SEAD Distribution Transformers Report Part 3:
Energy Efficiency Class Definitions

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SEAD Standards & Labelling Working Group Distribution Transformers Collaboration

Part 3: Energy Efficiency Class Definitions for Distribution Transformers

Suggested energy-efficiency classes for global harmonisation of programmes for distribution transformers

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ABOUT SEAD

The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative, a five-year, US$20 million initiative under the Clean Energy Ministerial (CEM) and the International Partnership for Energy Efficiency Cooperation (IPEEC), helps turn knowledge into action to accelerate the transition to a clean energy future through effective appliance and equipment energy efficiency programs. SEAD is a multilateral, voluntary effort among Australia, Brazil, Canada, the European Commission, France, Germany, India, Japan, South Korea, Sweden, the United Arab Emirates, the United Kingdom, and the United States. The Collaborative Labeling and Appliance Standards Program (CLASP), a non-profit organization with deep experience in supporting international appliance efficiency efforts, serves as the Operation Agent for SEAD. For more information about SEAD, please visit: www.superefficient.org.

COMMENTS

This report is one part of a four part study which taken together presents an overview of distribution transformer losses globally, the savings potential, the technology options for improvement, and a comparison of some of the efficiency programmes from around the world. The intended audience for this four part study includes policy makers and the technical advisors who work with them on designing and developing sustainable market transformation programmes. CLASP contracted N14 Energy Limited to prepare these reports, and Michael Scholand of N14 Energy would welcome any comments or suggestions relating to the report at the following email address (change the "[at]" to "@"): MScholand [at] n14energy.com

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Acronyms and Abbreviations

AC	Alternating Current
BEE	Bureau of Energy Efficiency (India)
BIL	Basic Impulse Insulation Level
CEM	Clean Energy Ministerial
CENELEC	European Committee for Electrotechnical Standardisation
CFR	Code of Federal Regulations (United States)
CGO	Conventional Grain Oriented
CLASP	Collaborative Labeling and Appliance Standards Program
CNIS	China National Institute of Standardization
CO_2	Carbon Dioxide
CSA	Canadian Standards Association
DOE	Department of Energy (United States)
EC	European Commission
ECCJ	Energy Conservation Centre Japan
EECA	Energy Efficiency and Conservation Authority (New Zealand)
EU	European Union
HEPL	High Efficiency Performance Level
Hz	Hertz
IEC	International Electrotechnical Commission
kg	kilogram
kV	kilovolt (i.e., thousand volts)
kVA	kilovolt-ampere
kW	kilowatt
LCC	life-cycle cost
MEPS	Minimum Energy Performance Standards
MVA	megavolt-ampere
MWh	megawatt-hours
NEMA	National Electrical Manufacturers Association
Pk	load-dependent coil losses (winding losses)
Po	no-load losses in the core
R&D	Research and Development
SEEDT	Strategies for Energy Efficient Distribution Transformers
SWER	Single Wire Earth Return
TCO	Total Cost of Ownership
TOC	Total Ownership Cost
US	United States
W	Watts

Consistent Terminology

There are many different naming conventions in practice around the world for the types of distribution transformers and their losses. The table below provides some of the examples of terminology used in the various documents reviewed, and the equivalent terms that will be used in this report for simplicity and consistency.

Examples of Terminology Used	Term Used in this Report
Oil-filled, oil-immersed, liquid-immersed, liquid-filled	Liquid-filled
Dry-type, open ventilated, cast-coil, resin-coil, epoxy-coil, encapsulated-winding	Dry-type
Core losses, iron losses, no-load losses, steel losses	Core loss
Coil losses, copper losses, winding losses, load losses	Coil loss

In this report, the terms "European Union" and "Europe" may be used interchangeably, however the intention is always to represent the twenty-eight member states of the European Union and the three countries of the European Economic Area. Together, this group includes: Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom. For these countries, the European Commission is in the process of establishing a MEPS requirement that would apply to distribution transformers in the European Union and European Economic Area countries.

1   Scope of Coverage

1.1   Transformer Groups

Transformers are static electrical devices that are used in electrical power systems to transfer electrical power between circuits through the use of electromagnetic induction. Although the definitions of the different types of transformers are not completely harmonised around the world, transformers are generally classified according to their high voltage winding and their function in the network. The table below summarises the broad groups of transformers and describes their most common uses. While the naming conventions are not necessarily consistent around the world, from a practical perspective, the following does represent how they are used in transmission and distribution systems.

Table 1-1. Overview of the General Transformer Groups

Transformer Group	Voltage	Phases	Typical Insulation	Common Use
Large Power	>245 kV (High voltage)	Single and Three	Liquid-filled	Stepping up to or down from higher voltages for transmission of electricity over distances; substation transformers
Medium Power	>36 kV and ≤230 kV (Medium voltage)	Single and Three	Dry-type or liquid-filled	Stepping voltages down from a subtransmission system to a primary distribution system
Medium Voltage Distribution	≤36 kV (Medium voltage)	Single and Three	Dry-type or liquid-filled	Stepping voltages down within a distribution circuit from a primary to a secondary distribution voltage
Low Voltage Distribution	≤1 kV (Low voltage)	Single and Three	Dry-type	Stepping voltages down within a distribution circuit of a building or to supply power to equipment

Although not true for the national grid in every country/region, transformers with their highest voltage at 36kV or below are generally referred to as "distribution transformers" – the focus of this paper. Distribution transformers are appropriately named because they are installed in the distribution circuit of electricity networks servicing residential areas and commercial and industrial customers. Distribution transformers are most often involved in stepping voltage down. In some markets, such as North America, there is also a special subgroup of low-voltage distribution transformers that have a primary voltage less than or equal to 1 kV. These transformers, called low voltage dry-type transformers, can be found situated within buildings or facilities, working to reduce losses within the building's internal electrical distribution system. Medium voltage distribution transformers operate between 1 and 36 kV, and can be dry-type including epoxy-cast resin (each of which are cooled with air) or liquid-filled (which are cooled with mineral oil or some other insulating liquid).

1.2   Global Energy Savings Potential

Transmission and distribution network losses are important because they represent a global economic loss of more than US$61 billion annually and annual greenhouse gas emissions of more than 700 million tonnes.[1] The following table provides an estimate of the transmission and distribution system losses around the world, based on case studies in a number of countries.

Overall, it was found that in general, one third of network losses occur in transformers, and of these transformer losses, seventy per cent occur in distribution transformers. The table below estimates that total electricity lost on utility networks around the world in 2005 was approximately 1,279 TWh, and of that, distribution transformers consumed 298.4 TWh.

Table 1-2. Estimated Transmission and Distribution Network Losses Globally (2005)

Region / Country	Electricity Use (TWh)	Network Losses (TWh)	Network Losses (%)
Europe	3,046	222	
Western Europe	2,540	185	7.3 %
Former Soviet Union	1,135	133	11.7 %
North America	4,293	305	7.1 %
Latin America	721	131	
Brazil	336	61	18.3 %
Asia	3,913	381	
Japan	964	98	9.1 %
Australia, New Zealand	219	21	9.5 %
China	1,312	94	7.2 %
India	497	133	26.7 %
Africa / Middle East	826	83	10 %
Global Total	13,934	1,279	9.2 %

After transmission and distribution power lines, distribution transformers represent the next highest source of losses in a utility's electrical network. Distribution transformers are relatively easy to replace (in comparison with power lines), and their efficiency can be easily measured and labelled. Taking life cycle cost into account, the specification and installation of high efficiency transformers is an economically sound investment despite the higher purchase price (see section 3 of this report).

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[1] The Potential for Global Energy Savings from High Efficiency Distribution Transformers; Leonardo Energy – Transformers report, February, 2005.

According to analysis conducted by Lawrence Berkeley National Laboratory[2], approximately 75 TWh of end-use electricity and 30 million metric tons of CO_2 emissions can be saved in 2030 by adopting the world's best efficiency regulations in the twenty-three countries who are participating in the Clean Energy Ministerial (CEM).[3] The energy savings globally will be even greater.

High efficiency transformers offer an economic benefit for society in addition to the reduced greenhouse gas emissions, improved reliability and potentially longer service life if lower temperature rises are experienced through the energy-efficiency improvements. With these benefits in mind, many countries around the world – including Australia, Brazil, Canada, China, Europe, India, Israel, Japan, Korea, Mexico, New Zealand, and the United States have taken action to establish mandatory and voluntary programmes to help change their domestic markets and encourage the uptake of energy-efficient transformers. These programmes are summarised in the Part 4 report of this study. Analysis and comparison of the different programmes can be found in Part 1 of the reports.

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[2] LBNL, 2011. Published on the web:
http://www.superefficient.org/Products/Distribution%20Transformers.aspx
[3] The 23 governments participating in CEM initiatives are Australia, Brazil, Canada, China, Denmark, the European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Norway, Russia, South Africa, Spain, Sweden, the United Arab Emirates, the United Kingdom, and the United States.

2   Technological Improvements

The engineering practices and techniques for improving the efficiency of a distribution transformer are well known and understood. A transformer design can be made more energy-efficient by improving the materials of construction (e.g., better quality core steel or winding material) and by modifying the geometric configuration of the core and winding assemblies.

Core and coil losses are linked to each other by the heat they generate and by the physical space they occupy. Transformer designs adhere to a specified temperature rise, which results from the heat generated by transformer losses during operation. The upper boundary on the temperature rise is a design constraint, based on industry practice and standards. If this temperature limit is exceeded, the excess heat will accelerate the aging of the winding insulation and shorten the transformer's service period.

In addition to the core and winding assemblies, a transformer has other non-electromagnetic elements that may constrain the design of a transformer such as the electrical insulation, the cooling media, and the steel enclosure that houses the transformer. Once the insulation requirements are established, a transformer design can vary both materials and geometry to reduce the losses.

Making a distribution transformer more energy-efficient (i.e., reducing electrical losses) is a design trade-off between more expensive, lower-loss materials and designs, and the value a customer attaches to those losses. For a given efficiency level, the core and coil losses are generally inversely related— reducing one usually increases the other. The following table presents a summary of the loss-reduction approaches for energy-efficient transformers.

Table 2-1. Loss-Reduction Interventions for Distribution Transformers

Objective	Approach	No-Load Losses	Load Losses	Effect on Price
Decrease Core Losses	Use lower-loss core materials	Lower	No change	Higher
	Decrease flux density by increasing core cross-sectional area	Lower	Higher	Higher
	Decrease flux density by decreasing volts/turn	Lower	Higher	Same to Higher
	Decrease flux path length by decreasing conductor cross-sectional area	Lower	Higher	Lower
Decrease Coil Losses	Use lower-loss conductor materials	No change	Lower	Higher
	Decrease current density by increasing conductor cross-sectional area	Higher	Lower	Higher
	Decrease current path length by decreasing core cross-sectional area	Higher	Lower	Lower
	Decrease current path length by increasing volts/turn	Higher	Lower	Lower

Core Losses

Core (or no-load) losses occur in the core material of the distribution transformer, and are present whenever the transformer is energized—i.e., available to supply or actively supplying a load. Core losses are independent of load. Core losses are primarily made up of two components: hysteresis losses and eddy current losses. Hysteresis losses are caused by the magnetic lag or reluctance of the steel molecules in the core material to reorient themselves with the 50 or 60 Hz alternating magnetic field applied by the primary winding. Eddy current losses are caused by electrical currents induced in the core by the alternating magnetic field, in the same way that the magnetic field induces current in the secondary winding. However, these currents do not leave the core, and simply circulate within the core steel lamination, eventually converting to heat.

Transformer cores in the past had relatively high losses, since they were fabricated from thick laminates of non-oriented, low-silicon, magnetic steels. Research and development by core steel manufacturers has reduced these losses, such that modern core steel now incorporates low concentrations of silicon (approximately 2–3 per cent) and trace amounts of other elements. It is cold-rolled to very thin laminations, and may also be grain-oriented or domain-refined (i.e., laser or mechanically scribed). Electrical core steel manufacturers have also developed improved lamination insulation materials, because each lamination must electrically isolated to reduce the eddy currents. The graph below depicts some of the steel innovations since the 1950's, with losses being reduced by more than a factor of 3 between 1950 and 2000.[4]

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[4] Reduction in core loss at constant magnetic flux between 1950 and 2000. Curve is for grain-oriented silicon steel manufactured by Nippon Steel Corporation. Z is cold-rolled grain oriented silicon steel, HI-B represents
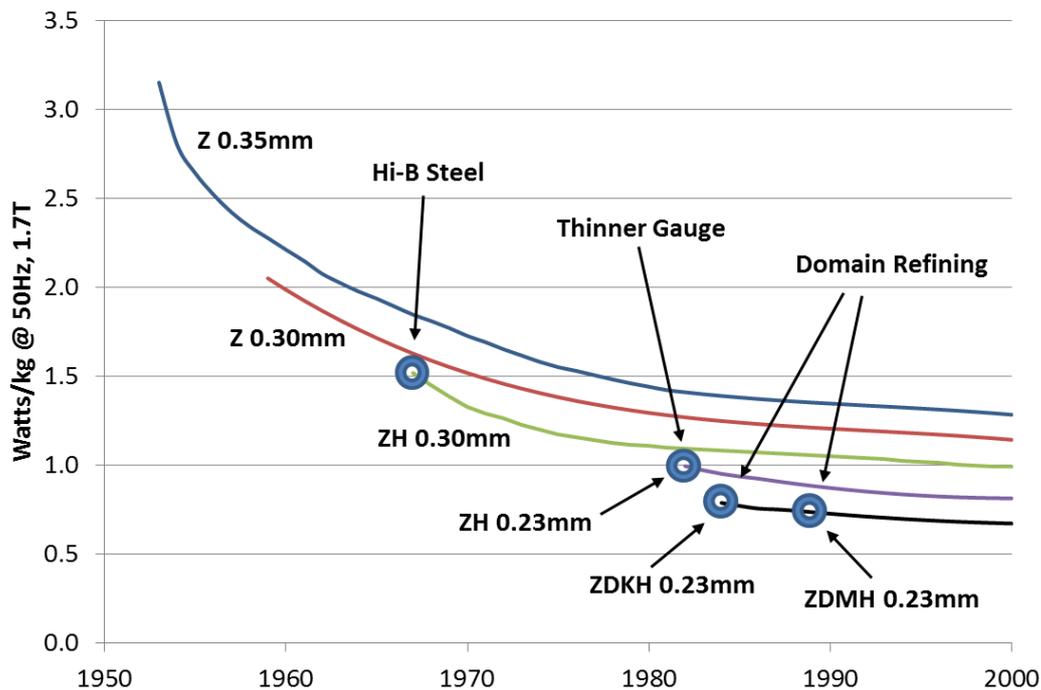
Figure 2-1. Nippon Steel's Core-Loss Reduction Trend, 1950-2000

Conventional grain oriented steel (CGO steel) is used for transformers with normal no-load loss characteristics, while transformers that require much lower no-load loss characteristics are built using higher-quality HiB steel (usually laser scribed). The steel sheets are 0.30 mm, 0.27 mm or 0.23 mm thick. Extremely low no-load losses can be achieved only by using wound core construction and amorphous metal, although this is not shown on the above graph. Amorphous material has highly specific properties (very thin sheets that are just 0.025 mm thick) and can be difficult to incorporate into mechanical production lines. Amorphous cores require a specially adapted design, usually of the wound core type.

Coil Losses

Coil losses, also called "winding losses", occur in both the primary and secondary windings when a transformer is under load. These losses, which are caused by the natural electrical resistance in the windings, vary approximately with the square of the current in each winding.[5] As shown in Table 2-1, methods of reducing coil losses will tend to increase no-load losses. One approach is to increase the cross-sectional area of the conductor (decreasing current density in the winding material), but this approach requires the core to

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domain-refined (laser scribed), and ZDMH represents mechanically scribed domain-refined HI-B steel, which is able to retain its enhanced performance following the stress-relieving anneal step in manufacturing a core.
[5] This is an approximation because load losses vary with the square of the current, but stray losses do not follow the same relationship.

be made larger to accommodate the larger conductor volume, increasing core losses. Transposition of a multi-strand conductor can also help to reduce coil losses.

Aluminium and copper windings are used in modern distribution transformer designs and are available for use in standard wire sizes and sheets used for windings called 'foil'. When the two materials are applied in exactly the same manner, copper has a higher electrical conductivity and has around 40 per cent lower resistive losses than aluminium. Compared to copper, aluminium is easier to form and work mechanically, and can be less expensive. By utilising aluminium conductor material at a lower current density (i.e., larger conductor cross-sectional area), aluminium transformer windings can be built with essentially the same load losses as copper. However, aluminium conductors increase core losses due to the larger cores, necessitated by the larger winding space (i.e., the "core window") through which the windings must pass. Some distribution transformer manufacturers choose to build an efficient design around a copper high-voltage winding and an aluminium low-voltage winding due to economics of the materials and ease of construction.

The main types of conductor coils which are used today in distribution transformers are:

- Spiral sheet windings that use wide sheets of strip or foil, made out of copper or aluminium. These sheet windings are generally used in place of helical coils for the low voltage (LV) windings of distribution transformers, particularly where there are only a small number of turns for the LV winding. Sheet windings have the unique ability to redistribute current to line up with the HV winding and cancel axial short circuit forces.
- Multilayer coils for high voltage (HV) windings. The winding is a single wound wire unit, consisting of several layers and a number of turns per layer.
- Disc coils, these are often used for the HV windings of dry-type transformers. The winding is constructed using a number of radially wound discs that are produced from a single length of conductor, separated from one another by insulating spacers.

Transformer Geometries

Transformer manufacturers employ the use of transformer design software when preparing a design for production. Using a range of input parameters (including the type of steel and conductors), the software is able to assist the design engineer in creating a cost-optimized transformer design to fulfil an order from a customer. This software design has specific information about the core and coil, including physical characteristics, dimensions, material requirements and mechanical clearances, as well as a complete electrical analysis of the final design.

The design software considers geometry or construction modifications such as a larger cross-sectional area or different core-stacking techniques. Construction methods and geometric modifications are inherent to the design and manufacturing process, and are generally controlled by the transformer engineer and/or software design tool to improve the efficiency of resultant designs.

3   Recommended Levels

After reviewing the various metrics available for establishing mandatory efficiency standards for transformers, the Team selected percentage efficiency as the most appropriate metric. This approach was identified as being preferable to defining maximum losses because it offers more flexibility in the design of the transformer while ensuring efficient performance overall.

Next, it was decided that the recommended level should be an equation based on the kVA rating, much like the Japanese Top Runner scheme. This approach was selected because it is apparent that there are a lot of differences between the preferred kVA ratings for the countries examined (see Part 1 report). The equation will enable countries that have different preferred kVA ratings from those used in this report to quickly adapt and calculate the expected performance levels that corresponds to a particular efficiency tier. In addition, this approach makes it easier for determining the required performance of kVA ratings that are not a typical rating but which would otherwise still be covered.

The equation used to create the IEC efficiency curves is given below. This equation has four variables which are adjusted to provide the best curve fit for the data:

$$Efficiency = 1 - \frac{2c^x}{S^y}$$

Where:

c	is a constant, that varies with the Tier level
S	is the kVA rating (IEC)
x	is a constant that is varies with transformer type
y	is a constant that varies with transformer type (and *x* + *y* = 1)

For example, for liquid-filled three-phase transformers, the following constants were selected:

c	0.0060 Tier 1; 0.0048 Tier 2; 0.0040 Tier 3 and 0.0032 Tier 4
x	0.78
y	0.22

Plugging these constants in the following equation for liquid-filled three-phase Tier 1:

$$Efficiency_{IEC} = 1 - \frac{2 \times 0.0060^{0.78}}{S^{0.22}} = 1 - \frac{0.0370}{S^{0.22}}$$

In this equation, *S* is equal to the kVA rating (the IEC kVA rating). Therefore, plugging in the value of 100 for *S* to determine the efficiency for a 100 kVA transformer, the minimum percentage efficiency is calculated as 98.66%.

The efficiency tiers themselves follow the same approach that was followed by the International Electrotechnical Commission (IEC) efficiency standards for electric motors. In other words, the least efficient / minimum level is presented as efficiency tier 1, and then increasingly higher efficiency levels are given higher tier numbers. This approach has two distinct advantages:

1) It leaves the efficiency scale open at the top end, so new product innovations in design, construction materials and technology can be recognised and differentiated with an incrementally higher tier level; and
2) It tracks the labelling system in Asia which is already widely understood in the market (e.g., the energy labelling scheme in India) where more stars means greater efficiency.

After normalising all of the efficiency levels from the various national programmes discussed in Parts 1 and 4 of this study, the levels were plotted anonymously spanning the kVA ratings of those programmes. To understand the upper bound of what is technically possible, the Team also plotted the "maximum technologically feasible" levels from the US Department of Energy's rulemakings on distribution transformers published in 2007 and 2013. These 'max-tech' designs constitute the highest efficiency level that can be achieved, not taking into account cost of materials or size of the transformer. The max-tech designs, therefore, represent an upper theoretical boundary, and are presented as green dots in each of the graphs.

3.1   Liquid-filled Three-Phase Analysis

The following figure presents the efficiency requirements of all the liquid-filled three-phase transformer programmes reviewed for this study. All of the requirements are harmonised to show efficiency at 50% loading, at 50Hz operation and using the IEC definition of kVA and efficiency. In this graph, the kVA ratings presented for each of the country programmes are plotted as anonymous dots. The countries and economies that are included in this graph are: Australia, China, European Commission (both draft requirements), India, Israel, Japan's Top-Runner, Korea, Mexico, Vietnam and the United States MEPS (both 2010 and 2016). This graph also includes the 'max-tech' designs published by the US DOE, which appear as green dots at the top of the graph. The least efficient designs in the graph are the Korean MEPS (see the Part 1 report), and appear as orange dots. Neither the orange dots nor the green dots were considered when setting the proposed levels.

Four equations represented by four coloured lines are super-imposed over the scatter-plot of efficiency requirements. The least efficient curve (Tier 1) represents a best fit of the low efficiency programmes (excluding that of the Korean MEPS programme). And the highest efficiency curve is tracking the premium efficiency designs based on the draft European Tier 2 regulation intended to become effective in 2021. In between these two boundaries, are two other curves are presented, representing Tiers 2 and 3. Tier 3 tends to track the US DOE 2016 requirement reasonably well. To assess the reasonableness of the curves, the simple average efficiency of all the programmes (excluding the max-tech and Korean MEPS

levels) is also plotted on this graph as a thin black line. This line generally falls between what is proposed as Tier 1 and Tier 2, and although it moves up or down based on the specific kVA ratings from the various countries used in the averaging, it is important to note that the slope of the curve aligns well with the four proposed Tier curves.
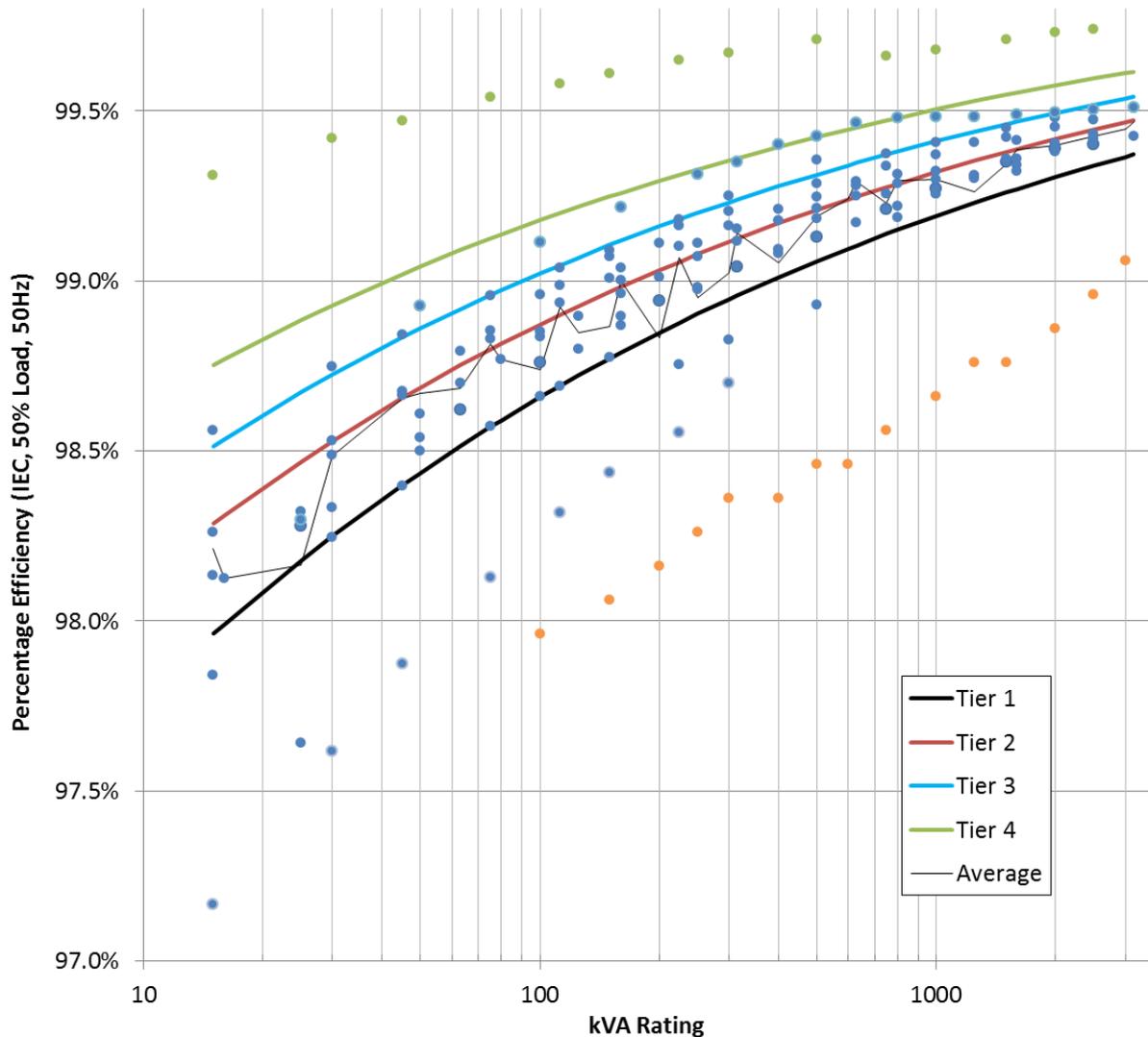

Figure 3-1. Liquid-filled Three-Phase Transformer Tiers, Minimum Efficiency Programmes

Next, the Team plotted these same four equations (Tier levels) on a graph that includes the higher efficiency programmes in the market, such as the Australian high efficiency performance levels from 2004 and draft 2011, the Chinese AMDT Grade 1, the European draft Tier 2 (2021), the five-star models from India, the Israeli high efficiency performance, the Japanese Top-Runner levels and the US MEPS for 2016. The same type of scatter plot was prepared which included the performance levels by kVA, all normalised to the same 50% loading, 50Hz operation and using the IEC definition of kVA and efficiency. As with the previous graph, a simple average efficiency was calculated across these programmes

(excluding max-tech), and is shown as a thin black line in the following graph. The average this time, calculated from the high efficiency level programmes around the world, falls between Tiers 3 and 4, and has the same slope as the four lines.

Figure 3-2. Liquid-filled Three-Phase Transformer Tiers, High Efficiency Programmes

Given the coincidence of the simple averages from the minimum efficiency programmes with the Tier 1-2 levels and the coincidence of the averages from the higher efficiency programmes with Tier 3-4 levels, these equations were considered to be provide relatively good alignment with the normalised data from the current efficiency programmes around the world.

In order to ensure that the market continues to look at energy-efficiency requirements in the future, a Tier 5 level was developed and is shown as a dotted line in the following figure. This figure includes all the MEPS and HEPL programmes for distribution transformers globally. Tier 5 is positioned at a point that exceeds all the current programmes, providing a 'reach' level that may be incentivised for the future.

Figure 3-3. Liquid-filled Three-Phase Transformer Tiers, All Programmes + Tier 5
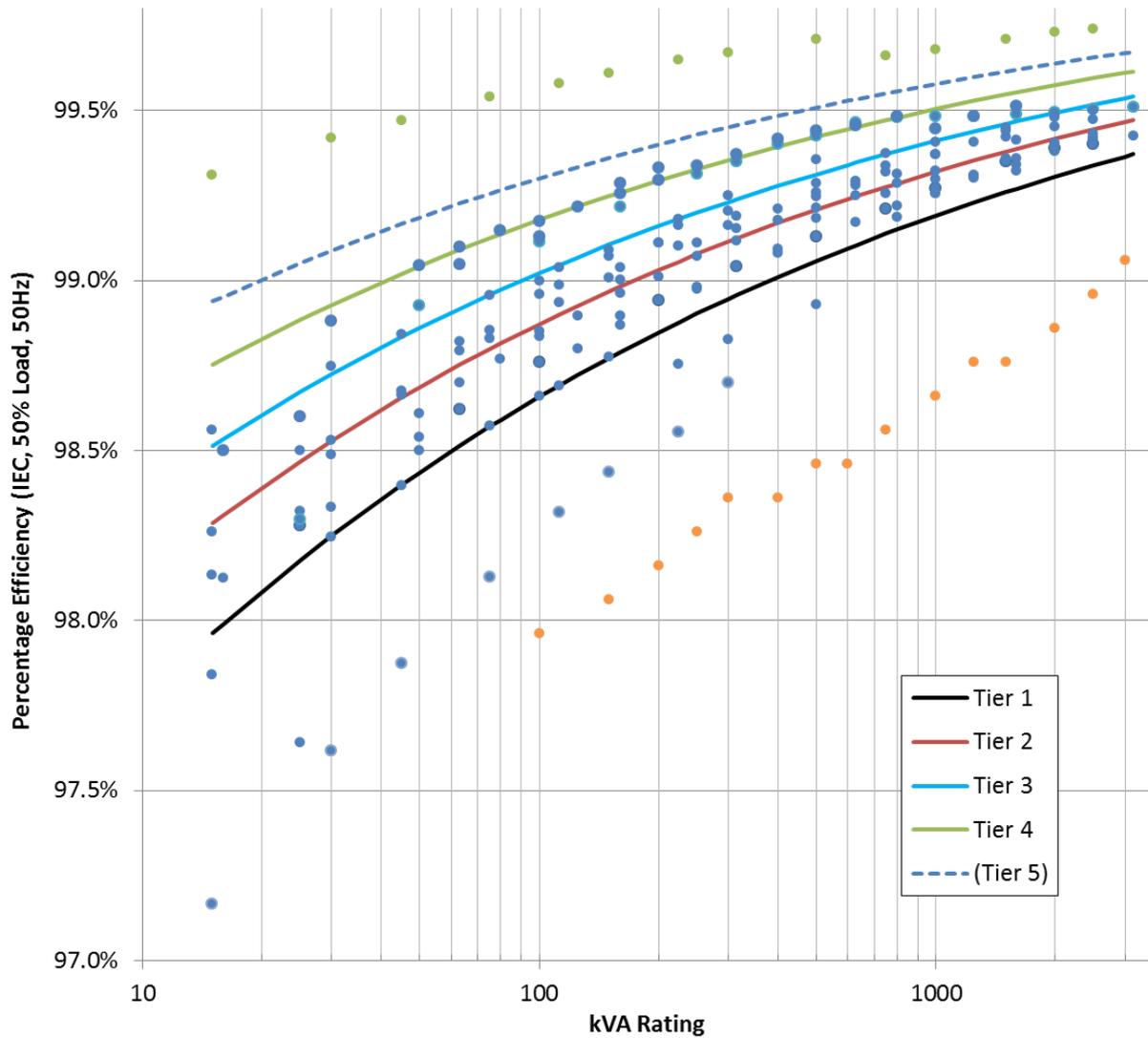
The table below presents the five equations used and a sample of 'preferred' kVA ratings, with Tier 5 as a draft level for the future. Please note that other kVA ratings could be accommodated into the table, by simply using the equations in the first row to determine the corresponding efficiency levels for any kVA rating from 15 through 3150 kVA.

Table 3-1. Efficiency for Liquid-Filled Three-Phase Distribution Transformers, 50Hz IEC

kVA	Tier 1 $= 1 - \dfrac{0.0370}{S^{0.22}}$	Tier 2 $= 1 - \dfrac{0.0311}{S^{0.22}}$	Tier 3 $= 1 - \dfrac{0.0270}{S^{0.22}}$	Tier 4 $= 1 - \dfrac{0.0226}{S^{0.22}}$	(Tier 5) $= 1 - \dfrac{0.0193}{S^{0.22}}$
15	97.96%	98.29%	98.51%	98.75%	98.94%
25	98.18%	98.47%	98.67%	98.88%	99.05%
50	98.44%	98.69%	98.86%	99.04%	99.19%
100	98.66%	98.87%	99.02%	99.18%	99.30%
160	98.79%	98.98%	99.12%	99.26%	99.37%
250	98.90%	99.08%	99.20%	99.33%	99.43%
315	98.96%	99.12%	99.24%	99.36%	99.46%
400	99.01%	99.17%	99.28%	99.39%	99.48%
500	99.06%	99.21%	99.31%	99.42%	99.51%
630	99.10%	99.25%	99.35%	99.45%	99.53%
800	99.15%	99.29%	99.38%	99.48%	99.56%
1000	99.19%	99.32%	99.41%	99.50%	99.58%
1250	99.23%	99.35%	99.44%	99.53%	99.60%
1600	99.27%	99.39%	99.47%	99.55%	99.62%
2000	99.31%	99.42%	99.49%	99.57%	99.64%
2500	99.34%	99.44%	99.52%	99.59%	99.66%
3150	99.37%	99.47%	99.54%	99.62%	99.67%

3.2   Liquid-filled Single-Phase Analysis

The following figure presents the efficiency requirements of all the liquid-filled single-phase transformer programmes reviewed for this study. All of the requirements are harmonised to show efficiency at 50% loading, at 50Hz operation and using the IEC definition of kVA and efficiency. Not all countries profiled in this study have requirements for single-phase transformers, however those that do have been plotted as anonymous dots.

The countries and economies that are included in this graph are: Australia (MEPS and HEPS from both 2004 standard and draft 2011), Brazil, China (JT/B industry standard), the Japanese Top-Runner, Korea (MEPS and HEPL), Mexico and the United States (2010 and 2016). This graph also includes the 'max-tech' designs published in the United States regulatory proceeding, which are plotted as green dots on the graph. The least efficient designs in the graph are those from the Korean mandatory efficiency standards, which are shown as orange dots.

Four equations represented by four coloured lines are super-imposed over the scatter-plot of efficiency requirements. The least efficient curve (Tier 1) represents a best fit of the low efficiency programmes (excluding that of the Korean MEPS programme). And the highest efficiency curve is tracking the efficiency of the US DOE 2016 regulation. In between these

two boundaries, are two other curves are presented, representing Tiers 2 and 3. To assess the reasonableness of the curves, the simple average efficiency of all the programmes is also plotted on this graph as a thin black line. However, the average excludes the US DOE max-tech levels and Korean MEPS (which are shown in orange). The average generally tracks Tier 2, although it moves up or down based on the specific kVA ratings from the various countries used in the averaging. It is important to note that the slope of the average curve aligns well with the four proposed Tier curves. A Tier 5 level was also plotted at a point that exceeds all the current programmes, providing a 'reach' level that may be incentivised for the future.

Figure 3-4. Liquid-filled Single-Phase Transformer Tiers, Minimum Efficiency Programmes

The table below presents the five equations used and a sample of 'preferred' kVA ratings, with Tier 5 as a draft level for the future. Please note that other kVA ratings could be accommodated into the table, by simply using the equations in the first row to determine the corresponding efficiency levels for any kVA rating from 5 through 1000 kVA.

Table 3-2. Efficiency for Liquid-Filled Single-Phase Distribution Transformers, 50Hz IEC

kVA	Tier 1 $= 1 - \dfrac{0.0355}{S^{0.22}}$	Tier 2 $= 1 - \dfrac{0.0295}{S^{0.22}}$	Tier 3 $= 1 - \dfrac{0.0254}{S^{0.22}}$	Tier 4 $= 1 - \dfrac{0.0210}{S^{0.22}}$	(Tier 5) $= 1 - \dfrac{0.0169}{S^{0.22}}$
5	97.51%	97.93%	98.22%	98.53%	98.81%
10	97.86%	98.22%	98.47%	98.74%	98.98%
15	98.04%	98.37%	98.60%	98.84%	99.07%
25	98.25%	98.54%	98.75%	98.97%	99.17%
37.5	98.40%	98.67%	98.86%	99.06%	99.24%
50	98.50%	98.75%	98.93%	99.11%	99.28%
75	98.63%	98.86%	99.02%	99.19%	99.35%
100	98.71%	98.93%	99.08%	99.24%	99.39%
167	98.85%	99.04%	99.18%	99.32%	99.45%
250	98.95%	99.12%	99.25%	99.38%	99.50%
333	99.01%	99.18%	99.29%	99.42%	99.53%
500	99.09%	99.25%	99.35%	99.47%	99.57%
667	99.15%	99.29%	99.39%	99.50%	99.60%
833	99.19%	99.33%	99.42%	99.52%	99.61%
1000	99.22%	99.35%	99.45%	99.54%	99.63%

3.3   Dry-Type Three-Phase Analysis

The following figure presents the efficiency requirements of all the dry-type three-phase transformer programmes reviewed for this study. All of the requirements are harmonised to show efficiency at 50% loading, 50Hz operation and using the IEC definition of kVA and efficiency. For this graph, the kVA ratings that were presented for each of the country programmes are plotted as anonymous dots. The programmes included in this graph are: Australia, Canada, China (Grade 3), European Commission (draft, Tier 1), Israel, Japan, Korea and the USA regulations for both 2010 and 2016. This graph also includes the 'max-tech' designs published in the recent US regulatory proceeding, which are plotted as green dots on the graph. The least efficient designs in the graph are those from the Korean mandatory efficiency standards which are shown as orange coloured dots.

As was done for the three-phase liquid-immersed distribution transformers, four equations represented by four coloured lines are super-imposed over the scatter-plot of efficiency requirements. The least efficient curve (Tier 1) represents a best fit of the low efficiency programmes (excluding the Korean MEPS programme). And the highest efficiency curve is slightly above the premium efficiency designs based on the draft European MEPS regulation intended to become effective in 2015. In between these two curves (Tier 1 and Tier 4), there are two other curves, representing Tiers 2 and 3. Tier 3 is approximately at the recent US

DOE requirement for dry-type transformers which takes effect in 2016. By way of a further comparison, the simple average efficiency of all the programmes plotted on this graph (excluding the 'max tech' line) is shown as a thin black line. This line generally falls between what is proposed as Tier 1 and Tier 2, and it moves up or down based on the specific kVA ratings from the various countries in the averaging. It is important to note that the slope of the average curve aligns well with the four proposed Tier curves.
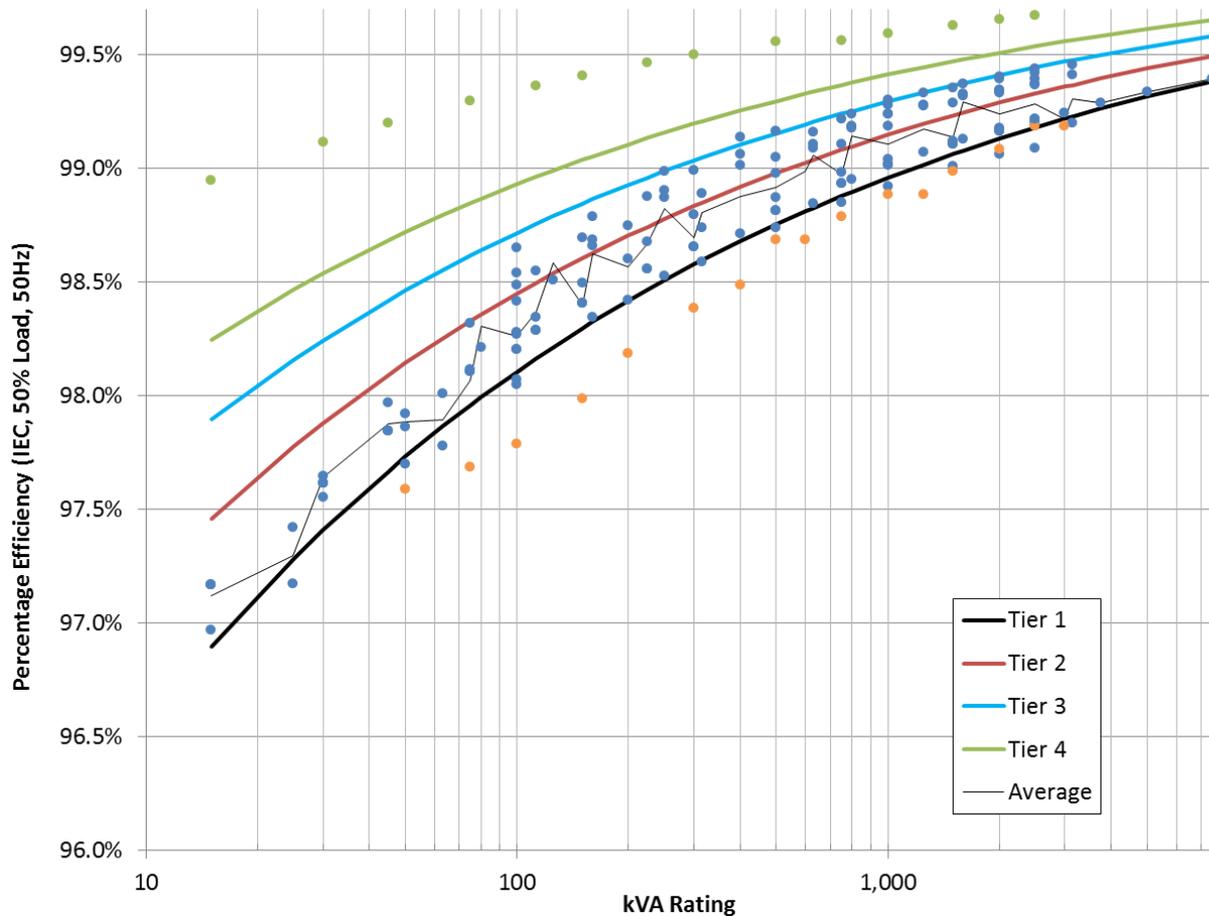

Figure 3-5. Dry-Type Three-Phase Transformer Tiers, Minimum Efficiency Programmes

Next, the Team plotted these same four equations (Tier levels) on a graph that includes the higher efficiency programmes in the market, such as the Australian high efficiency performance levels from 2004 and the new draft levels, China's Grade 1, the European draft Tier 2 (2021), the Israeli high efficiency performance, the Japanese Top-Runner level, the Korean HEPL and the US MEPS for 2016. The graph also includes the 'max tech' designs from the recent regulatory proceeding. The same type of scatter plot was prepared which included the performance levels by kVA, all normalised to the same 50% loading, 50Hz operation and using the IEC definition of kVA and efficiency. As with the previous graph, a simple average efficiency was calculated across these programmes, shown as a thin black line in the following graph. The average this time, calculated from the high efficiency level

programmes around the world, falls between Tiers 3 and 4, and has the same slope as the four lines.
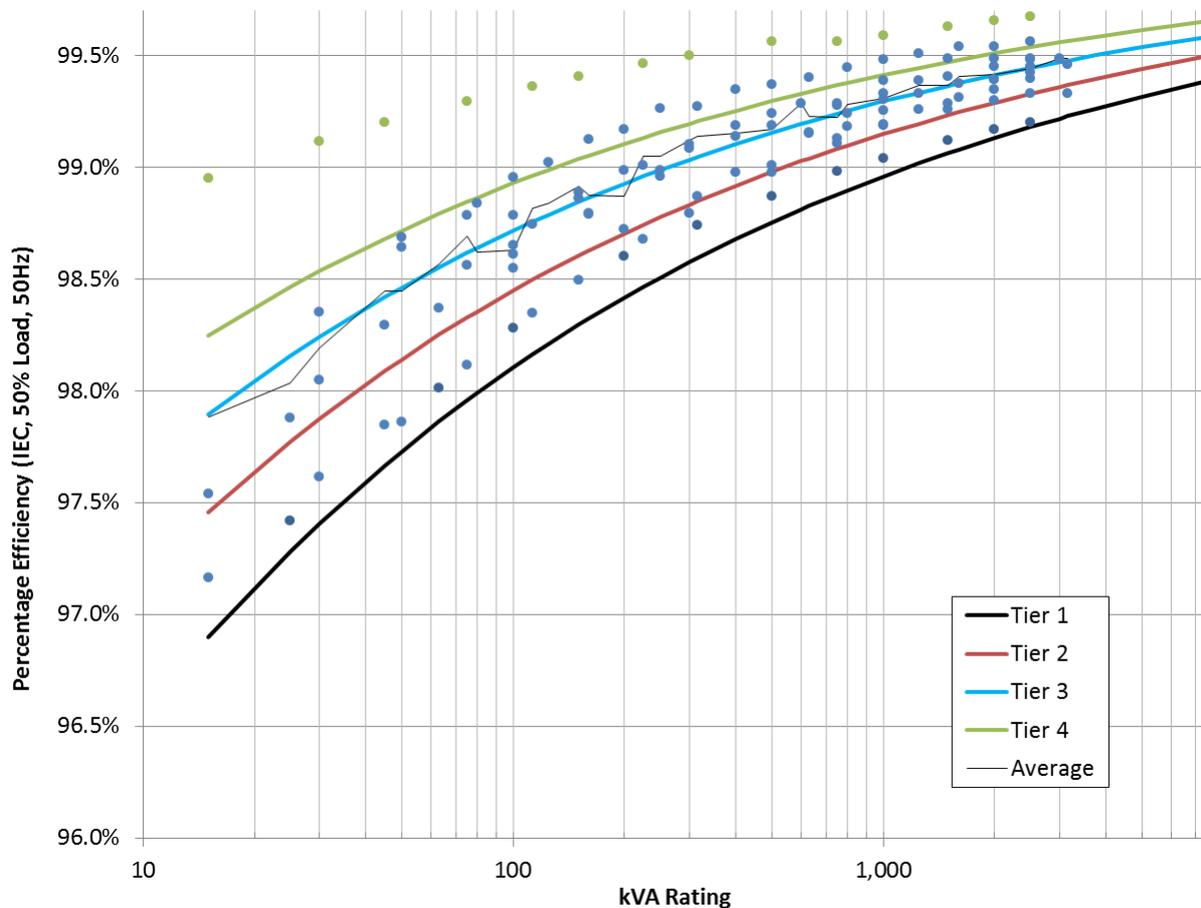

Figure 3-6. Dry-Type Three-Phase Transformer Tiers, High Efficiency Programmes

Given the coincidence of the simple averages from the minimum efficiency programmes with the Tier 1-2 levels and the coincidence of the averages from the higher efficiency programmes with Tier 3-4 levels, these equations were considered to provide relatively good alignment with the normalised data from the current efficiency programmes around the world.

In order to ensure that the market continues to look at energy-efficiency requirements in the future, a Tier 5 level was developed and is shown as a dotted line in the following figure. This figure includes all the MEPS and HEPL programmes for distribution transformers globally. Tier 5 is positioned at a point that exceeds all the current programmes, providing a 'reach' level that may be incentivised for the future.

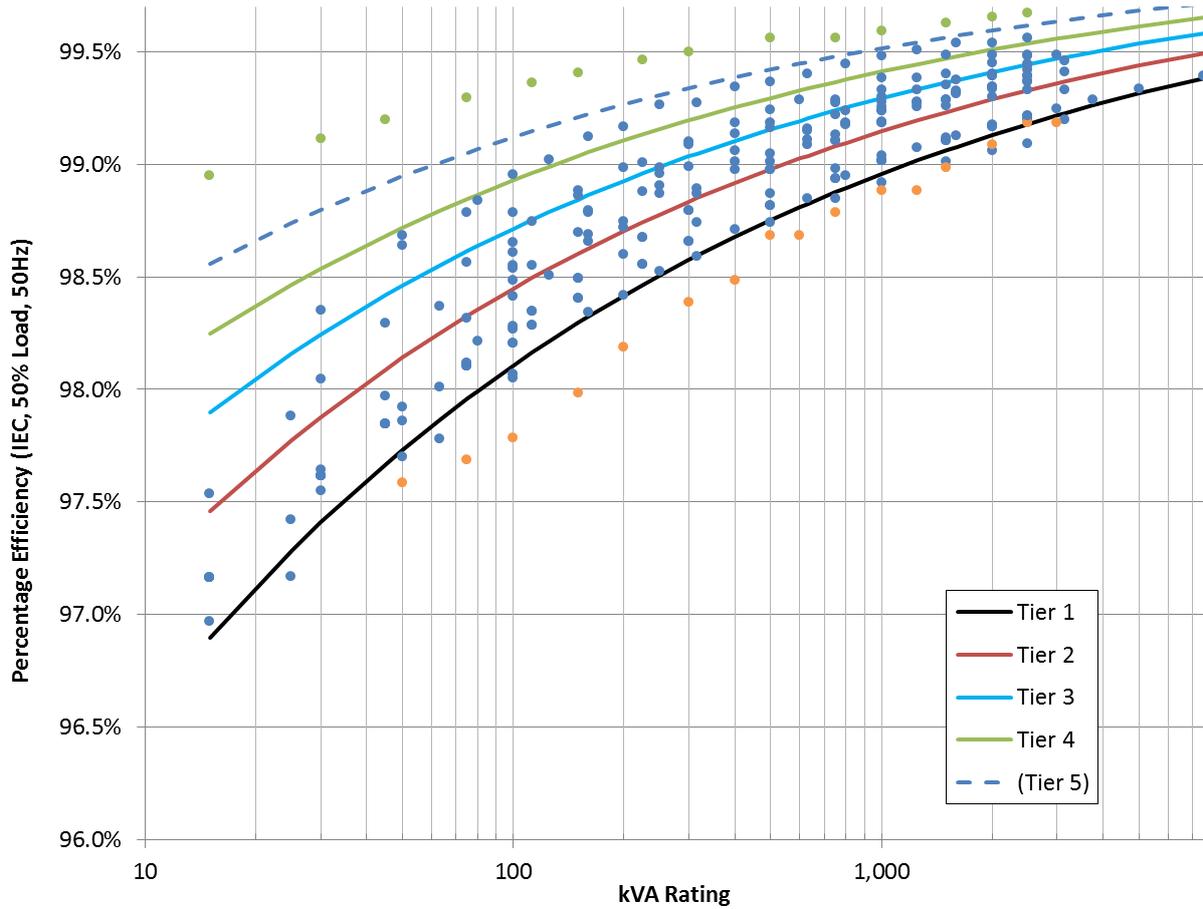**Figure 3-7. Dry-Type Three-Phase Transformer Tiers, All Programmes + Tier 5**

The table below presents the five equations used and a sample of 'preferred' kVA ratings, with Tier 5 as a draft level for the future. Please note that other kVA ratings could be accommodated into the table, by simply using the equations in the first row to determine the corresponding efficiency levels for any kVA rating from 15 through 3150 kVA.

Table 3-3. Efficiency for Dry-Type Three-Phase Distribution Transformers, 50Hz IEC

kVA	Tier 1 $= 1 - \dfrac{0.0628}{S^{0.26}}$	Tier 2 $= 1 - \dfrac{0.0514}{S^{0.26}}$	Tier 3 $= 1 - \dfrac{0.0425}{S^{0.26}}$	Tier 4 $= 1 - \dfrac{0.0355}{S^{0.26}}$	(Tier 5) $= 1 - \dfrac{0.0292}{S^{0.26}}$
15	96.90%	97.46%	97.90%	98.25%	98.56%
25	97.28%	97.77%	98.16%	98.46%	98.74%
50	97.73%	98.14%	98.46%	98.72%	98.95%
100	98.10%	98.45%	98.72%	98.93%	99.12%
160	98.32%	98.63%	98.86%	99.05%	99.22%
250	98.51%	98.78%	98.99%	99.16%	99.31%
315	98.59%	98.85%	99.05%	99.21%	99.35%
400	98.68%	98.92%	99.10%	99.25%	99.39%
500	98.75%	98.98%	99.15%	99.30%	99.42%
630	98.83%	99.04%	99.20%	99.34%	99.45%
800	98.90%	99.10%	99.25%	99.38%	99.49%
1000	98.96%	99.15%	99.29%	99.41%	99.52%
1250	99.02%	99.20%	99.33%	99.44%	99.54%
1600	99.08%	99.25%	99.38%	99.48%	99.57%
2000	99.13%	99.29%	99.41%	99.51%	99.60%
2500	99.18%	99.33%	99.44%	99.54%	99.62%
3150	99.23%	99.37%	99.48%	99.56%	99.64%

3.4 Dry-Type Single-Phase Analysis

The following figure presents the efficiency requirements of all the dry-type single-phase transformer programmes reviewed for this study. All of the requirements are harmonised to show efficiency at 50% loading, 50Hz operation and using the IEC definition of kVA and efficiency. For this graph, the kVA ratings that were presented for each of the country programmes are plotted as anonymous dots.

The countries and economies that are included in this graph are: Australia (MEPS and HEPL from both 2004 standard and the draft under review), Canada MEPS, the Japanese Top-Runner, Korea's (MEPS and HEPL), and the United States MEPS both 2010 and 2016. This graph also includes the 'max-tech' designs published in the United States regulatory proceeding, which are presented as green dots on the graph. The least efficient designs in the graph are those from the Korean mandatory efficiency standards which are shown as orange coloured dots.

As was done for the three-phase liquid-immersed distribution transformers, four equations represented by four coloured lines are super-imposed over the scatter-plot of efficiency requirements. The least efficient curve (Tier 1) represents a best fit of the low efficiency

programmes (excluding the Korean MEPS programme). And the highest efficiency curve is slightly above the premium efficiency designs based on the draft new Japanese Top-Runner programme. Tier 3 corresponds to the current Japanese Top-Runner programme and Tier 2 corresponds to the Korean HEPS and US DOE standard from 2010 and 2016 (the US DOE standard did not change when it was updated for 2016). By way of a further comparison, the simple average efficiency of all the programmes plotted on this graph (excluding the 'max tech' line) is shown as a thin black line. This line generally falls around what is proposed as Tier 2, and it moves up or down based on the specific kVA ratings from the various countries in the averaging. The slope of the average curve aligns well with the four proposed Tier curves. A Tier 5 level was also plotted at a point that exceeds all the current programmes, providing a 'reach' level that may be incentivised for the future.

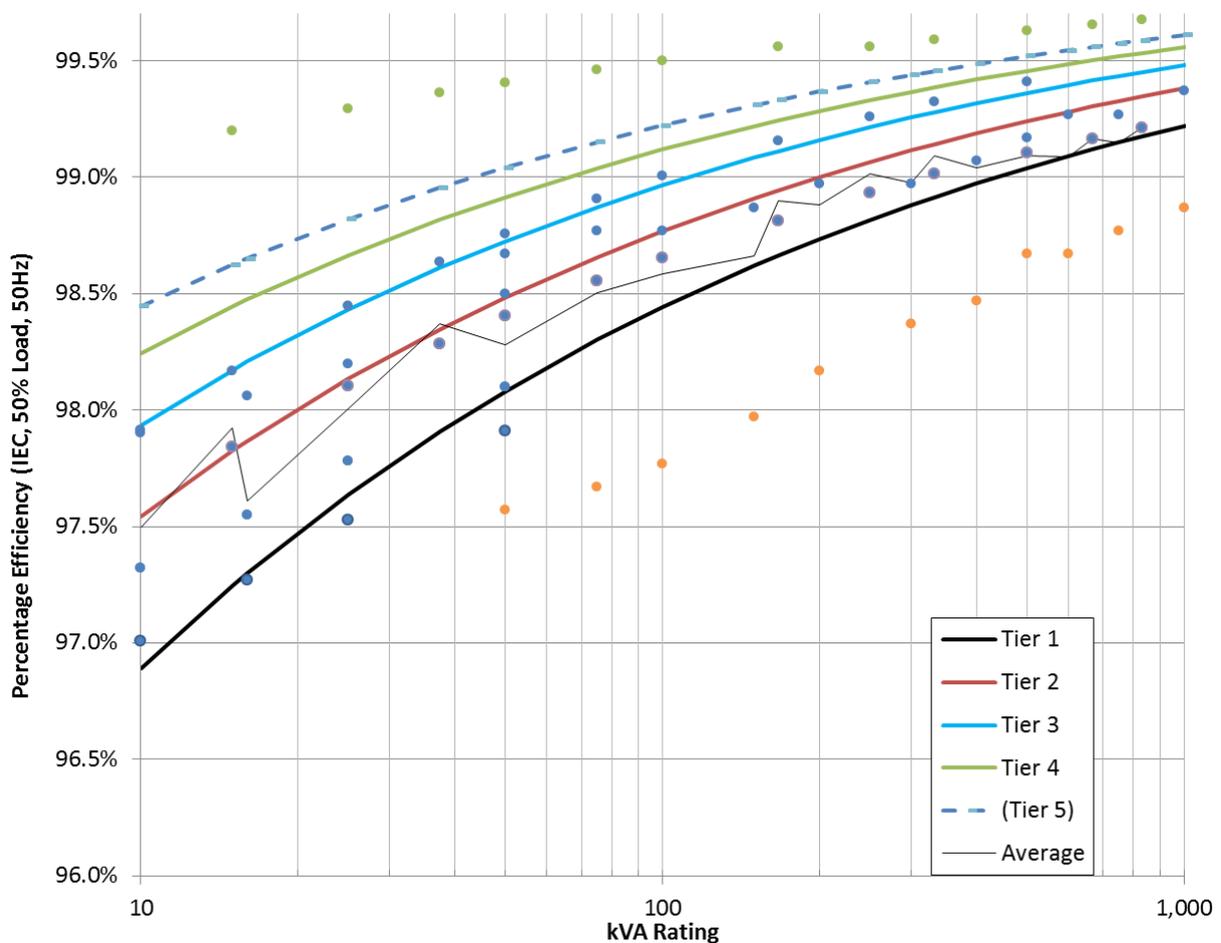**Figure 3-8. Dry-Type Single-Phase Transformer Tiers, Minimum Efficiency Programmes**

The table below presents the five equations used and a sample of 'preferred' kVA ratings, with Tier 5 as a draft level for the future. Please note that other kVA ratings could be accommodated into the table, by simply using the equations in the first row to determine the corresponding efficiency levels for any kVA rating from 5 through 1000 kVA.

Table 3-4. Efficiency for Dry-Type Single-Phase Distribution Transformers, 50Hz IEC

kVA	Tier 1 $= 1 - \dfrac{0.0620}{S^{0.30}}$	Tier 2 $= 1 - \dfrac{0.0490}{S^{0.30}}$	Tier 3 $= 1 - \dfrac{0.0412}{S^{0.30}}$	Tier 4 $= 1 - \dfrac{0.0351}{S^{0.30}}$	(Tier 5) $= 1 - \dfrac{0.0310}{S^{0.30}}$
5	96.17%	96.98%	97.46%	97.84%	98.09%
10	96.89%	97.54%	97.94%	98.24%	98.45%
15	97.25%	97.82%	98.17%	98.44%	98.62%
25	97.64%	98.13%	98.43%	98.66%	98.82%
37.5	97.91%	98.35%	98.61%	98.82%	98.95%
50	98.08%	98.48%	98.73%	98.92%	99.04%
75	98.30%	98.66%	98.87%	99.04%	99.15%
100	98.44%	98.77%	98.97%	99.12%	99.22%
167	98.66%	98.94%	99.11%	99.24%	99.33%
250	98.82%	99.06%	99.21%	99.33%	99.41%
333	98.91%	99.14%	99.28%	99.39%	99.46%
500	99.04%	99.24%	99.36%	99.46%	99.52%
667	99.12%	99.30%	99.41%	99.50%	99.56%
833	99.18%	99.35%	99.45%	99.53%	99.59%
1000	99.22%	99.38%	99.48%	99.56%	99.61%

3.5   Recommendations and Next Steps

In this chapter, the existing MEPS and voluntary programmes designed to promote energy-efficiency throughout the distribution transformer markets were analysed and best-fit curves were applied which cover the range of efficiency values presented. Similar to the Japanese Top-Runner programme, mathematical equations were developed for each of the best-fit curves to facilitate calculation of efficiency across the various kVA ratings in the market.

The following table presents the set of equations developed for both liquid-filled and dry-type transformers in single-phase and three-phase configurations. These equations yield a percentage efficiency at 50% of rated load for 50Hz operation and the IEC definition of kVA. There were four equations developed for each group of distribution transformer, with Tier 1 being the least efficient and Tier 4 being the most efficient. In each case, the maximum technologically feasible levels were included in the graphs, to show that levels above Tier 4 may be possible in the future, as innovation in manufacturing and materials are invested in improving the efficiency of distribution transformers. A Tier 5 level was added as an indicator of a future premium efficiency level for market-pull programmes.

Table 3-5. Efficiency Equations for Distribution Transformers, 50Hz and IEC kVA (%)

Type	Tier 1	Tier 2	Tier 3	Tier 4	(Tier 5)
Liquid-Filled Three-Phase	$= 1 - \dfrac{0.0370}{S^{0.22}}$	$= 1 - \dfrac{0.0311}{S^{0.22}}$	$= 1 - \dfrac{0.0270}{S^{0.22}}$	$= 1 - \dfrac{0.0226}{S^{0.22}}$	$= 1 - \dfrac{0.0193}{S^{0.22}}$
Liquid-Filled Single-Phase	$= 1 - \dfrac{0.0355}{S^{0.22}}$	$= 1 - \dfrac{0.0295}{S^{0.22}}$	$= 1 - \dfrac{0.0254}{S^{0.22}}$	$= 1 - \dfrac{0.0210}{S^{0.22}}$	$= 1 - \dfrac{0.0169}{S^{0.22}}$
Dry-Type Three-Phase	$= 1 - \dfrac{0.0628}{S^{0.26}}$	$= 1 - \dfrac{0.0514}{S^{0.26}}$	$= 1 - \dfrac{0.0425}{S^{0.26}}$	$= 1 - \dfrac{0.0355}{S^{0.26}}$	$= 1 - \dfrac{0.0292}{S^{0.26}}$
Dry-Type Single-Phase	$= 1 - \dfrac{0.0620}{S^{0.30}}$	$= 1 - \dfrac{0.0490}{S^{0.30}}$	$= 1 - \dfrac{0.0412}{S^{0.30}}$	$= 1 - \dfrac{0.0351}{S^{0.30}}$	$= 1 - \dfrac{0.0310}{S^{0.30}}$

In the following table, the above equations have been adjusted to convert for 60Hz operation at the IEEE definition of kVA (i.e., rated power based on output rather than input).

Table 3-6. Efficiency Equations for Distribution Transformers, 60Hz and IEEE kVA (%)

Type	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Liquid-Filled Three-Phase	$= 1 - \dfrac{0.03584}{S^{0.227}}$	$= 1 - \dfrac{0.03019}{S^{0.227}}$	$= 1 - \dfrac{0.02627}{S^{0.227}}$	$= 1 - \dfrac{0.02203}{S^{0.227}}$	$= 1 - \dfrac{0.01851}{S^{0.227}}$
Liquid-Filled Single-Phase	$= 1 - \dfrac{0.0346}{S^{0.227}}$	$= 1 - \dfrac{0.02899}{S^{0.227}}$	$= 1 - \dfrac{0.02476}{S^{0.227}}$	$= 1 - \dfrac{0.02031}{S^{0.227}}$	$= 1 - \dfrac{0.01649}{S^{0.227}}$
Dry-Type Three-Phase	$= 1 - \dfrac{0.06352}{S^{0.26}}$	$= 1 - \dfrac{0.0527}{S^{0.26}}$	$= 1 - \dfrac{0.04383}{S^{0.26}}$	$= 1 - \dfrac{0.03682}{S^{0.26}}$	$= 1 - \dfrac{0.03045}{S^{0.26}}$
Dry-Type Single-Phase	$= 1 - \dfrac{0.04044}{S^{0.30}}$	$= 1 - \dfrac{0.03132}{S^{0.30}}$	$= 1 - \dfrac{0.02585}{S^{0.30}}$	$= 1 - \dfrac{0.02169}{S^{0.30}}$	$= 1 - \dfrac{0.01896}{S^{0.30}}$

Annex A. Utility Purchasing Practices

When purchasing distribution transformers, utilities will often use a purchasing practice referred to the Total Owning Cost (TOC) or Total Cost of Ownership (TCO) which involves the capitalisation of losses. This approach to specifying and purchasing transformers is used to minimise the total investment over the lifetime of a transformer, enabling the utility to maximise its energy savings at the lowest cost. Loss capitalisation is not easy to assess and takes a lot of time to determine the correct factors to apply. The answers to the following questions are needed as a precursor to any specification issue:

- At what cost should the lost energy be evaluated?
- What is the load factor that should be applied?
- What is the internal rate of return that needs to be applied to any discounting?
- What interest rates should be applied to the capital purchase?

The biggest issue with loss capitalisation is that it needs to look at the life of the transformer normally assumed to be around 40 years, which is the length of time that utilities traditionally use for discounting the asset values in their accounts. Any method of capitalisation must be simply a mechanism to attempt to estimate the likely total life costs assuming a degree of consistency in the business environment.

How can the future uncertainties be eliminated by the assessment of the losses? One method is to look at the annualised cost of transformer operation. The annualised cost approach is intended to get the best solution in terms of the balance of capital employed versus losses. The total service charge applicable will normally be based on the cost of capital employed together with an element of the capital repayment for the year spread much like a mortgage payment over the life of the transformer.

Alternatively, another approach is to develop annualised cost factors applied to the no load loss and load losses (sometimes called the "A and B factor") can be applied to a discounted present value model which looks to the life of the transformer and provides new cost factors for the tendered losses. These factors multiplied by the tendered losses when added to the purchase price yield the whole life cost.

The annualised value approach is perhaps closer to the way many businesses operate, but this approach makes it difficult to build in known future changes in loading, interest rates and other factors.

The whole life cost method which utilises the discounted cash flow method allows much more variance in future policy to be included, but the uncertainty of the future needs to be addressed. It is more cumbersome to develop the loss factors, but it does make specification easier as the end result would be added costs determined by the loss factors multiplied by the guaranteed losses.

Many transformer purchasers have historically adopted a policy of capitalisation of the load and no load losses of the transformer in that information pertaining to the financial aspects

of operation are provided to the manufacturer in order that the offered transformer can be optimized for a specific application. In some economies, recent trends with regard to de-regulation of the utility industry have changed the emphasis from least life-cycle cost to first cost, losing the longer term focus. However, this optimisation does support the minimisation of the whole life cost of asset ownership and should be part of any good asset management strategy. It should be noted that aspects of the financial costs of the losses may be commercially, regulatory or even legislatively driven. Therefore, purchasers should select the annualised or whole life cycle approach depending on the degree of support provided in terms of better future predictions.

The approach taken is to evaluate the cost of ownership either on an annualised basis or on a whole life basis, which includes both the capital cost of the transformer, and an estimation of the cost of the losses. At the tendering stage, the evaluation formula is provided to all manufacturers, so that the transformer design can be optimised to minimise the total lifetime costs. The purchaser uses the formula together with the tendered guaranteed losses and the tendered price to select the best offer. Often it may be economically advantageous in the longer term to pay a higher initial purchase price for a transformer with lower losses.

In this chapter, the concepts of annualised cost of transformers and whole life costing are discussed, and then a worked example is provided for the Tier levels of the liquid-filled, three-phase distribution transformers.

A.1 Annualised Cost Approach

The annualised cost approach requires the purchaser to provide a formula in terms of the annualised cost of operation by adding the annualised cost of the no load and load losses to the cost of servicing the capital required to purchase the transformer. Annual transformation costs for a transformer can be derived from the following formula, which takes into account the transformer price and the losses:

$$\text{Transformation cost per annum (\$)} = RC + P(D^2 \times T_1 \times qz) + Q(T_2 \times qy) \qquad \text{(Eq. A-1)}$$

where:

C	=	initial cost of the transformer ($)
R	=	total service charge on capital ($/$/annum)
P	=	load loss at CMR, at normal ratio (kW)
Q	=	no-load loss at rated voltage (kW)
q	=	unit charge ($/kWhr)
D	=	demand factor
z	=	copper loss load factor = $0.2L + 0.8L^2$
y	=	no-load factor
T_1	=	Hours in operation at average demand or load factor per annum
T_2	=	Hours transformer is energised per annum
L	=	percentage of losses attributable to copper loss

Assuming the following information relative to the formula:

$$
\begin{aligned}
R &= \$0.075 \text{ per \$ per annum} \\
q &= \$0.10 \text{ per kWh} \\
D &= 0.5 \quad (50\% \text{ loading}) \\
L &= 0.9 \\
z &= 0.828 \\
y &= 1.0 \\
T_1 &= 8760 \text{ hours} \\
T_2 &= 8760 \text{ hours}
\end{aligned}
$$

For the data given in the above example, the formula therefore reduces to:

Total transformation cost per annum (\$) = 0.075C + 181.3P + 876.0Q   (Eq. A-2)

This formula can then be used to rank transformer quotes being considered for purchase on the basis of the annualised costs. The formula can be easily tailored to individual applications for example where the demand factor varies, e.g. 0.5 for heavily loaded transformers or 0.2 for lighter loaded units. This method focuses on the known factors of the current prices and interest rates and considers that the business will borrow the cash on a long term basis to pay for the transformer.

There are a number of uncertainties that need to be understood and clarified by the purchaser during the development of the formula which include:

1. Demand factor or load factor. This will vary with time of day and time of year. The simple approach taken in this document is to estimate the average load factor for the whole year. More detailed analysis could be made in terms of monthly or even weekly loading where this data is available in order to obtain a more accurate figure.

2. Cost of energy lost. This is given as a single value in the formula but the formula could be further developed to cover multiple costing or to include maximum demand charges where these are implemented by the purchaser. Similarly different costs could be attributed to no load loss from load loss to reflect the different costs of generation for the two loss types.

3. Number of hours the transformer will be in operation per annum. For example generator transformers may be loaded on the basis of double shift operation, and may or not be energised when the load is not been delivered.

A.2   Whole Life Costing Approach

The whole life costing model is intended to attribute a present value to the whole life costs of operating the transformer in its proposed location. In order to achieve this, the two loss factors developed as in the annualised cost method can be used as inputs to a discounted

present value calculation looking into the future to develop the whole life costing model. However, each purchaser may prefer different approaches based on historical methodologies.

By using this approach future changes such as load growth or reductions can be factored into the calculation. In this method the discounted present value of the cost of energy consumed in transformation throughout the life of the transformer is added to the purchase price. The lowest total cost being the preferred option, which may not be the lowest purchase price.

When purchasing a transformer, a utility will include a statement expressing its valuation of no load and load losses. These two valuations are expressed on a cost per Watt basis, where the cost is in the same currency as the purchase order. For instance, in the United States, a utility would specify its no-load and load-loss valuation in dollars per Watt ($/W). The transformer manufacturer then uses this information in their design process, and prepares a design that trades off higher first cost against lower lifetime operating cost. The higher the valuation of losses, the more efficient a transformer design.

When assessing the various bids, the following equation is used by the utility for selecting the lowest total cost of ownership for the transformer designs specified:

> TOC = Purchase Price + Valuation of Core Loss + Valuation of Load Loss

In this equation, the purchase price represents what the manufacturer would charge the utility for the purchase. This price is a reflection of the materials and construction techniques, and thus more efficient transformers will tend to have higher purchase prices.

The valuation of core loss is a calculation that assigns a value to each watt of loss in the core of the transformer. In other words, if core losses are valued at US$5 per Watt and a transformer design has 100W of core loss, then the valuation of core loss entered into the total cost of ownership calculation will be US$500. Adding valuation of losses allows the overall design assessment result in the most cost-optimised purchase decision for the utility. It serves to off-set the higher first cost of an energy-efficient design due to the fact that lower losses associated with the more efficient design will result in a lower operating cost associated with core losses.

The valuation of load loss is very similar to that of valuing core loss. Each watt of load loss is multiplied by the value of the load losses, to arrive at a total cost associated with the load loss that should be incorporated into the purchasing decision. In other words,

> Valuation of core loss = A x core loss (watts)
> Valuation of load loss = B x load loss (watts)
>
> Where:
> > A = equivalent first cost of core losses ($/watt)
> > B = equivalent first cost of load losses ($/watt)

Utilities around the world have developed and customised ways to calculate the valuation coefficients, A and B.

The following formula is used to calculate the net present value factor which is then applied to the two annualised loss factors in order to obtain a whole life cost estimate.

$$C = [a \times (1 + b)^n + b - a] / [(1 + b)^n - 1] \qquad \text{(Equn. A-3)}$$

where:
C – is the cost per \$ annual cost of losses
a – is the cost of capital borrowed
b – is the interest rate payable on deposits
n – is the expected life of the transformer

If it is assumed that the cost of a loan is 7.5%, the interest payable on deposits is 5% and the life of the transformer is taken as 40 years then C equals 0.0833.

The capitalised value of the losses over the life of the transformer as detailed in the equation (2) is then as follows:

A = Total cost of No load loss is then 876/C = 876/0.0833 = \$10516/kW
B = Total cost of Load loss is then 181.3/C = 181.3/0.0833 = \$2176/kW

The estimated whole life cost for assessment of the designs is then the values of no load and load losses multiplied by the above A and B and added to the purchase price. Total whole life cost of transformation is then determined as follows:

TOC (\$) = purchase price (\$) + (10516 x no load loss) + (2176 x load loss)

As these methods make some basic assumptions of future costs and operating data, some degree of sensitivity analysis may be required in order to optimise the formula prior to issue as part of a contract. Factors which are uncertain over the life of the transformer include, the demand profile, interest rates, cost of capital and energy costs.

The example above gives a single cost for the energy consumed. There is no reason why the two loss factors could not have different costs attributed to them.

Any expected load increase to which the transformer will be subjected through its life can be considered as part of this analysis. The expected life of the transformer and the cost of financing may be treated in more detail to also arrive at the figures.

There are many different methods that can be used in making a discounted cash flow or net present value calculation and the above example uses only one of these.

A.3   Worked Example

A purchaser wishes to procure a new transformer rated at 11/0.433 kV, 500 kVA and intends to capitalise the losses in accordance with the methods outlined above. A decision is required on which of the three submitted offers is the most advantageous to the purchaser. The following bids are received:

> Manufacturer A: Price - $32,500; No load loss 0.5 kW; Load loss 3.1 kW
> Manufacturer B: Price – $35,000; No load loss 0.25 kW; Load loss 2.8 kW
> Manufacturer C: Price - $30,000; No load loss 0.8 kW; Load loss 5.2 kW

Without consideration of the capitalisation of the losses, the purchaser would usually opt for the lower price and so the order of preference would be C, then A then B. Note that option C is the highest loss option.

Application of the annualised cost formula as detailed is made on all three offers:
Annualised cost ($) = 0.075C + 181.3P + 876.0Q

The annualised cost of each of the three offers is calculated at:

> Manufacturer A - $5,244
> Manufacturer B - $5,123
> Manufacturer C - $6,950

By considering the annualised cost of transformation the preferred order is B, then A, and then C. This is the reverse of the first cost preference order. Note that in this example option B is the most expensive option in terms of first cost.

The alternative method is the whole life costing. The present value discount factor to be applied to the loss figures for one year is given by C= 0.0833. The whole life running costs additional to the purchase price is given by:

Whole life running costs ($) = 181.3P/0.0833 + 876.0Q/0.0833, where P and Q are the tendered losses. The whole life cost is simply the sum of the purchase price plus the whole life running costs:

> Whole life cost = running costs + purchase price

The whole life costs for each of the three offers is calculated in this manner and is:

> Manufacturer A - $44,505
> Manufacturer B - $43,723
> Manufacturer C - $49,751

Therefore the preferred order is B, then A, and then C. This is the reverse of the first cost preferred order, but identical to the annualised cost approach.

It can be seen that in this example the annualised cost and the whole life cost approaches produces the same answer as the annualised cost is simply projected through the life of the transformer. If the purchaser wishes to consider other cash flows in the decision process such as known maintenance costs and dates, or loading changes due to planned network alterations, then these can be incorporated into the whole life cost method but not in the annualised cost method.