costs and commercial margin used to convert from manufacturing costs to final price.

7. PERFORMANCES OF DISTRIBUTION TRANSFORMERS INSTALLED IN METALLIC ENCLOSURES – AN AUSTRALIAN EXPERIENCE

7.1. Introduction

In the last 20 years the Australian market is showing an increasing demand for packaged substations with three phase distribution power transformers. Unfortunately, the standards and regulations do not cover this area very well and in the last few decades the electrical supply authorities and transformer manufacturers have developed different designs based on unique specifications and distinctive combination of construction features. Most factory assembled packaged substations currently used in Australia utilize metallic enclosures, which include various types of ventilation systems. Those products evolved over the last 30-35 years from the transformer substations developed by electrical utilities in Victoria and New South Wales. The recently developed substations were designed around modern, compact Medium Voltage switchgear (11 - 36 kV), fully enclosed Low Voltage switchboards and largely customized, purpose-built, unique Australian distribution transformers. Highly restrictive local environmental and urban planning regulations have resulted in development of very compact packaged substations with extremely arduous service conditions for built-in distribution transformers. The limited footprints and ever increasing transformer ratings have resulted in reducing the ratio between the physical dimensions of the installed distribution transformer and its rated power. This research is focused on Australian oil-immersed, ONAN cooled and hermetically sealed distribution transformers rated 150 to 2,500 kVA, highlighting their distinctive features: unique design, superior loading capability, high reliability performances and safety features. The assessment techniques discussed in previous chapters are developed for distribution transformers operating "in free air" and no allowance is made for built-in distribution transformers. This chapter provides information necessary for better understanding of physical phenomena of thermal processes taking place during the operation of distribution transformers installed in metallic enclosures, without being heavily involved in design investigations.

7.2. Development of kiosk substations

IEC 61330 defines prefabricated substations as "type-tested equipment comprising transformer, low-voltage and High-Voltage switchgear, connections and auxiliary equipment in an enclosure to supply low-voltage energy from a high-voltage system". The packaged substations in Australia are better known as pad-mounted or kiosk substations. They include MV switchgear (11 or 22 kV), a 22(11) kV/0.4 kV transformer (750 - 2,000 kVA) and an LV switchboard; all installed in a compact metallic enclosure. Some modern substations also include communication, control and metering equipment. Design of kiosk substations is a multifaceted process, which in addition to assessment of numerous technical requirements (such as selection of equipment and consideration of requirements for high availability of electrical power) also includes appraisal of safety aspects (for the operators and the general public) as well as a variety of rigorous environmental and local planning issues.

The new manufacturing methods developed around such a composite product and implemented in Europe over the last few decades, are an evident example of a successful concept of industrial dependability. In Europe, distribution power transformers and MV and LV switchgear are fully standardized and type-tested "off-shelf" products and development of uniform designs for kiosk substations based on such products is a logical improvement path. The first IEC standard for pre-fabricated HV/LV substations was published in 1995 (IEC 61330 Ed. 1.0 B, 1995). It specifies the service conditions, rated characteristics, general structural requirements and test methods for "High-voltage/low voltage prefabricated substations", which include HV cable connections (up to 52 kV) and distribution transformers up to 1,600 kVA.

Although the above standard has not become an Australian Standard yet, a number of Australian electrical distribution companies have been discretely using this standard since 1997. Unfortunately, a strict application of the IEC recommendations for pre-fabricated kiosk substations in Australia is not a straightforward exercise. The most complications are due to highly customized Australian distribution transformers, which are designed for specific users and conditions, resulting in extremely nonflexible solutions. In addition, there is a range of differing requirements for loading of transformers installed in kiosk substations. Most packaged kiosk substations are manufactured in very limited volumes, they are not type-tested and very little technical data is publicly available.

7.3. Applicable Standards

In addition to IEC 61330 and other standards and technical regulations which independently deal with all major parts of kiosk substations, there are Wiring Rules (2000), an Australian standard, which covers the general aspects of electrical installations at all voltage levels and as such also includes some requirements for MV/LV substations.

The Australian standard Loading guide for oil-immersed power transformers AS 2374.7-1997, which is reproduced from an equivalent IEC standard - IEC 60354 Ed. 2.0 B (1991) provides some recommendations for loading of distribution transformers when installed in enclosures and buildings. Unfortunately, the data given in IEC 60354 is an excerpt from the previous version of the Australian standard published in 1984 (Australian Standard AS 1078-1984) and does not include distribution transformers above 1,000 kVA.

7.4. Performance of Kiosk Transformers

7.4.1. Factors Affecting Life of Distribution Transformers

Distribution transformer life expectancy is a function of its design and components, manufacturing techniques, operating conditions (including loading patterns, ambient temperatures and network events) and maintenance policies. It is also a complex function of many other more or less influential factors, which are usually an estimate only and cannot be expressed explicitly and accurately (e.g. exact performances of the insulation system). Although most Australian electrical utilities expect that an average design life for a modern oil-immersed distribution transformer should be in excess of 20 - 30 years, this fact does not constitute any expressed or implied warranty by manufacturers.

Climatic conditions other than exposure to higher temperatures (lightning, wind and air pollution), uninterrupted system faults and physical damage by various external influences are considered to be by far the greatest concern regarding the expected life of distribution transformers in Australia. As distribution transformers are relatively inexpensive, very reliable and easy to replace, they are expediently considered to be of much less critical importance than larger power transformers and other parts of the power system. A commonly applied methodology to install a slightly larger distribution transformer than necessary and rely on its low load factor has resulted in acceptance of an unofficial policy where distribution transformers require a reduced level of attention. It has been widely accepted that the loading evaluation, although necessary, has no factual relevance to the expected service lifetime of a distribution transformer. Consequently, there is very limited information on the loading of distribution transformers in Australia.

Although the above principles are somewhat valid for smaller pole-mounted distribution transformers (up to 500 kVA), the larger distribution transformers, as well as those installed in kiosk substations require much more rigorous analysis of their service conditions and respective loading capabilities. Firstly, there is a very emaciated possibility of using non-optimal (increased) rating of those transformers due to material limits imposed by the enclosure. Secondly, degradation of insulating materials caused by increased ambient temperature due to restricted air flow around the transformer is considered to be much more critical for its lifetime than the external influences. Finally, the large distribution transformers in most cases supply loads which request very high reliability of supply (e.g. hospitals, large residential blocks, commercial and industrial sites). Reliability analysis of such transformers is much more complex than simply relying on a quick replacement of a failed transformer.

7.4.2. Loading of Distribution Transformers

The maximum intermittent loading of distribution transformers for normal cycling, long-term and short-term loading is vaguely defined in Australian Standard AS 2374.7-1997 as 1.5, 1.8 and 2.0 p.u. of the rated current respectively. Although, it is well known that smaller transformers have generally better overloading capabilities, there is no confirmation of that fact in Australian Standard AS 2374.7-1997, which recommends the same loading limits for all power transformers below 2,500 kVA (defined as "distribution transformers").

The author of this thesis has tested a large number of distribution transformers and the tests have shown that relative differences in thermal performances of distribution transformers are due to designation to operate in "free air" or "enclosed" and due to transformer size. The tests suggested that in addition to "free air" or "enclosed" classification, distribution transformers should be further classified into four categories:

- small distribution transformers: below 500 kVA;
- medium distribution transformers: 750 - 1,000 kVA;
- large distribution transformers: 1,250 - 2,000 kVA.;
- very large distribution transformers: 2,500 kVA and above.

7.4.3. Design Features

Both standards' series, Australian Standards 2374 and IEC Standards 60076, deal with oil-immersed power transformers, which are installed in "free air". If different service conditions apply, such as restricted airflow around transformer's cooling system when transformer is "enclosed", then transformer rating (and respective continuous and intermittent loading limits) should be reduced to allow for departure from the prescribed service conditions. The requirements in Australia are somewhat different, as the full name-plate rating for distribution transformers is required for each application (in free air and in an enclosure), forcing manufacturers to develop two completely different electrical designs for the same nominal transformer rating.

In addition, the constructional features of Australian distribution transformers for kiosk application are unique. Contrary to their European counterparts, distribution transformers in Australia have bushings mounted on the side tank walls.

Due to size limits imposed on enclosures, the kiosk transformers are extremely compact and usually very narrow and tall. Kiosk transformers have very low electrical losses and they employ very efficient cooling systems (almost exclusively based on natural ventilation). Modern Australian distribution transformers installed in kiosk substations are very reliable, safe to operate and require very little maintenance. Most of them include an oil containment, which prevents leakage of insulating oil outside of the enclosure. Unfortunately, introduction of this "environmentally friendly" feature has further burdened transformers as the oil containment in most cases restricts airflow inside the enclosure.

7.4.4. Ambient Temperature

The thermal deterioration of the transformer insulation (as the most important factor for loading considerations) is the function of the hot spot temperature and the top oil temperature, which are dependant on ambient temperature.

The actual ambient temperature varies as function of the climate, the season, the time of the day, etc. Table 13 from AS 2374.1 shows the maximum ambient temperatures defined for standard oil-immersed distribution transformers in free-air operation:

TABLE 13 - NORMAL SERVICE CONDITIONS FOR TRANSFORMER OPERATING IN FREE AIR

Maximum ambient temperature	40^0C
Average daily ambient temperature	30^0C
Average yearly ambient temperature	20^0C

Australian kiosks employ both, the hermetically sealed and the free-breathing distribution transformers. However, the users have given preferences to hermetically sealed transformers due to their superior performances and very low maintenance requirements. Those transformers are designed for top-oil temperature rise 60K (Kelvin) and average winding temperature rise 65K.

Temperature limits for sealed distribution transformers with "A" thermal class of the insulation system, assuming normal cyclic loading are presented in Table 14.

TABLE 14 - TEMPERATURE LIMITS FOR OIL-IMMERSED DISTRIBUTION TRANSFORMERS

Insulation system (top-oil temperature)	105^0C
Rated hot-spot winding temperature	98^0C
Maximum permissible hot spot temperature	140^0C

The above values do apply even if ambient temperatures are different to those in Table 13 (in Australian conditions demands for the maximum ambient temperature of 45^0C are not rare) or if an operation inside the kiosk substation or building is required.

7.5. Impact of the Enclosure on Transformer Temperature Rises

The IEC standard IEC 61330 compares transformer top-oil temperature rise in an enclosure and in free-air (for the same load) and the difference between those two values is defined as "the temperature class of the enclosure". It recommends three temperature classes for the enclosure: 10K, 20K and 30K. In addition to its temperature class, the enclosure is defined by its rated maximum power, i.e. the free-air rating of the largest transformer, which fits into that enclosure. It is clearly stated that the maximum power, expected to be delivered from the kiosk, is lower than the free-air rating of the transformer. The correlation of the temperature class of the enclosure and the ambient temperature is given in this example: a 20K class enclosure could release the full rating of the transformer only at an ambient temperature of 0^0C (i.e. average yearly ambient temperature 20^0C – 20K=0^0C). The Australian Standard AS 2374.7 recommends two methods in assessing the impact of the enclosure on the transformer hot spot temperature and the top oil temperature. The preferred (but not always feasible) method is to conduct the factory temperature rise tests on the transformer installed in the enclosures. The alternative method assesses the additional temperature rises experienced by the transformer operating in the enclosure by measuring the temperature rise of air inside the enclosure. It is suggested that half of the temperature rise of air inside the enclosure should be added to the transformer top-oil temperature rise obtained by testing in free-air operation. For example, an extra air-temperature rise in the kiosk-substation of 20^0C will increase top oil temperature rise of the transformer by 10^0C. A variation of this method is to correct transformer temperature rise by applying values for the temperature rise of air inside the enclosure recommended in AS 2374.7.

Some of those recommended corrections are presented in Table 15.

TABLE 15 - CORRECTIONS FOR INCREASE IN AMBIENT TEMPERATURE DUE TO KIOSK ENCLOSURE

Temperature increase in ambient due to enclosure	**Transformer size (kVA)**			
	250	500	750	1,000
	10^{0}C	15^{0}C	20^{0}C	-

The author has thoroughly investigated both variations of the second method and it appears that Table 3 in AS 2374.7, which provides recommendations for correction for increase in ambient temperature due to the enclosure, should be extended by considering the following:

- constructional features of enclosure, including equipment arrangement, ventilation system and protection (IP) level (IEC 60529); for example, the tests have shown that enclosures with a level of protection above IP24D (effective protection against ingress of solid foreign objects with diameter larger than 12.5 mm, against ingress of splashing water and against access to hazardous parts with a wire) cause very high restrictions on airflow and uneven distribution of temperatures of internal air;
- losses in transformer and switchgear; with a large number of transformer-switchgear arrangements the range of losses released in the kiosk-substation could be very wide. For example, a kiosk with a non-standard "high-loss" 750 kVA transformer (AS 2374.1.2-2003) and a fully enclosed LV switchboard could have higher total losses than a kiosk with an efficient "low-loss" 1,000 kVA transformer and a "low-loss" switchgear;
- external conditions (solar radiation, wind, slope sites);

- larger distribution transformers (1,000 kVA-2,500 kVA);
- provision for enclosures manufactured from alternative materials.

Application of the second method by assessing impact of the enclosure on the extra transformer top-oil temperature as 50% of the air temperature rise inside the enclosure is very difficult, simply because it is not clear how and where to measure temperature inside the enclosure. The analysis has also shown that the thermal classes for enclosures 10K, 20K and 30K, as recommended in IEC 61330 would not be the best solution for Australian conditions. 30K class substations, where the top-oil temperature rise inside enclosure is 30^0C higher than the top-oil temperature rise in free-air, would require very expensive distribution transformers.

The authors suggest that the thermal classes for Australian conditions should be limited to 10K, 15K and 20K as the same output could be achieved more efficiently with an effective ventilation system than with an over-designed transformer (AS 4388-1996). It seems that most Australian users prefer the 15K temperature class enclosure. Incidentally, designs for kiosk transformer for this type of enclosure appear to be the most economical under the current set of technical specifications in Australia (AS 4388-1996).

7.6. Case Study

The author has thoroughly investigated features of a range of kiosk substations (300 kVA - 2,000 kVA) locally developed and installed in Australia.

7.6.1. Enclosure

Most Australian manufacturers claim that their prototype enclosures have been successfully subjected to the full set of normal type tests. Some manufacturers offer a special type test to assess the effects of arcing due to an internal fault. The constructions features related to internal-arc tests have not been taken into account when assessing thermal performances of distribution transformers, as at present time, there is no big interest in the Australian market for kiosks with internal-arc containment features.

The kiosk-substations installed in Australia are very compact and fully outdoor-operated. The kiosk contains of a metallic enclosure with transformer and switchgear compartments and a base. Typically, the enclosure and compartments are made of 2.5 mm thick galvanized mild steel sheets. Some versions utilize aluminium or stainless steel sheets. The kiosk base is made of a reinforced concrete or hot-dip galvanized steel channels. The transformer compartment is in the middle, completely segregated from the LV and the MV switchgear compartments. Some kiosks include extensive ventilation and anti-condensation systems, lift-off enclosure facilities and oil-containments.

The ventilation system include air baffles, air ducts, prefabricated air grilles, holes punched in side-walls, outlet air openings above access doors in both switchgear compartments and air-grilles in transformer compartment walls as shown in Figure 14.

Most manufacturers offer enclosures in three to four different sizes, covering transformer sizes 300 to 2,500 kVA. Number of switching functions in MV compartment has considerable impact on size of the enclosure, as most transformers have already been “optimised” for kiosk application (i.e. significantly reduced in size comparing with ordinary outdoor type distribution transformers).

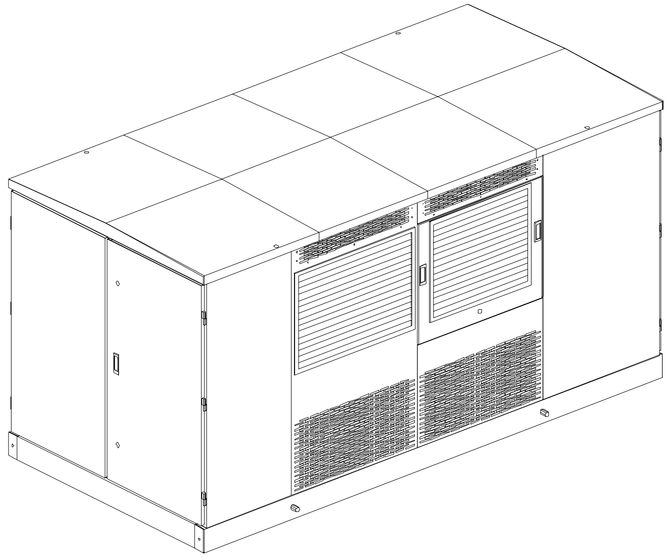

FIGURE 14 - A TYPICAL METALLIC ENCLOSURE FOR KIOSK SUBSTATION WITH VENTILATION OPENINGS ON SIDEWALLS

The standard required degree of protection for switchgear and transformer compartments is IP24D. The safety margin is achieved by designing standard enclosure in such a way that it is able to dissipate all heat generated inside and accumulated on its outside surfaces, for a slightly higher level of protection (e.g. IP25D, which has a higher level of protection against ingress of water). Ventilation openings are arranged to prevent any undesired condensation on electrical equipment and inner wall surfaces. The optimum airflow is achieved when the minimum quantity of heat dissipated by the transformer is discharged in switchgear compartments. A simplified air temperature diagram along the sidewall for a 1,000 kVA kiosk-substation is shown in Figure 15. The measurements taken during the temperature rise test show that the air temperature inside the enclosure is a mixture of different temperatures and a complex function of the position (distances from the heat-source, ventilation openings and air-flow barriers inside the enclosure). It is very difficult to talk about "average" temperature inside the enclosure because of large temperature divergences in all directions.

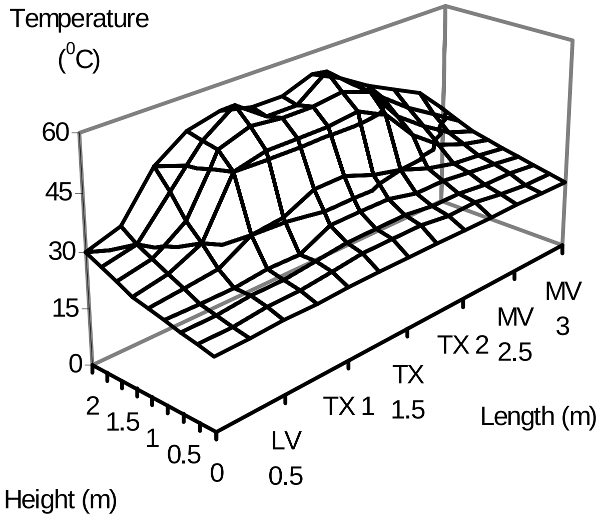

FIGURE 15 - AIR TEMPERATURE IN A 1,000 KVA KIOSK METALLIC ENCLOSURE MEASURED AT DISTANCE 50 MM FROM THE SIDE WALL (OUTSIDE AIR TEMPERATURE IS 18.8^{0}C)

The author adopted temperatures at two heights as relevant for transformer loading assessment:

- Topheight (50mm below the kiosk ceiling);
- Midheight (approximately half of the internal height of the kiosk and 50 mm from the sidewalls).

Typical temperature rises in a 1,000 kVA kiosk are shown in Figure 16. A simple methodology to calculate air-temperature around the transformer inside enclosure based on AS 4388-1996 has been developed. The calculated values are approximately 2^{0}C above the measured values and as such provide a small safety factor in transformer loading calculations.

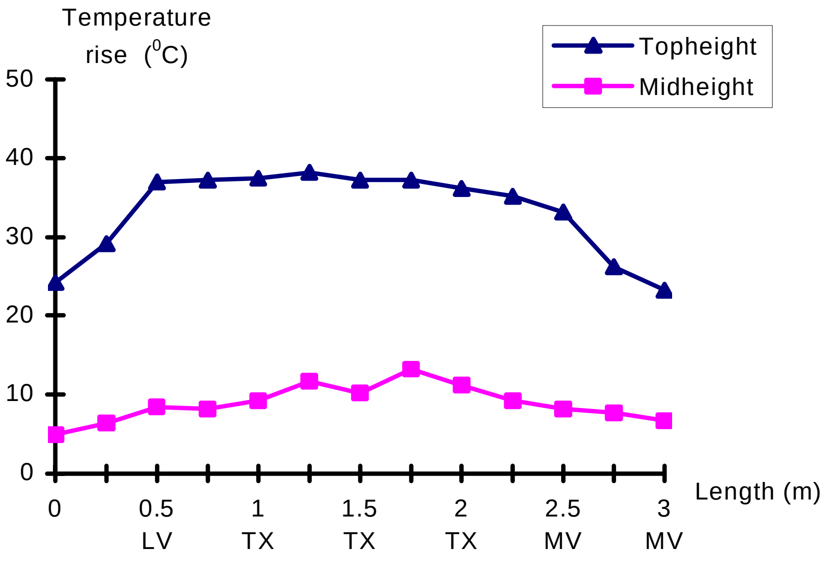

FIGURE 16 - TOPHEIGHT AND MIDHEIGHT TEMPERATURE RISES IN LOW VOLTAGE (LV), TRANSFORMER (TX) AND MEDIUM VOLTAGE (MV) COMPARTMENTS

The fact that the increase in transformer top oil temperature rise by 6^{0}C halves its life (AS 1078-1984) emphasizes importance of an accurate forecast of air temperatures inside the enclosure.

7.6.2. Transformer

Selection criteria for a distribution transformer are out of scope of this paper, and it has been assumed that all factors, such as network performance, specific load requirements and environmental considerations have been taken into account by selecting an appropriate rating and suitable design. Table 16 presents data for a typical Australian oil-immersed, *ONAN* distribution transformer designed for installation in kiosk substations.

TABLE 16 - TYPICAL DISTRIBUTION TRANSFORMER INSTALLED IN KIOSK SUSBTATION

Transformer data		
Transformer rated power (in enclosure)	kVA	1,000
Transformer total losses	W	8,950
Transformer thermal time constant	hours	3.7
LV compartment loss (typical)	W	580
HV compartment loss (typical)	W	300
Sun radiation (maximum)	W/m^2	980
Ventilation (inlets)	m^2	1.08
Ventilation (outlets)	m^2	1.20
Top oil temperature rise	^0C	59
Average winding temperature rise	^0C	63
Thermal gradient (average)	^0C	14
Maximum ambient temperature	^0C	40
Top-height temperature rise in transformer	^0C	35
Mid-height temperature rise in transformer	^0C	27
Pre-overload conditions		
Load (% of rated power)	%	75
Ambient temperature	^0C	30
Overloading		
Overload duration	hours	2
Overload (% of rated power)	%	145
Top oil temperature	^0C	103
Hot spot temperature	^0C	133
Bushings overload (short time)	%	150
Continuous loading for various free air temperatures		
Loading (% of rated power) at 10^{0}C	%	112
Loading (% of rated power) at 20^{0}C	%	103
Loading (% of rated power) at 30^{0}C	%	90
Loading (% of rated power) at 40^{0}C	%	82

Limiting the peak load to the transformer nameplate rating would result in an uneconomical use of the transformer overload capability. Short-time peak overloads, without significantly decreasing the life expectancy, are permitted (and very often requested) from distribution transformers installed in kiosk substations.

While the loading of the transformer, during the overload, can increase rapidly, the oil temperature increases more gradually with a time constant in the order of a few hours. The temperature gradient between windings and oil reaches its ultimate value quickly, but the slow rising temperature of cooler oil suppresses quick winding temperature rise. Hot-spot temperatures considerably above 98^0C can be carried for short periods of time without decreasing normal life expectancy, if this is offset by extended operation below 98^0C.

Table 17 compares overload requirements defined in AS 2374.7-1997 and capabilities of a typical Australian kiosk transformer (24 hours cyclic loading, maximum ambient temperature is 30^0C, duration of overload is 2 hours and preceding loading is 75% of the rated power). The kiosk transformer is thermally optimised and has a low temperature gradient and an increased thermal time constant. The difference between performances of the average transformer and the transformer designed for kiosk application is obvious.

TABLE 17 - OVERLOAD CAPABILITIES IN % OF RATED POWER

Rating	**AS2374.7 Requirements**	**Kiosk transformer**
1,000 kVA	130 %	145 %

7.7. CONCLUSION

The reliability of the entire LV network and thus most activities in residential, industrial and commercial areas depends on the reliability of kiosk substations and their most important part – the distribution transformer. Designing such an important part of distribution network requires knowledge and control not only of the functioning of its components, but also of the external influences to which they are subjected.

Most large distribution transformers in Australia are installed inside very compact metallic enclosures. Those transformers are specially designed for such an application and have thermal performances, which well exceed standard requirements. Classification of kiosk enclosures as proposed by IEC 61330 has been reviewed and a narrower range of temperature classes for enclosures has been suggested.

Loading of distribution transformers in kiosk-substations is not properly covered by the Australian Standards. Recommendations given by IEC 61330 are not fully applicable for Australian conditions. A design investigation was formulated to show the performance of optimised distribution transformer designs when installed in kiosk-substations. Simple methodology was developed to forecast temperature rises in transformer compartments at two different levels: midheight and topheight of the transformer compartment. Heat run tests confirmed calculated temperature rises under different overload conditions. Comparison between data for average transformers given in AS 2374.7-1997 and thermally optimised kiosk transformers confirmed the need to further investigate this topic. Future analysis should also include assessment of improved designs and the total operating costs for distribution transformers in kiosk substations.

8. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

8.1. Summary of Conclusions and Recommendations

Efficiency of distribution transformers is in range of 96 - 98.5% for standard models and above 99% for high efficiency models and is relatively high in comparison with majority of other machines and devices. However, as almost all electric power passes through distribution transformers before it is consumed at its final destination (converted to mechanical power, light or heat), the amount of energy, which distribution power transformers dissipate is very high.

The Australian distribution networks employ about 670,000 distribution transformers and about 19,000 new units are added to electrical distribution networks each year. It is estimated that the average life of distribution transformers is in order of 25 years, and the purchasing decisions based on poor assessment technologies and short-term objectives will have lasting effects on future generations. Such a poor economic choice could be avoided through introduction of new regulatory regime for minimum efficiency targets for distribution transformers and application of an advanced assessment methodology.

Introduction of mandatory Minimum Energy Performance Standards for distribution transformers in Australia has significantly helped to reverse the recent trends in purchasing policies, which were focused on low initial costs. However, the new regulatory regime should be supported by proven and accessible methodologies to optimise selection of distribution transformers. This research offers a new solution for assessment of distribution transformers based on:

- development of cost efficiency schedules for selected designs and representative kVA ratings;
- thorough financial analysis of distribution transformer losses.

This refined methodology highlights importance of design and costing stages in the assessment process. Further, it recommends moving from simple capitalisation of transformer losses by extending evaluation of the total operating costs through introduction of new evaluation factors based on life cycle cost concepts and on expected service and loading conditions. The fact that Australian distribution transformers are highly customized (designed for specific users and conditions) introduces additional complexities into assessment process. The presented case study on pad-mounted distribution transformers highlights importance of selecting proper kVA rating as well inclusion of expected service and loading conditions into total assessment process.

8.2. Emerging Technologies for Distribution Transformers

This research project did not include the following design and technology options:

- special conductor materials, such as silver and high-temperature superconductors;
- amorphous core material;
- carbon composite materials for removal of heat;
- high-temperature insulating material;
- power electronics technologies.

The aim of this research is assess only technologies incorporated in commercially available distribution transformers products, which are practical to manufacture, install, operate and maintain. A recommendation for further research would be to include the working prototypes, which are considered technologically feasible.

8.2.1. Silver as a Conductor Material

Although the use of silver as a conductor is technologically feasible (few distribution transformers with silver windings were built in the USA during World War II due to war-time lack of copper), this technology would be impracticable to implement. Silver has superior electrical properties in comparison to copper, and at room temperature (25^0C), however it has many limitations: high price, lower melting point, lower tensile strength and limited availability.

8.2.2. High-Temperature Superconductors

The original application of low-temperature superconducting materials (LTS) cooled by liquid helium has been improved by introduction of a new class of high-temperature superconducting (HTS) materials in 1987 McConnel (2000). These new superconducting materials use liquid nitrogen as a coolant, which is readily available and is considerably less expensive than liquid helium. There are number of research programs launched worldwide to explore use of HTS in power transformers. However, the use of superconductors in transformer manufacturing is still considered to be in experimental stages.

These issues are identified as limiting factors for commercial use of superconductors in production of distribution transformers:

- low-temperature superconductors are not feasible for commercial use due to inability of conductors to return to the superconducting state following a high fault current condition WEC (1982);

- high-temperature superconducting prototype built transformers include unique extremely brittle conductors with unacceptable variation in losses and require complex cryogenic support components.

Consequently, at this stage these transformers built on superconducting technology are not considered to be technologically feasible and practicable to manufacture.

8.2.3. Amorphous Core Material in Stacked Core Configuration

There are very limited applications of amorphous materials in distribution transformer cores. These materials have some obvious advantages: amorphous metals are extremely thin, have very high electrical resistivity, have very small magnetic domain definition and consequently no load losses in the distribution transformer cores made from these materials are 60-70% lower than no load losses in conventional designs. However, these cores saturate at only 1.57 Tesla (conventional low-silicon magnetic steels saturate at flux levels of 2.08 Tesla) and they have higher excitation currents. In addition, fragility of this material make amorphous transformer designs less space effective (they require larger winding windows, and consequently have a space factor of only 85%, whilst the space factor on conventional designs is 95 - 98%. Taking into account the above factors, the final result would be a distribution transformer with lower no load losses, lower flux density, higher space factor, larger core with greater load losses and higher production costs. In addition, as discussed by Nadel (2001) amorphous material is considered a viable core material only for wound-core arrangements. This material is not presently viable for stacked core configurations.

8.2.4. Carbon Composite Materials for Heat Removal

An emerging technology that may improve future designs for distribution transformers is the use of carbon fibre composite materials for heat removal. In addition to excellent electrical insulation performances, these materials are very good heat conductors. The first prototype suggests possibility of reducing size and core losses by 35% DOE *Screening Analysis* (2001). Unfortunately, this technology is not feasible for larger distribution transformers. It seems that this technology is still be several years away from commercialisation.

8.2.5. High-Temperature Insulating Material

The transformer industry is currently investigating several high temperature insulating materials. The aim is to create an electrical insulation that can withstand higher operating temperatures, which can conduct heat more effectively out of the core-coil assembly. Improved electrical insulation performances would result in smaller transformer volumes and consequently in lower losses. Unfortunately, this technology is not yet commercially feasible.

8.2.6. Power Electronics Technology

The application of power electronics technology for power transformers is in the early stages of development. A small transformer was built at Purdue University DOE *Screening Analysis* (2001), however no distribution transformer prototype has ever been manufactured using this technology.

8.3. Recommendations for Further Research

Recommendations for further research include:

- extension of the scope of research to include wider range of distribution transformers (single phase distribution transformers and dry type distribution transformers);
- assessment of emerging technologies and analysis of alternative design solutions;
- comprehensive assessment of impacts on environment;
- more inclusive analysis of impacts of new assessment methodologies on distribution utilities;
- it is recommended that the MEPS for distribution transformers are refined by including more rigorous analysis of retrospective analysis of impacts of MEPS on distribution transformer prices. This analysis should consider two separate components leading to price impacts: changes in manufacturing costs and commercial margin used to convert from manufacturing costs to final price.

9. PUBLICATIONS

No	Authors	Title	Conference / Proceedings
1.	M. All-Dabbagh S. Corhodzic	DISTRIBUTION NETWORK BEHAVIOUR UNDER DIFFERENT GROUNDING CONDITIONS	AUPEC'96 Melbourne 1996
2.	S. Corhodzic	THERMAL CHARACTERISTICS OF OIL-IMMERSED DISTRIBUTION TRANSFORMERS INSTALLED IN PADMOUNTED SUBSTATIONS	AUPEC'98 Hobart 1998
3.	A. Kalam S. Corhodzic	LOADING OF OIL-IMMERSED DISTRIBUTION TRANSFORMERS INSTALLED IN PADMOUNTED KIOSK SUBSTATIONS	INT-PEC'99 Churchill, Vic 1999
4.	A. Kalam S. Corhodzic	ASSESSMENT OF DISTRIBUTION TRANSFORMERS USING LOSS CAPITALISATION FORMULAE	AUPEC /EECON'99 Darwin 1999
5.	A. Kalam S. Corhodzic	ASSESSMENT OF DISTRIBUTION TRANSFORMERS USING LOSS CAPITALISATION FORMULAE	Journal of Electrical and Electronic Engineering Australia, Issue May 2000

6.	A. Kalam S. Corhodzic	ANALYSIS OF LOSS CAPITALISATION FORMULAE USED FOR ASSESSMENT OF AUSTRALIAN DISTRIBUTION TRANSFORMERS	IEEE/PowerCon 2000 Perth 2000
7.	A. Kalam S. Corhodzic	DEVELOPMENT OF UNIVERSAL STEP-UP TRANSFORMER FOR TASMANIAN POWER STATIONS	DISTRIBUTION 2003 Adelaide 2003
8.	A. Kalam S. Corhodzic	PERFORMANCES OF DISTRIBUTION TRANSFORMERS INSTALLED IN METALLIC ENCLOSURES – AN AUSTRALIAN EXPERIENCE	IEEE Transactions on Power Delivery July, 2005

REFERENCES

ABARE (2004), *Australian Energy: National and State Projections to 2019-20* Australian Bureau of Agricultural and Resource Economics e-Report 04.11, August 2004

AEEMA/ESAA (1998), *Specification for Polemounting Distribution Transformers*, Australian Electrical and Electronics Manufacturers Association and Electricity Supply Association of Australia, January 1998.

Australian Standard AS 1078-1984, *Guide to Loading of Oil-Immersed transformers*, 1984.

Australian Standard AS 2374.1-1997, *Power Transformers, Part 1: General*, 1997.

Australian Standard AS 2374.1.2-2003: *Power Transformers, Minimum Energy Performance Standard (MEPS) requirements for distribution transformers*, 2003.

Australian Standard AS 2374.7-1997, *Power Transformers: Loading Guide for Oil-Immersed Power Transformers*, December 1997.

Australian Standard AS 2735-1984, *Dry Type Power Transformers*,1984.

Australian Standard AS 3000:2000, *Wiring Rules*, September 1999.

Australian Standard AS 4388-1996, *A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low voltage switchgear and controlgear,* June 1996.

Australian Standards AS 2374 Series (Parts 1-8), *Power transformers*.

Barnes, P. et al. (1996), *Determination Analysis of Energy Conservation Standards for Distribution Transformers,* Technical Report ORNL/6847, Oak Ridge National Laboratory, 1996.

BEE (2003), *Determination Analysis of Standards & Labelling Program for Distribution Transformers*, Technical Report, Bureau of Energy Efficiency (India), 2003.

BPA (1986), *Transmission and Distribution Efficiency Improvement R & D Survey Project,* Bonneville Power Administration: DOE/BP-17102-1, 1986.

Canadian Standard CAN/CSA-C802.1-00 (2001), *Minimum Efficiency Values for Liquid-Filled Distribution Transformers,* 2001.

Canadian Standard CAN/CSA-C802.2-00 (2001), *Minimum Efficiency Values for Dry-Type Distribution Transformers,* 2001.

CIGRÉ (2003), *Guide on Economics of Transformer Management,* Working Group WG12-20, 2003.

COAG (1997), *Council of Australian Governments: Principles and Guidelines for National Standard Setting and Regulatory Action by Ministerial Councils and Standard-Setting Bodies.* Endorsed by COAG April 1995, Amended by COAG, November 1997.

DOE *ANOPR – FNR* (2004), US Department of Energy - Office of Energy Efficiency and Renewable Energy, Energy Conservation Program for Commercial and Industrial Equipment: Energy Conservation Standards for Distribution Transformers; *Proposed Rule, Advanced Notification of Proposed Rulemaking, Federal Registration Notice*, 10 CFR Part 430, July 2004.

DOE *Framework* (2000), US Department of Energy - Energy Efficiency and Renewable Energy, Building Technologies Program - Appliances and Commercial Equipment Standards – Distribution Transformers, *Framework Document for Distribution Transformer Energy Conservation Standards Rulemaking, Draft for Public Comment,* November 2001.

DOE *Screening Analysis* (2001), US Department of Energy - Energy Efficiency and Renewable Energy, Building Technologies Program - Appliances and Commercial Equipment Standards - Distribution Transformers, *Draft Screening Analysis*, 2001.

DOE *LCC* (2002), US Department of Energy - Energy Efficiency and Renewable Energy, Building Technologies Program - Appliances and Commercial Equipment Standards – Distribution Transformers, *Distribution Transformer Rulemaking, Life Cycle Cost*

Analysis (Draft for Review Only), Lawrence Berkeley National Laboratory, Berkeley, June 2002.

EEA (2003), *Proposed EECA Minimum Energy Performance Standards for Distribution Transformers*, Electrical Engineers Association New Zealand, November 2003.

EECA (2004), *Appliance and Equipment Energy Efficiency Forward Programme 2004-05* Energy Efficiency and Conservation Authority New Zealand, June 2004.

EES & EC (2001), *Energy Labelling and Standards Programs throughout the World.* Energy Efficient Strategies and EnergyConsult, for NAEEEC, December 2001.

EIA (2003), *International Energy Outlook*. Energy Information Administration, 2003.

Ellis, M. (2000), *National Appliance and Equipment Energy Efficiency Program Analysis of Potential for Minimum Energy Performance Standards for Distribution Transformers.* Prepared for the Australian Greenhouse Office by Mark Ellis & Associates with the assistance of Professor Blackburn T. (UNSW), March, 2001.

Feinberg, R. (1979), *Modern Power Transformer Practice*, Wiley, New York, 1979.

Franklin, A. C. and Franklin D. P. (1993), *The J & P Transformer Book,* Butterworth-Heinemann, London, 1993.

GWA (1991), *Residential Appliances in Australia: An assessment of market and technology developments, with particular reference to energy efficiency*. George Wilkenfeld and Associates for State Electricity Commission of Victoria Demand Management Unit, June 1991.

GWA (1999), *Regulatory Impact Statement: Energy Labelling and Minimum Energy Performance Standards for Household Electrical Appliances in Australia*. George Wilkenfeld and Associates with assistance from Energy Efficient Strategies, for Australian Greenhouse Office, February 1999.

GWA (1999a), *Regulatory Impact Statement: Energy Labelling and Minimum Energy Performance Standards for Household Electrical Appliances in Australia. Supplementary cost-benefit analysis on* *transition to a revised energy label.* George Wilkenfeld and Associates, for Australian Greenhouse Office, November 1999.

GWA (2000), Draft for Public Comment: *Regulatory Impact Statement: Minimum energy performance standards and alternative strategies for electric motors* George Wilkenfeld and Associates for Australian Greenhouse Office, September 2000.

GWA (2002), *Regulatory Impact Statement: Minimum energy performance standards and alternative strategies for electricity distribution transformers*, George Wilkenfeld and Associates with Energy Efficient, Draft for Public Comment: Report for Australian Greenhouse Office, January 2002.

GWA (2004, *A preliminary cost benefit study of the transition to the GAEEEP*, George Wilkenfeld and Associates for SEAV, February 2004.

GWA (2004a), *National Appliance and Equipment Energy Efficiency Program (NAEEEP): Coverage of the Residential, Commercial and Manufacturing Sectors*, George Wilkenfeld and Associates for Australian Greenhouse Office, August 2004.

Harrison, T. H., and Richardson, B. (1988), *Transformer Loss Reductions*, CIGRÉ International Conference on Large High Voltage Electric Systems, 1988.

Holt, S., J.Weston and R.Foster (2001), *The Australian Experience of Mandatory Product Standards.* Paper for the Collaborative Labelling and Appliance Standards Program (CLASP) Asia Regional Symposium on Energy Efficiency Standards and Labelling, May 2001.

Howe, B. (1993), Distribution Transformers: A Growing Energy Savings Opportunity, E-Source, Inc., 1993.

ICF (1998), *Transforming Dollars in Sense*, ICF Inc., Report prepared for EPA, 68-D4-0088, 1998.

IEA (2003), *World Energy Investment Outlook.* International Energy Agency, 2003.

IEC Standard IEC 60076, *Power transformers*, IEC 60076 Series, (Parts 1-10).

IEC Standard IEC 60076-1:1993, *Power Transformers*, 1993.

IEC Standard IEC 60354 Ed. 2.0 B (1991), *Power Transformers: Loading Guide for Oil-Immersed Power Transformers*, October. 1992.

IEC Standard IEC 60529 Ed 2.1:2001, *Degrees of protection provided by enclosures (IP Code),* February 2001.

IEC Standard IEC 61330 Ed. 1.0 B (1995), *High-voltage / low-voltage prefabricated substations*, December 1995.

IEEE Standard IEEE PC57.12.33 (2001), *Draft Guide for Distribution Transformer Loss Evaluation*, Report No. IEEE PC57.12.33/D8, 2001.

IPART (1999), *Regulatory Mechanism to Encourage Effective Management of Network Losse*s, Report by Intelligent Energy Systems for Independent Pricing and Regulatory Tribunal (NSW), Research Paper No.15, March 1999.

Kennedy, B.W. (1998), *Energy Efficient Transformers* McGraw-Hill, 1998.

LE (2005), *The Potential for Global Energy Savings from High Efficiency Distribution Transformers*, Leonardo Energy, European Copper Institute, Brussels, February 2005.

Lenasi, K. (1981), Cost *Effective Active Part of Power Transformer*, JK CIGRÉ, Beograd, 1981 (in Slovenian).

Ling, P.J.A. (2003), *Overcoming Transformer Losses,* Electrical Construction and Maintenance, August 2003.

McConnell, B. (2001), *Scaling Size-Performance Relations in Transformers*, Oak Ridge National Laboratory, 2001.

McConnell, B. W. (2000), *Transformers - A Successful Application of High Temperature Superconductors*, IEEE Transactions on Applied Superconductivity, Vol. 10, No. 1, pp 716-720, March 2000.

McDermott, M. (1999), *The Scope for Energy Saving in the EU Through the Use of Energy Efficient Electricity Distribution Transformers*, Technical report, European Commission, Thermie Programme, 1999.

McDermott, M. (2000), *Energy Efficient Distribution Transformers-Utility Initiatives,* Technical report, European Copper Institute, 2000.

McMahon, J. (2004), *Comparison of Australian and US Cost Benefit Approaches to MEPS,* Lawrence Berkeley National laboratory, Berkeley, USA, April 2004.

MEA (2002), *Energy Labelling & Minimum Energy Performance Standards for Domestic Gas Appliances*, Mark Ellis & Associates, Energy Efficient Strategies and George Wilkenfeld & Associates, for the Sustainable Energy Authority Victoria, November 2002.

MEA (2003), *Regulatory Impact Statement: Minimum Energy Performance Standards and Alternative Strategies for Linear Fluorescent Lamps* Mark Ellis and Associates for AGO, Draft for Public Discussion, December 2003.

MEPS *Fact Sheet* (2004), *Summary of MEPS Requirements for Distribution Transformers* – Fact Sheet, 2004.

MIT (1943), *Magnetic Circuits and Transformers*, MIT Electrical Engineering Course Book, Cambridge, 1943.

MR (2004), Media Release # MR 057/04, http://www.accc.gov.au, Issued: 7th April 2004.

Nadel, S. (2001), *Energy Conservation Standards for Distribution Transformers Rulemaking*, DOE Docket Number EE-RM/ST-00-550, comment No. 14, January 16, 2001. American Council for an Energy-Efficient Economy, 2001.

NAEEEC (1999), *National Appliance and Equipment Energy Efficiency Program,* National Appliance and Equipment Energy Efficiency Committee, Canberra, 1999.

NAEEEC (2000), *National Appliance and Equipment Energy Efficiency Program: Projected combined impacts from an extended and enhanced program,* National Appliance and Equipment Energy Efficiency Committee, Canberra, March 2000.

NAEEEC (2001), *National Appliance and Equipment Energy Efficiency Program: MEPS Profile, Distribution Transformers,* National Appliance and Equipment Energy Efficiency Committee, Canberra, March 2001.

NAEEEP (1999), *National Appliance and Equipment Energy Efficiency Program* National Appliance and Equipment Energy Efficiency Committee, Canberra, 1999.

NAEEEP (2000), *National Appliance and Equipment Energy Efficiency Program: Projected combined impacts from an extended and enhanced program*, Canberra, March 2000.

NAEEEP (2001), *National Appliance and Equipment Energy Efficiency Program: Achievements 2000* Australian and New Zealand Minerals and Energy Council, March 2001.

NAEEEP (2001a), *Minimum Energy Performance Standards – Distribution Transformers,* Australian and New Zealand Minerals and Energy Council, Canberra, March 2001.

NAEEEP (2001b), *National Appliance and Equipment Energy Efficiency Program: Achievements 2000* Australian and New Zealand Minerals and Energy Council, March 2001.

NAEEEP (2001c), *National Appliance and Equipment Energy Efficiency Program: Future Directions 2002-04* Australian and New Zealand Minerals and Energy Council, March 2001.

NAEEEP (2002), *Standby Power Consumption: a long-term strategy to achieve Australia's one-watt goal 2002 to 2102*, July 2002.

NAEEEP (2002a), *A Review of the Stringency Levels for the Mandatory Minimum Efficiency of Three-Phase Cage Induction Motors in Australia*. September 2002.

NAEEEP (2003), *When you can measure it, you know something about it: Projected Impacts 2000–2020*, Report 2003/02, January 2003.

NAEEEP (2004), *Greenlight Australia: Discussion Paper for Improving the Efficiency of Lighting in Australia, 2005–2015*, Report 2004/08, 2004.

NAEEEP (2005), *National Appliance and Equipment Energy Efficiency Program: Projected Impacts 2005-2020*, National Appliance and Equipment Energy Efficiency Committee, Prepared by George Wilkenfeld and Associates, Canberra, January 2005.

NEMA (2002), *Guide for Determining Energy Efficiency for Distribution Transformers*, NEMA Standards Publication TP 1-2002, 2002.

NGS (1998), *The National Greenhouse Strategy*, Commonwealth of Australia, Canberra, 1998.

NRC (2000), *Proposed Amendment to Canada's Energy Efficiency Regulations: Dry Type Transformers*, Natural Resources Canada Bulletin, December 2000.

OGEM (2003), *Electricity Distribution Losses*, Technical report, Office of Gas and Electricity Markets, 2003.

ORG (2000), *Report on Distribution System Losses,* Prepared for the Office of the Regulator-General, Victoria, February 2000.

PCMS (1999-2005), Personal communication and results of market survey and analysis provided on a confidential basis, 1999-2005.

Shibata, E. (2003), *Amorphous Transformers in Japan*, Production and Electricity, September 2003.

Shincovich, J. T. and R. E. Stephens (1981), *A Method for Economic Evaluation of Distribution Transformers*, Task Force on Distribution Transformer Evaluation for the EEI Transmission and Distribution Committee, April 1981.

Syneca (2003), *MEPS for Electric Motors: Regulatory Impact Statement* Syneca Consulting for Australian Greenhouse Office, Draft, December 2003,

TSD (2004), Ernest Orlando Lawrence Berkeley National Laboratory and Navigant Consulting, Inc., *Technical Support Document: Energy Efficiency Program For Commercial And Industrial Equipment: Electrical Distribution Transformers*, prepared for U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program, Appliances and Commercial Equipment Standard, Washington, DC 20585, July 2004.

USEPA (1998a), *Energy Star Transformer Program: promoting competitiveness &environmental quality for America's Electric Utilities,* US Environmental Protection Agency, 1998.

USEPA (1998b), *Transforming Dollars Into Sense: The economic and environmental benefits of high-efficiency distribution transformer,* Prepared by ICF Incorporated for the US Environmental Protection Agency, Atmospheric Pollution Prevention Division, Washington DC, 1998.

WEC (1982), Westinghouse Electric Corporation, *Applications of Low-Temperature Technology to Power Transformers*, U. S. Department of Energy, DOE/ET/29324-1, February 1982.

Wilkenfeld (2002), *Minimum Energy Performance Standards and Alternative Strategies For Electricity Distribution Transformers, Regulatory Impact Statement,* Prepared by Wilkenfeld G. and Associates for the Australian Greenhouse Office, Public Discussion Draft, January 2002.

APPENDICES

APPENDIX 1 - DISTRIBUTION TRANSFORMERS – TYPICAL PRODUCT DATA

Table A1-1 Single Phase Distribution Transformers Registered with Australian Greenhouse Office (Energy Efficiency) – Status: January 2005

Manufacturer	Model	Network Voltage kV	Rated Output kVA	High Efficiency
ETEL	D217	22	25	-
	D240	11	15	-
	D241	11	30	-
	D216	22	16	-
	D218	22	25	-
	D242	22	50	-
	D253	11	10	-
	D252	22	10	-
	D254	11	25	-
	D255	11	50	-
ABB Transformers	X015NGS3F	11	15	-
	X030NGS3G	11	30	-
	X050NGS3G	11	50	-
	50kVA, LW,LS	11	50	-
	10kVA, LW,LS	11	10	-
	16kVA, LW,LS	11	16	-
	25kVA, LW,LS	11	25	-
Tyree Transformers Aust. Pty Ltd	50M2A-B	22	50	-
	25M2A-B	22	25	-
	25M7A-A	22	25	-
	16M1A-C	11	16	

Table A1-2 Three Phase Distribution Transformers Registered with Australian Greenhouse Office (Energy Efficiency) – Status: January 2005

Manufacturer	Model	Network Voltage kV	Rated Output kVA	High Efficiency
Schneider Electric (Australia) Pty Limited	MG2000	11	2000	-
	MG400	11	400	-
	MG500	11	500	-
	MG600	11	600	-
	MG750	11	750	-
	MG800	11	800	-
	MG1000	11	1,000	-
	MG300	22	300	-
	MG1500	11	1,500	-
	MG200	22	200	-
	MG2500	11	2,500	-
	MG1250	11	1,250	-
	MG315	22	315	-
	MG100	22	100	-
	MG160	22	160	-
Tyree Transformers Aust. Pty Ltd	500M4B	11	500	-
	200M5B-C	22	200	YES
	100M4A	11	100	YES
	25M4A-C	11	25	-
	315M5B-B	22	315	-
	63M5A-B	22	63	-
	400M4B-C	11	400	YES
Wilson Transformers Co. Pty Ltd	100KVA	11	1,000	YES
	1500KVA	11	1,500	YES
	750KVA	11	750	YES
	500KVA	11	500	YES
	315KVA	11	315	YES
	200KVA	22	200	YES
	2000KVA	11	2,000	-
	100KVA	11	100	-
ABB Transformers	X300PHM3B	22	300	-
	XK10NHM3F	11	1,000	-
	X030NHW3F	11	30	-
	X050NHW3G	11	50	-
	X075NHW3G	11	75	-
	X100NHW3H	11	100	-
	X150NHW3B	11	150	-
	X200NHW3F	11	200	-
	X300NHM3M	11	300	-
	X750NHM3F	11	750	-

ABB Transformers	X500PHM3A	22	500	-
	HK15NKM2A	11	1,500	-
	X050PHW3C	22	50	-
	X075PHW3B	22	75	-
	X150PHW3A	22	150	-
	X200PHM3B	22	200	-
	X500NHM3N	11	500	-
	25KVA, LW,LS	11	25	-
	63KVA, LW,LS	11	63	-
	100KVA, LW,LS	11	100	-
	200KVA, LW,LS	11	200	-
	315KVA, LW,LS	11	315	-
	500KVA, LW,LS	11	500	-
	750KVA, LW,LS	11	750	-
	1000KVA, LW,LS	11	1,000	-
	1500KVA, LW,LS	11	1,500	-
	2000KVA, LW,LS	11	2000	-
	XK10PHM3B	22	1,000	
	XK20NHM3E	11	2,000	-
ETEL	D221	22	63	-
	D222	22	100	-
	D250	22	200	-
	D232	22	315	-
	D224	22	200	-
	D243	11	15	-
	D214	11	750	-
	D098	11	500	-
	D215	11	1,000	-
	D206	11	30	-
	D207	11	50	-
	D208	11	75	-
	D209	11	100	-
	D210	11	150	-
	D211	11	200	-
	D212	11	300	-

AREVA Ultra-compact liquid filled distribution transformer (Siltrim)

Table A1-3 Ratings and dimensions

	1,600 kVA	2,000 kVA	2,300 kVA
Rated voltage kV	20	20	20
No Load Losses kW	2.0	2.4	2.5
Load Losses (at 120 °C) W	13,000	18,000	19,000
Impedance (at 120 °C) %	6	6	6
Length (l) mm	1,992	2,110	2,245
Width (w) mm	770	770	770
Height (h) mm	1,676	2,040	2,125
Total weight kg	3,430	4,400	5,580

Description

There are increasing requirements for a distribution transformer that can fit into compact volumes such as inside wind turbine towers. Until recently, the solutions available came with a significant compromise: a rising winding temperature. This resulted in reduced life expectancy and overheated environment for the surrounding power electronics and low-voltage equipment. Areva has developed an innovative, highly technically advanced solution, SILTRIM distribution transformer. That patented design allows to retain low winding temperature despite transformers extremely compact size. SILTRIM is specifically built for complex mechanical & electrical environments and is installable in the harshest environmental locations, meeting the demand for up to 2.3 MVA and 20 kV.

Advantages

- Long life cycle, compact, fire resistant, explosion-proof;
- Designed for high harmonics environment and overload conditions;
- Low heat dissipation;
- Near-zero maintenance, recyclable;
- Further resistance to vibration with optional vibration pads;
- Highest level of availability and reliability.

It is test-proven for extremely high level of over-voltage and is equipped with a pressure-relief device as additional safety measure against explosion. It offers lower winding hotspot temperatures resulting to longer working life with high availability and reliability. SILTRIM handles high harmonics environment and overload conditions. It is designed to provide protection against over- fluxing, through its correct application of operating flux density and use of magnetic core material.

Performances and Application Field

The high level of SILTRIM's performance (higher efficiency, low temperature rise, fire resistance) combined with its compactness is obtained by using excellent heat dissipation dielectric such as silicon oil or *Midel*.

The SILTRIM transformer is ideally suited for installation in wind turbines towers, compact sub-stations, on-and off-shore platforms. Extremely compact, it fits into reduced spaces and remains cool. It offers lower winding hotspot temperatures resulting to longer working life with high availability and reliability.

TPC liquid filled distribution transformer – Typical modern European distribution transformer
Table A1-4 Technical Data

Type		**Pole-mounted**			**Ground-mounted**			**Ground mounted reduced noise level**
Rated power	kVA	50	100	160	100	160	250	250
Rated primary voltage	kV	15 or 20						20
Off load tap changing	%	± 2.5 by step of 2.5 %						
Operating volts/Test volts/BI L	kV	17.5 / 38 / 95 or 24 /50 / 125						24 / 50 /125
Off load secondary voltage	V	410 off load between phases, 237 between phases and neutral						
Vector group symbol		Yzn11	Dyn11	Dyn11	Dyn11	Dyn11	Dyn11	Dyn11
No Load Losses (W)		125	210	375	210	375	530	460
Load Losses (W) - (75°C)		1,350	2,150	3,100	2,150	3,100	4,200	4,000
Impedance voltage	*U*cc %	4	4	4	4	4	4	4
No-load current	Io%	1	1	1.5	1	1.5	1	2.1
Acoustic power LWA	dB(A)		49	57	49	57	60	44

Table A1-5 Dimensions and Weights

Type		**Pole-mounted**			**Ground-mounted**			**Ground mounted reduced noise level**
Rated power	kVA	50	100	160	100	160	250	250
Length	mm	935	1,125	115	914	894	1,200	1,174
Width	mm	730	730	780	730	770	800	779
Height	mm	1,044	1,140	1,193	1,027	1,083	1,300	1,410
Total weight	kg	390	476	549	515	615	974	1,095
Mineral oil weight	kg	129	132	117	133	148	270	274

Product Description

- Three-phase totally filled and hermetically sealed mineral oil immersed distribution transformer;
- Pole-mounted: 50, 100, 160 kVA; ground-mounted: 100, 160 and 250 kVA;
- Primary voltages 15 or 20 kV;
- Secondary voltage 410 V;
- Frequency 50 Hz;
- Equipped with a built-in protection shut down system.

Advantages

The TPC is a new technical generation of distribution transformers. It offers reaction to every type of failure that may occur by ensuring systematic disconnection of the HVA network. The TPC has its own HV protection so that in the case of a fault it disconnects itself from the grid without tripping the HV protection devices of the source substation, and without generating any abnormal LV voltage. It doesn't explode and it doesn't pollute. It avoids HV network disruptions. Integration of a patented protection and disconnection system with fuse interruption of the power means: power interruption occurs within 20 msec (which cannot be done with a switch). This protection system is equipped with a locking device which avoids operation of the short-circuit system during transport and handling operations. This model is interchangeable with transformers of earlier technical generations. This transformer has same conventional components and characteristics as the previous models (i.e. similar tank design and compatibility with existing LV protection systems). The TPC can be used to replace a conventional transformer of an earlier technical generation (HN 52-S-20 EDF specification) without modifying the installation. The differences are in the on-load connection of HVA bushings for pole-mounted transformers and reduced overall dimensions (for example, a 250 kVA TPC is smaller than a 160 kVA EDF HN 52-S-20).

Application Field

The TPC is mainly dedicated to pole-mounted or ground mounted new installations in substations, renewal of transformers and installations in sensitive areas (e.g. fire risk, high level of pollution, high traffic areas etc.)

Protection System

- 2 HVA fuses;
- 2 micro fuses together with 2 strikers;
- 1 three-phase short-circuit system;
- 1 pressure detector;
- 1 oil level detector associated to a striker;
- in addition, the connections and coils insulation have been reinforced to avoid the risks of electrical earth faults.

Main Components

- 1 locking system of the short-circuiting switch (to be used during transport and handling);
- 1 HVA off-load tap changer;

- 1 filling hole;
- 1 rating plate;
- 2 lifting lugs;
- 1 device for earth continuity between tank and cover;
- 1 M12 earthing bolt;
- anti-corrosion tank treatment;
- RAL 7033 final standard paint.

Pole-mounted type

- 3 synthetic HVA bushings 24 kV / 250 A fitted with insulated bird-proof terminals that allow live connection;
- these bushings are in accordance with seaside installation conditions (extended creepage distance);
- 4 LV porcelain bushings 1 kV / 250 A;
- 1 standard mounting device.

Ground-mounted type

- 3 HVA plug-in bushings 24 kV / 250 A fixed parts;
- 4 LV porcelain bushings 1 kV / 250 A up to 160 kVA fitted with 4 individual flexible PVC sheaths (IP2X IK07);
- 4 LV busbars for 250 kVA fitted with 4 individual flexible PVC sheaths (IP2X IK07 that allow connection of 1 or 2 cables);
- 4 rollers.

APPENDIX 2- SUMMARY OF AS FOR POWER TRANSFORMERS

AS 2374.1-1997 POWER TRANSFORMERS - GENERAL

Scope

This part of International Standard IEC 76 applies to three-phase and single-phase power transformers (including auto-transformers) with the exception of certain categories of small and special transformers such as:

- single-phase transformers with rated power less than 1 kVA and three-phase transformers less than 5 kVA;
- instrument transformers;
- transformers for static converters;
- traction transformers mounted on rolling stock;
- starting transformers;
- testing transformers;
- welding transformers.

When IEC standards do not exist for such categories of transformers, this part of IEC 76 may still be applicable either as a whole or in part. For those categories of power transformers and reactors which have their own IEC standards, this part is applicable only to the extent in which it is specifically called up by cross-reference in the other standard. At several places in this part it is specified or recommended that an 'agreement' shall be reached concerning alternative or additional technical solutions or procedures. Such agreement is to be made between the manufacturer and the purchaser. The matters should preferably be raised at an early stage and the agreements included in the contract specification.

Abstract

Specifies the technical requirements for single and three-phase power transformers, including auto transformers, but excludes single-phase transformers rated at less than 1 kVA, three-phase transformers rated at less than 5 kVA, and certain special transformers such as instrument, starting, testing and welding transformers, transformers for static converters and those mounted on rolling stock. Based on but not equivalent to and has been reproduced from IEC 76-1:1993. Includes Australian variations such as commonly used power ratings and preferred methods of cooling, connections in general use, and details regarding connection designation.

History

- First published as part of AS C61-1931;
- Second edition 1946;
- Third edition 1963;
- Fourth edition 1970;
- Revised and redesignated in part as AS 2374.1-1982 and AS 2374.4-1982;
- AS 2374.1-1982 and AS 2374.4-1982 revised, amalgamated and designated AS 2374.1-1997.

AS 2374.1.2-2003: POWER TRANSFORMERS - MINIMUM ENERGY PERFORMANCE STANDARD (MEPS) REQUIREMENTS FOR DISTRIBUTION TRANSFORMERS

Scope

This standard applies to dry-type and oil-immersed type, three-phase and single-phase power transformers with power ratings from 10 kVA to 2,500 kVA and system highest voltage up to 24 kV. This standard does not apply to certain categories of special transformers such as

- transformers other than those on 11 or 22 kV networks;
- instrument transformers;
- auto transformers;
- traction transformers mounted on rolling stock;
- starting transformers;
- testing transformers;
- welding transformers;
- three phase transformers with three or more windings per phase;
- arc-furnace transformers;
- earthing transformers;

- rectifier or converter transformers;
- uninterruptible power supply (ups) transformers;
- transformers with an impedance less than 3% or more than 8%;
- voltage regulating transformers;
- transformers designed for frequencies other than 50 Hertz;
- gas-filled dry-type transformers;
- flame-proof transformers.

Abstract

Specifies minimum power efficiency levels and high power efficiency levels for oil-immersed and dry-type distribution transformers, with power ratings from 10 kVA to 2500 kVA, intended to be used on 11 kV and 22 kV networks. It is expected that this Standard will be called into legislation by individual States and Territories mandating these requirements under Minimum Energy Performance Standard (MEPS) regulations.

History

- First published as AS 2374.1.2-2003.

AS 2374.2-1997: POWER TRANSFORMERS - TEMPERATURE RISE

Scope

This part of International Standard IEC 76 identifies transformers according to their cooling methods, defines temperature-rise limits and details the methods of test for temperature-rise measurements. It applies to transformers as defined in the scope of IEC 76-1.

Abstract

Specifies temperature-rise limits and methods of test for measuring temperature rise. Based on but not equivalent to, and has been reproduced from IEC 76-2:1993. Includes Australian variations.

History

- First published as part of AS C61-1931;

- Second edition 1946;
- Third edition 1963;
- Fourth edition 1970;
- Revised and redesignated in part as AS 2374.2-1982;
- Second edition 1997.

AS 2374.3.0-1982: POWER TRANSFORMERS - INSULATION LEVELS AND DIELECTRIC TESTS - GENERAL REQUIREMENTS

Scope

This standard specifies the insulation levels and dielectric tests for power transformers.

Abstract

Specifies the insulation levels and dielectric tests for power transformers as defined in AS 2374.1. Based on IEC 76-3.

AS 2374.3.0-1982/AMDT 1-1992: POWER TRANSFORMERS - INSULATION LEVELS AND DIELECTRIC TESTS

AS 2374.3.1-1992: POWER TRANSFORMERS - INSULATION LEVELS AND DIELECTRIC TESTS - EXTERNAL CLEARANCES IN AIR

Abstract

Sets out minimum clearances in air between live parts of bushings on oil-immersed power transformers and objects at earth potential. The text has been reproduced from IEC 76-3-1:1987 and the tabulated minimum clearances have been modified.

History

- First published as AS 2374.3.1-1992.

AS 2374.5-1982: POWER TRANSFORMERS - ABILITY TO WITHSTAND SHORT-CIRCUIT

Scope

This standard specifies the design of power transformers as defined in AS 2374, Part 1, and the requirements necessary both in regard to their ability to withstand short-circuit and the means of demonstrating that ability.

NOTES:

1. Pending the publication of a standard that applies to dry-type transformers, the requirements of this standard may be applied to dry-type transformers subject to agreement between the purchaser and the manufacturer and taking into account the principles established in Sections 2 and 3.
2. A reduced schedule of short-circuit tests may be applied to Category I transformers by agreement between purchaser, manufacturer and testing authority. Guidance on the reduced schedule is given in Appendix A.

Abstract

Specifies the design of power transformers as defined in AS 2374.1, and the requirements necessary both in regard to their ability to withstand short-circuit and the means of demonstrating that ability. Based on IEC 76-5.

AS 2374.6-1994: POWER TRANSFORMERS - DETERMINATION OF TRANSFORMER AND REACTOR SOUND LEVELS

Scope

This standard defines the methods by which the sound levels of transformers, reactors and their associated cooling equipment shall be determined so that compliance with any specification requirements may be confirmed and the characteristics of the noise emitted in service determined.

This standard is intended to apply to measurements made in the manufacturer's works since conditions may be very different when measurements are made on site because of the proximity of other objects, background extraneous noises, etc. Nevertheless, the same general rules as are given herein may be followed when on-site measurements are made.

In those cases where sufficient power is available in the factory to permit full energisation of reactors, the methods to be followed are the same as for transformers. Such measurements shall be made by agreement between the manufacturer and the purchaser. Alternatively, measurements may be made on site where conditions are suitable.

The methods are applicable to transformers and reactors covered by IEC Publications 76, 726 and 289, without further limitation as regards size or voltage and when fitted with their normal auxiliary equipment, inasmuch as it may influence the measurement result. Although the following text refers only to transformers, it is equally applicable to reactors provided that it is recognized that the current taken by a reactor is dependent on the voltage applied and, consequently, that a reactor cannot be tested at no-load.

This standard provides a basis for calculation of sound power levels.

The methods of measurement and the environmental qualification procedure given in Appendix A are in accordance with ISO Standard 3746. Measurements made in conformity with this IEC standard tend to result in standard deviations which are equal to or less than 3 dB.

Abstract

Defines sound power versus sound pressure and sets out the methods by which the sound power levels of transformers, reactors, and their associated cooling equipment shall be determined. Standard and reduced sound power level limits for transformers only have been added in an Australian Appendix. Technically equivalent to IEC 551:1987, with the addition of Appendix AA.

History

- First published as part of AS C61-1931;
- Second edition 1946 (endorsement of BS 171-1936 with amendments);
- Third edition 1963;
- Fourth edition 1970;
- Revised and redesignated in part as AS 2374.6-1982;
- Second edition 1994.

AS 2374.6-1994/AMDT 1-2000: POWER TRANSFORMERS DETERMINATION OF TRANSFORMER AND REACTOR SOUND LEVELS

AS 2374.7-1997: POWER TRANSFORMERS - LOADING GUIDE FOR OIL-IMMERSED POWER TRANSFORMERS

Scope

This guide is applicable to oil-immersed transformers complying with IEC 76. It indicates how, within limits, transformers may be loaded above rated conditions. For furnace transformers, the manufacturer should be consulted in view of the peculiar loading profile.

Abstract

Provides guidance on determining the acceptable relationship between transformer rating and proposed load cycle when considering the effect of operating temperatures on life expectancy due to insulation deterioration and thermal ageing. Includes recommendations for loading above the nameplate rating and guidance for choosing appropriate rated quantities and loading conditions for new installations. It applies to the same range of transformers complying with AS 2374.1-1997. This Standard is technically equivalent to and reproduced from IEC 354:1991 and includes Australian informative appendices on determination of the thermal time-constant and indirect measurement of winding hot-spot temperature.

History

- First published as AS CC10-1965;
- Revised and redesignated AS 1078.1-1972;
- Revised and redesignated AS 1078-1984;
- Revised and redesignated AS 2374.7-1997;

AS 2374.7-1997/AMDT 1-1998: POWER TRANSFORMERS - LOADING GUIDE FOR OIL-IMMERSED POWER TRANSFORMERS

AS 2374.8-2000: POWER TRANSFORMERS - APPLICATION GUIDE

Scope

This Standard applies to power transformers complying with the series of publications IEC 60076.

It is intended to provide information to users about:

- certain fundamental service characteristics of different transformer connections and magnetic circuit designs, with particular reference to zero-sequence phenomena;

- system fault currents in transformers with YNynd and similar connections;
- parallel operation of transformers, calculation of voltage drop or rise under load, and calculation of load loss for three-winding load combinations;
- selection of rated quantities and tapping quantities at the time of purchase, based on prospective loading cases;
- application of transformers of conventional design to convertor loading;
- measuring technique and accuracy in loss measurement.

Part of the information is of a general nature and applicable to all sizes of power transformers. Several chapters, however, deal with aspects and problems which are of the interest only for the specification and utilization of large high-voltage units. The recommendations are not mandatory and do not in themselves constitute specification requirements. Information concerning loadability of power transformers is given in IEC 60354, for oil-immersed transformers, and IEC 60905, for dry-type transformers. Guidance for impulse testing of power transformers is given in IEC 60722.

Abstract

Provides a guide for the application, calculations and measurements of conventional design and loaded three-phase and single-phase power transformers (including auto-transformers). Certain categories of small and special transformers are not covered. Recommendations are not mandatory and do not in themselves constitute specification requirements.

History

- First published as AS 2421-1981;
- Revised and redesignated as AS 2374.8-2000.

APPENDIX 3 - SUMMARY OF KEY DOCUMENTS

http://www.energyrating.gov.au/considered.html#transformers

NAEEEC introduced MEPS for certain distribution transformers on 1 October 2004. Details are contained in the MEPS profile and Regulatory Impact Statement (see below) and in AS 2374.1.2-2003. The following reports have been released for distribution transformers:

- MEPS Technical Report – Distribution Transformers, detailed technical report by Mark Ellis & Associates gives data on market, overseas programs, emissions, test procedures and program options (published in March 2000);
- MEPS Profile – Distribution Transformers: proposes MEPS levels for a range of distribution transformers which operate on 11k and 22kV systems from 10kVA to 2500 kVA (published in March 2001):
- Regulatory Impact Statement: MEPS for Electricity Distribution Transformers, Report 2001/18 (published in February 2002).

MEPS – Analysis of Potential for Minimum Energy Performance Standards for Distribution Transformers

Author: Mark Ellis & Associates, March 2000

Location: http://www.energyrating.gov.au/library/detailstech-transform2000.html

Prepared for the Australian Greenhouse Office by Mark Ellis & Associates with the assistance of Professor Trevor Blackburn (UNSW). Final Report, March 8th, 2000. Gives data on market, overseas programs, emissions, test procedures and program options. Concentrates on MEPS for distribution transformers, which operate on 11 kV and 22 kV systems from 10 kVA to 2,500 kVA; includes liquid filled and dry type.

MEPS Profile – Distribution Transformers

Author: NAEEEC, March 2001

Location: http://www.energyrating.gov.au/library/detailsprofile-transform2001.html

Proposes MEPS levels for a range of distribution transformers, which operate on 11k and 22kV systems from 10kVA to 2500 kVA; includes liquid filled and dry type. Sets out the timetable for public consultation in the development of the new MEPS levels.

Regulatory Impact Statement: Minimum Energy Performance Standards and Alternative Strategies for Electricity Distribution Transformers

Authors: George Wilkenfeld and Associates, January 2002

Location: http://www.energyrating.gov.au/library/details200218-transformers.html

Electricity distribution transformers are essential for the operation of the electricity system. Their function is to step the supply voltage down from transmission voltages of 33,000 volts and above to the 415 volt three-phase supply which most electricity users receive (a single phase of this supply is 240 volts). Industry sources estimate that there are about 577,000 utility-owned distribution transformers in use in Australia, and their number is increasing at about 1.5% per annum.

The proposal is to introduce mandatory minimum energy performance standards for all electricity distribution transformers of up to 2500 kVA capacity, falling within the scope of a proposed new part of Australia Standard AS2374-1-2 2001: Power Transformers: minimum energy performance standards for distribution transformers. They are expressed in terms of minimum efficiency levels at half rated load. It is recommended that: States and Territories implement the proposed mandatory minimum energy performance standards. The mode of implementation should be through amendment of the existing regulations governing appliance energy labelling and MEPS in each State and Territory. The amendments should:

- add electricity distribution transformers to the schedule of products for which minimum energy performance standards are required, and refer to the MEPS levels in Tables 1 and 2 of AS 2374.1.2 (proposed part);
- add electricity distribution transformers to the schedule of products requiring energy labelling, so that any transformer for which the claim of "high efficiency" or "energy efficient" are made must meet the energy efficiency criteria in Tables 3 and 4 of AS2374.1.2 (proposed part);
- require registration of models, so invoking Appendix A of the proposed Standard;

- allow transformers manufactured or imported prior to the date of effect of the regulations to continue to be lawfully sold indefinitely.

Governments will make the register of electricity distribution transformer characteristics publicly accessible, so prospective purchasers can compare their energy efficiencies.

MEPS Requirements for Distribution Transformers

Author: NAEEEC, March 2001

Location: http://www.energyrating.gov.au/transformers2.html

From 1 October 2004, distribution transformers manufactured in or imported into Australia must comply with Minimum Energy Performance (MEPS) requirements which are set out in AS 2374.1.2-2003. The scope of transformer MEPS covers oil-immersed and dry-type distribution transformers with power ratings from 10 kVA to 2500 kVA intended to be used on 11 kV and 22 kV networks. The intention of MEPS is to increase energy efficiency by eliminating low efficiency transformers from the market and to encourage the use of high efficiency transformers. The standard also defines minimum efficiency levels for "High Power Efficiency Transformers". Only products, which meet the specified efficiency levels can apply this term to promotional or advertising materials. Transformers within the scope of MEPS are required to have on their rating plate a statement that indicates compliance with AS 2374.1.2.

The Minimum Energy Performance Standards (MEPS) for distribution transformers are set out as power efficiency levels at 50% of rated load in AS 2374.1.2 when tested in accordance with AS 2374.1 or AS 2735, as applicable.

MEPS does not apply to the following types of transformers:

- transformers other than those on 11 kV or 22 kV networks;
- instrument transformers;
- auto transformers;
- traction transformers mounted on rolling stock;
- starting transformers;
- testing transformers;

- welding transformers;
- three phase transformers with three or more windings per phase;
- arc-furnace transformers;
- earthing transformers;
- rectifier or converter transformers;
- uninterruptible power supply (UPS) transformers;
- transformers with an impedance less than 3% or more than 8%;
- voltage regulating transformers;
- transformers designed for frequencies other than 50 Hz;
- gas-filled dry-type transformers; or
- flame-proof transformers.

MEPS Levels

MEPS levels, set out as minimum power efficiency levels at 50% of rated load for various transformer types, are set out below. Reference should be made to AS 2374.1.2-2003 for detailed conditions and test methods.

Table A3-1 Minimum Power Efficiency Levels for Oil-Immersed Transformers

Type	**kVA**	**Power efficiency @ 50% load**
Single phase and SWER	10	98.30
	16	98.52
	25	98.70
	50	98.90
Three phase	25	98.28
	63	98.62
	100	98.76
	200	98.94
	315	99.04
	500	99.13
	750	99.21
	1,000	99.27
	1,500	99.35
	2,000	99.39
	2,500	99.40

Table A3-2 Minimum Power Efficiency Levels for Dry-Type Transformers

Type	**kVA**	**Power efficiency @ 50% load**	
		Um=12 kV	**Um=24 kV**
Single phase and SWER	10	97.29	97.01
	16	97.60	97.27
	25	97.89	97.53
	50	98.31	97.91
Three phase	25	97.17	97.17
	63	97.78	97.78
	100	98.07	98.07
	200	98.46	98.42
	315	98.67	98.59
	500	98.84	98.74
	750	98.96	98.85
	1,000	99.03	98.92
	1,500	99.12	99.01
	2,000	99.16	99.06
	2,500	99.19	99.09

High Power Efficiency Levels

Table A3-3 High Power Efficiency Levels For Oil-Immersed Transformers

Type	**kVA**	**Power efficiency @ 50% load**
Single phase and SWER	10	98.42
	16	98.64
	25	98.80
	50	99.00
Three phase	25	98.50
	63	98.82
	100	99.00
	200	99.11
	315	99.19
	500	99.26
	750	99.32
	1,000	99.37
	1,500	99.44
	2,000	99.49
	2,500	99.50

Minimum efficiency levels for "High Power Efficiency Transformers, set out as minimum power efficiency levels at 50% of rated load for various transformer types, are set out in Table A3-3. Reference should be made to AS 2374.1.2-2003 for detailed conditions and test methods.

Table A3-4 Table High Power Efficiency Levels for Dry-Type Transformers

Type	kVA	Power efficiency @ 50% load	
		Um=12 kV	Um=24 kV
Single phase and SWER	10	97.53	97.32
	16	97.83	97.55
	25	98.11	97.78
	50	98.50	98.10
Three phase	25	97.42	97.42
	63	98.01	98.01
	100	98.28	98.28
	200	98.64	98.60
	315	98.82	98.74
	500	98.97	98.87
	750	99.08	98.98
	1,000	99.14	98.04
	1,500	99.21	99.12
	2,000	99.24	99.17
	2,500	99.27	99.20

Note: For intermediate power ratings the power efficiency level shall be calculated by linear interpolation.

APPENDIX 4 - SCALING RULES FOR DISTRIBUTION TRANSFORMERS

Theoretical Analysis of Scaling Factors

The certain fundamental relations between distribution transformers' ratings and their physical size and performance have been well known (Feinberg, 1979; CIGRÉ, 2001 and McConnell, 2001).

Figure 4-1 presents a simplified cross sectional area of a basic three-leg core type distribution transformer (including windings in one of the windows).

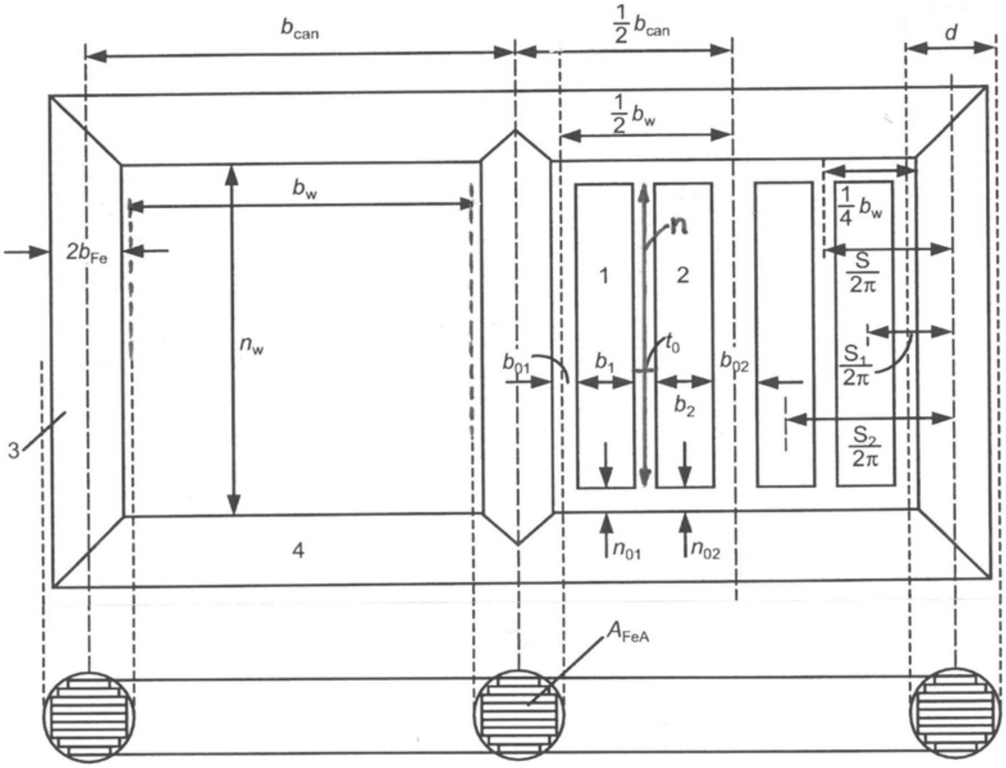

FIGURE A4-1 DISTRIBUTION TRANSFORMER –BASIC DIMENSIONS

Rating

The rating per phase of the transformer S (MVA), could be expressed as a function of frequency f (Hz), flux density B_m (T), the cross sectional area of the magnetic core A_{Fe} (m^2), number of turns N_1 and current I_1 (A) in winding "1".

$$S = 4.44\, fB_m A_{Fe} N_1 I_1 \qquad [4\text{-}1]$$

Alternatively, the rating could be expressed as:

$$S = 2.22\, fB_m A_{Fe} A_{Con} \qquad [4\text{-}2]$$

assuming that the current density is the same in both windings and that A_{Con} is the overall cross sectional area of both windings (m^2), or

$$S = 1.11 fB_m g A_{Fe} k_w A_w \qquad [4\text{-}3]$$

where g is the current density (A/mm^2) in both windings, A_w is the core window area (m^2) and k_w is window space factor (e.g. 0.3-0.4 for 11 kV transformers). It should be noted that for constant MVA rating, flux density and current density, the product of conductor cross sectional area A_{Con} and core cross-sectional A_{Fe} is constant.

Equation [4-2] could be rewritten as:

$$A_{Fe} = \sqrt{\frac{S^2}{\left(2.22 fB_m g A_{Con}\right)}} = \sqrt{S}\sqrt{\frac{2.22 fB_m g A_{Con} A_{Fe}}{\left(2.22 fB_m g A_{Con}\right)^2}} = \sqrt{S}\sqrt{\frac{A_{Fe}}{2.22 fB_m g A_{Con}}} \qquad [4\text{-}4]$$

or

$$A_{Fe} = K_{AS}\sqrt{S} \qquad [4\text{-}5]$$

Factor K_{AS} is defined as the “output coefficient” for distribution transformers and it is constant over a relatively wide MVA rating range. For three phase oil immersed distribution transformers K_{AS} is in the range of 0.04 – 0.05 (a nominal median value is 0.044). From Equations [4-1] and [4-5], it is also possible to express the volt/turn ratio V/N as:

$$\frac{V}{N} = 4.44 fB_m A_{Fe} = \sqrt{\left(4.44 fB_m\right)^2 K_{AS}{}^2 S} \qquad [4\text{-}6]$$

or

$$\frac{V}{N} = K_{VS}\sqrt{S} \qquad [4\text{-}7]$$

where K_{VS}, the “winding coefficient, is also constant for a wide range of MVA ratings.

These two coefficients, the output coefficient and the winding coefficient are related as follows:

$$K_{VS} = 4.44 f B_m K_{AS} \qquad [4\text{-}8]$$

The typical design values for three phase distribution transformers used in the above Equations are presented in Table 4-1.

Table A4-1 Typical Design Values for Three Phase Oil-Immersed Distribution Transformers

Design Parameter	**Range**	**Typical Value**
Flux – *B* (T)	1.55 – 1.80	1.72
Current Density – *g* (A/mm$_2$)	1.5 – 3.0	2.4
A_{Fe}/A_{Con}	1.4 – 2.8	1.6
K_{AS}	0.04 – 0.05	0.044
K_{VS}	14 – 20	17

Equations [4-5] and [4-7] are used in scaling performances of distribution transformers. The mean turn length s is a function of $A_{Fe}^{0.5}$ and $b_w/4$, where b_w is the width of the core window (Fig. 4-1). Consequently, s is a function of $S^{0.25}$:

$$s \rightarrow \left(A_{Fe}^{0.5} + b_w / 4\right) \rightarrow S^{0.25} \qquad [4\text{-}9]$$

As an example for scaling factors, the load losses could be expressed as:

$$P_{LL} = \frac{S^2 \mathrm{R}}{1000V} = \frac{K_1 S^2 N^2 s}{A_{Con} V^2} = K_2 \frac{S^2 S^{0.25}}{SS^{0.5}} = K_3 S^{0.75} \qquad [4\text{-}10]$$

The other scaling factors could be derived in a similar way. Some of them are graphically presented in Figure 4-2. Table 4-2 presents comparison of theoretical values and calculated scaling factors for three-phase oil immersed distribution transformers developed for Australian market.

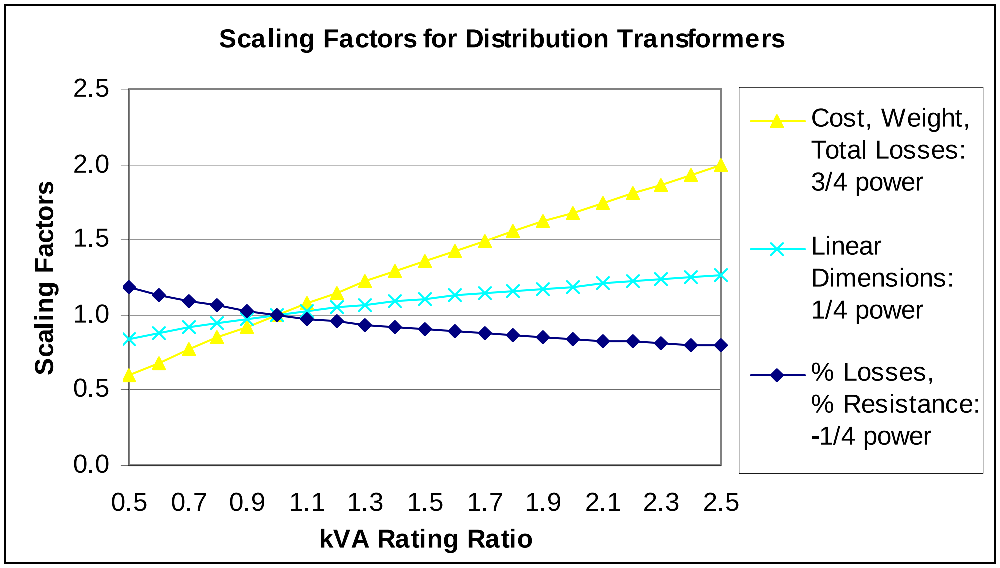

FIGURE A4-2 SOME COMMON SCALING FACTORS FOR DISTRIBUTION TRANSFORMERS

Table A4-2 Scaling Factors for Category 3 Pad-mounted Distribution Transformers (1,250 kVA-2,000 kVA)

Quantity	**Theoretical Scaling Factor**	**Calculated Scaling Factor**
Weight	(kVA rating ratio) $^{0.75}$	(kVA rating ratio) $^{0.62-0.72}$
Cost	(kVA rating ratio) $^{0.75}$	(kVA rating ratio) $^{0.51-0.63}$
Length	(kVA rating ratio) $^{0.25}$	
Width	(kVA rating ratio) $^{0.25}$	
Height	(kVA rating ratio) $^{0.25}$	
Total Losses	(kVA rating ratio) $^{0.75}$	(kVA rating ratio) $^{0.65-0.75}$
No-load losses	(kVA rating ratio) $^{0.75}$	
Exciting Current	(kVA rating ratio) $^{0.75}$	
% Total loss	(kVA rating ratio) $^{-0.25}$	
% No-load loss	(kVA rating ratio) $^{-0.25}$	
% Exciting Current	(kVA rating ratio) $^{-0.25}$	
% Resistance	(kVA rating ratio) $^{-0.25}$	
% Reactance	(kVA rating ratio) $^{0.25}$	
Volts/turn	(kVA rating ratio) $^{0.5}$	

APPENDIX 5 - ASSESSMENT OF AEEMA/ESAA LOSS EVALUATION FACTORS

The loss evaluation factors for distribution transformers defined in the non-binding industry standard Specification for Polemounting Distribution Transformers AEEMA/ESAA (1998) are as follows GWA (2002):

- distribution transformers below 100 kVA, K_{NLL}=\$6.30/W and K_{LL}=\$0.70/W;
- distribution transformers 100 kVA and above, K_{NLL}=\$6.30/W and K_{LL}=\$1.80/W;

Table A5-1 Calculation of Net Present Value of Transformer Losses based on AEEMA/ESAA, (1998) – GWA (2002)

Item	**Unit**	**1,500 kVA Low Efficiency**	**1,500 kVA High Efficiency**
Rating	kVA	1,500	1,500
Full load (power factor = 1)	kW	1,500	1,500
Core loss	kW	4.5	3.0
Winding loss @ 50% load	kW	4.5	3.0
Efficiency at 50% load	-	98.8%	99.2%
No load loss factor	$/W	6.30	6.30
NPV of no load energy lost	$	28,350	18,900
Load loss factor	$/W	1.80	1.80
NPV of load loss	$	36,450	24,300
Purchase price	$/kVA	40	40
Purchase price	$	60,000	60,000
Total capitalised cost	$	96,450	84,300
NPV of loss/total cost	-	37.8%	28.8%
Lifetime	years	30	30
Annual throughput @ 50% load	kWh	6,570,000	6,570,000
Annual loss @ 50% load	kWh	78,840	52,560
Implied costs of losses, 50% load	$/kWh	0.049	0.049
Implied costs of losses, 20% load	$/kWh	0.055	0.055

From AEEMA/ESAA evaluation factors it is possible to estimate the value which distributors who adopt that specification place on energy losses in distribution transformers. Table A5-1 gives an example using typical data for two 1,500 kVA transformers of different efficiency levels.

The Net Present Value (NPV) of the energy lost, at a discount rate of 10%, has been calculated by assuming that the annual energy losses at 50% loadings would be constant for the 30 years of transformers' operating life. Under these assumptions, the value of losses implied by the ESAA/AEEMA formula is 4.9 c/kWh for transformers operating at 50% load and 5.5 c/kWh at 20% load. The implied value of lost energy is the same irrespective of the efficiency of the transformer. However, as the total capitalised cost for more efficient transformer is $12,150 lower, it would be prudent to purchase this more efficient transformer. Typically, the NPV of the capitalised losses is in order of one a third of the initial cost of the transformer, so the use of the formula assigns significant value to energy efficiency in the selection process.

However, as GWA (2002) pointed out "the value of energy loss appears to be too low, given that the average sale price of electricity (which a distributor-retailer would gain in full as cost-free revenue is about 8.8 c/kWh. The AEEMA/ESAA specification is advisory only, and there are indications that its use is declining as distributors (who are no longer distributor-retailers) respond to the new regulatory and commercial climate: for distribution-only organisations, the appropriate value of losses is the marginal cost of supplying an additional kWh to the network, rather than the revenue to be gained from selling a kWh to end users. For efficient capital investment to take place, the value assigned to losses needs to be a long range projection of the cost of generation, effectively the Long Run Marginal Cost (LRMC) of additional generation. In pre-electricity market days the Bulk Supply Tariff was based upon LRMC projections of Generation and Transmission costs and it was simply used by distributors as part of their investment analysis. What is now required is a broadly equivalent long run estimate of electricity pool prices at the market regional reference node. Each distributor should use the same value, with adjustment made by the distributor for the cost of transmission and distribution to the point of loss consumption" IPART (1999).

Electrical utilities should assign a value to distribution transformer energy losses, which is equal to the value of the revenue from selling that energy to the customer. In addition, there should be additional component related to the value of the postponement of the capital cost of distribution network augmentation. This additional component is highly variable (as described in Chapter 5).