SEAD | Super-efficient Equipment and Appliance Deployment

CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

SEAD Distribution Transformers Report Part 1: Comparison of Efficiency Programs

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SEAD Standards & Labelling Working Group
Distribution Transformers Collaboration

Part 1: Comparison of Efficiency Programmes for Distribution Transformers

A report citing the similarities and differences amongst the available distribution transformer test methods and efficiency levels.

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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)
CRGO	Cold Rolled 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 Why Distribution Transformers?

1.1 Setting the Context

In the 1800's, prior to the invention of transformers, electrical power was distributed as direct current at low voltage. The voltage drop in the distribution wires restricted the use of electricity to urban areas where distances between customers were small and generating equipment could be situated on short distribution circuits. All equipment had to operate on the same (generator) voltage, and losses in the distribution network were high.

This situation was clearly not sustainable, and thus in parallel with these development efforts, engineers were working on alternating current (AC) electricity. Building on the magnetic induction work by Michael Faraday[1] in the 1830's, Otto Bláthy, Miksa Deri, Károly Zipernowsky of Ganz Company (ZBD Transformer) in Hungary first designed and used the transformer in both experimental, and commercial systems. Later on Lucien Gaulard, Sebastian Ferranti, and William Stanley perfected the design. But it wasn't until 1886 that William Stanley, working for Westinghouse, built the first refined, commercially used transformer. George Westinghouse and Stanley made the transformer cheap to produce, and easy to adjust for final use. The first AC-power system that used a transformer was installed in Massachusetts in 1886. A picture of Stanley's first practical transformer made in 1885 appears below.[2]

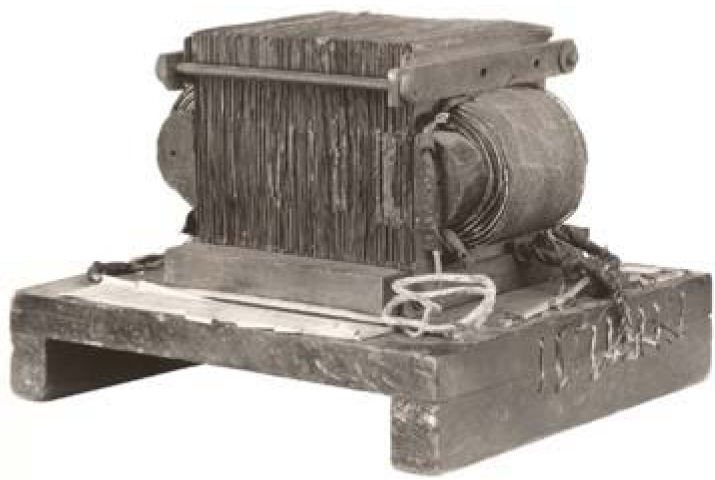

Figure 1-1. First Practical Transformer from 1885

This innovation laid the foundation for all transmission and distribution systems around the world, establishing alternating current (AC) as the principal form of electrical energy for transmission and distribution, and enabling significant energy savings to be realised by

[1] Michael Faraday discovered electromagnetic induction in 1831, the principle on which all transformers operate. AC voltage is applied to one cliquid (primary), inducing a voltage in another cliquid (secondary), proportional to the number of turns of each winding around the core.
[2] Photo credit: http://edisontechcenter.org/Transformers.html

stepping voltages up and down for transmission and distribution[3]. The use of transformers made it possible to cost-effectively transmit electrical power over hundreds of kilometres, enabling the siting of generating stations far from consumers and centres of commerce. This has the added advantage of establishing interconnected electrical grids that are more robust and reliable, should a problem occur at one node in the system.

1.2 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. For the purposes of this document, transformers are grouped into four broad categories:

- Large Power;
- Medium Power;
- Medium Voltage Distribution; and
- Low Voltage Distribution.

Transformers with their highest voltage above 36kV are generally referred to as large power transformers or medium power transformers, depending on the voltage. These transformers are often used in the transmission of electricity. Medium power transformers are generally considered as those with power ratings greater than 2500 kVA and less than or equal to 60 MVA three phase with voltage ratings > 36 kV to ≤ 230 kV. Large power transformers are generally viewed as those with base self-cooled power ratings exceeding 60 MVA and always including all high voltage ratings of 230 kV as well as all extra high voltage (EHV) ratings of 245 kV or more. Large power transformers can be found at generating power stations and electrical substations to convert electrical power to high voltages for transmission and then back down again at the other end to a medium power transformer for transferring power to a subtransmission circuit. From medium power transformers, the voltage is further reduced by medium voltage distribution transformers into circuits where the electricity is distributed to end users.

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

[3] Electrical power is equal to voltage times current. If the voltage is increased, the current will decrease proportionally, holding power constant. Since losses in transmission and distribution power lines are directly proportional to the current being carried in the wire, increasing the voltage can reduce losses associated with the transmission and distribution of electrical energy.

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).

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 & ≤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

Liquid-filled transformers, most often used by electric utilities, have several performance advantages over dry-type transformers. Liquid-filled transformers tend to be more efficient, have greater overload capability and have a longer service life. This longer service life is due to a greater ability to reduce coil hot-spot temperatures and to have higher dielectric withstand ratings. Liquid-filled transformers are also physically a lot smaller than dry-type for a given kVA rating, which can be important in areas with restricted space. However, liquid-filled transformers are often filled with mineral oil which has a higher flammability potential than dry-types and local environmental laws may require containment troughs or other facilities to guard against insulating fluid leaks.[4]

[4] Note: there is a market trend that is becoming increasingly common in the ≤36 kV market towards ester fluids which mitigates this problem. Ester based fluid are fire safe, readily biodegradable, free from corrosive sulphur compounds and have excellent moisture tolerance. For more information on ester fluids, visit the website of M&I Materials Limited: http://www.midel.com/productsmidel/about-esters

Using liquid (usually mineral oil) as both an insulating and cooling medium, liquid-filled transformers incorporate spacers between the windings to allow the fluid to flow and cool the windings and core. Liquid-filled transformers are housed in a tank that facilitates circulation of fluid through the winding ducts and around coil ends. The heat removed from the core-coil assembly by the fluid is then exhausted to the environment through the tank walls (which can include fins to enhance cooling effectiveness), or through the use of external radiators with passive or active fluid circulation and cooling fans. For transformers designed to IEEE specifications, the standard winding insulation used in modern liquid-filled units consists of thermally upgraded Nitrogen-rich Kraft paper, mineral oil and magnet wire. The wire is covered with enamel or thermally upgraded Kraft paper, and the thermal design generally anticipates a 20°C average ambient for the transformer to achieve its expected life. The thermal index for such a system is 180,000 hours (20 years continuous operation) at 110°C, consisting of 65°C average winding rise, 15°C hot spot increment and max average ambient of 30°C for 24 hours or maximum peak ambient of 40°C. At higher ambient temperatures, the winding temperature rise has to be reduced to operate within the same 110°C hot spot temperature.

Dry-type transformers tend to be used most often by commercial and industrial customers. Generally, the installation location can be a critical consideration here – higher-capacity transformers used outdoors are almost always liquid-filled, while lower-capacity transformers used indoors are often dry-type. Dry-type transformers typically are housed in enclosures, with the windings insulated through varnish, vacuum pressure impregnated (VPI) varnish, epoxy resin or cast resin. Dry type insulation can provide excellent dielectric strength and are often designed to withstand high operating temperatures up to 220°C. Temperature rise ratings of dry-type transformers are based on the thermal performance of the type of insulation used - some ratings commonly used in North America, China and elsewhere are 220°C, with 30°C hot spot allowance; 185°C, with 30°C hot spot allowance; and 150°C, with 30°C hot spot allowance, and 105°C with 10°C hot spot increment. The 105°C insulation class is generally reserved for fractional kVA transformers.

1.3 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.[5] 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.

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

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 can be an economically sound investment despite the higher purchase price.[6]

According to analysis conducted by Lawrence Berkeley National Laboratory[7], 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).[8] 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

[6] Please see the Utility economic analysis chapter in the report titled "Part 3: Energy Efficiency Class Definitions for Distribution Transformers".
[7] LBNL, 2011. Published on the web: http://www.superefficient.org/Products/Distribution%20Transformers.aspx
[8] 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.

benefits in mind, many countries / economies around the world – including Australia, Brazil, Canada, China, European Union, 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.

2 Transformer Test Methods

The purpose of a transformer is to convert power from one system voltage to another. For a distribution transformer, this voltage relationship, or voltage ratio, is determined by the ratio of the number of turns on the high voltage winding to the number of turns on the low voltage winding. As the alternating current in the high voltage winding changes polarity 50 or 60 times a second (called "Hertz"), it induces a current in the low voltage winding that is proportional to the voltage of the high voltage winding divided by the turns ratio. As the transformer works, it incurs power (and hence energy) losses in the high voltage winding, the low voltage winding, the core steel and in the surrounding transformer tank / housing and fittings. These losses in the surrounding tank / housing and fittings are called stray losses. The magnitude of the total losses of the transformer relative to the power throughput determines its efficiency.

While there are many aspects of a distribution transformer that can be measured, in Part 2 of these reports, test methods for measuring distribution transformers are compared and a recommendation on a potential harmonised approach is presented. That report includes a discussion on the test methods used in different countries, and a comparison of the main methods followed, to provide a recommendation on an approach that could harmonise test standards for distribution transformers.

2.1 Why Have a Harmonised Test Standard?

Testing standards underpin all product standards and labelling programmes because they are the means by which product energy performance is measured and compared. Harmonisation of energy performance test procedures is a means of facilitating technology diffusion and trade objectives. Harmonised test methods can encourage trade, conformity assessment, comparison of performance levels, technology transfer and the accelerated adoption of best practice policy. For example if energy efficiencies are to used internationally in performance schemes and if transformers are to be imported/exported, it is necessary to specify the measurement accuracies (or uncertainty levels) of test methods to ensure that the manufacturer, the user and the Energy Regulator all get the same result when testing energy efficiencies of transformers.

A test standard adopted for regulatory purposes must meet the following objectives:

- Coverage - the testing standard scope must cover that of the regulated product;
- Metric – the testing standard must be capable of determining energy consumption, efficiency or other metric that constitutes the basis of the regulation;
- Accurate – is designed to minimise random or systemic errors, establishes maximum margins of error and avoids the use of optional approaches;
- Representative - provides robust measurement of energy consumption reflective of in-situ energy use under conditions where the product is used;
- Repeatable - gives the same result each time a product is tested in the same laboratory;

- Reproducible - gives the same result each time a product is tested in different laboratories;
- Low cost – is not overly expensive or time consuming to conduct, and balances the robustness of the test and cost of testing; and
- Portable (optional) – if necessary, should be designed to be applied on-site with separate energy source generation (e.g., large distribution transformers can be difficult to transport to laboratories).

Both governments and manufacturers stand to gain from the harmonisation of testing methods. Benefits to governments include:

- Lower development costs for preparing a test method;
- Comparative test results for products sold domestically and in neighbouring economies;
- The ability to transpose and adapt analyses from other markets to determine appropriate domestic efficiency requirements;
- Adopting minimum performance thresholds and applying them as a starting point in a domestic regulatory programme;
- Adopting a common set of upper thresholds that can be used for market pull programmes such as labelling and incentive schemes; and
- Faster and less expensive testing – for compliance and other purposes – as harmonised testing creates a larger choice of laboratories who can conduct product tests.

For manufacturers, having one harmonised test method with specified measurement uncertainties used by markets around the world will reduce their testing costs associated with demonstrating regulatory and/or product labelling compliance. The manufacturers need only conduct one test and the result would be universally accepted by these markets as being accurate and representative of the performance of their product. A harmonised test method also enables them to look ahead to longer-term rewards for innovation around advanced product designs that will be more energy efficient and have lower life-cycle costs for consumers. Having a consistent test method enables countries to establish a common set of efficiency thresholds that would not only be broad enough to encompass all current market circumstances but which also include aspirational efficiency thresholds as pointers for future market development.

For more information on the comparison of test standards, please see the report titled “Part 2: Test Method Review Report”.

3 Country-Level Transformer Programme

This section provides a brief summary of the test standards and energy-efficiency policies and promotion programmes used in each of the countries that are profiled in the report on voluntary and mandatory energy-efficiency programmes for transformers. The promotion of more energy efficient transformers is supported by a number of policy instruments and programmes around the world. Examples of these policy instruments include:

- Minimum Energy Performance Standards (MEPS)
- Voluntary or mandatory product labelling
- Financial incentives, subsidies and tax breaks
- Communication and outreach materials
- Tools including on-line calculators and smart-phone apps for buyers
- On-site metering and audits
- Technical support and advice on procurement
- Support for R&D and demonstration projects

Of these policy instruments, minimum energy performance standards (MEPS) are one of the most powerful tools, as they require that entire markets shift to higher levels of efficiency. When combined with supporting policies including financial incentives and communications programmes, and with monitoring, verification and enforcement activities to ensure regulatory compliance, MEPS will change markets and ensure the realisation of national benefits from cost-effective energy savings.

In the "Part 4: Country Profiles for the Internationally-Comparable Test Methods and Efficiency Class Definitions for Distribution Transformers" report, tables are presented with the values from their respective source documents. In some cases, the values are comparable, but in others, there are underlying differences that prevent direct comparisons. For example, transformers must operate at the frequency of the system where they are installed (i.e., 50Hz or 60Hz) and the efficiency of a transformer will vary slightly with the frequency of the network. Furthermore, some policy makers establish energy performance requirements for transformers on a basis of maximum losses for the core and coil at full load separately, while others establish maximum losses summed together for a particular kVA rating. Still other policy makers specify the efficiency at a percentage loading point.

In addition, there are some slight but important differences between how the power rating of a transformer is reported in different markets. In countries applying IEEE standards (generally North America), the kVA power rating of the transformer is defined as the rated capacity at the output of the device – that is, it represents the available capacity at the load point. However, in other parts of the world employing IEC standards, the kVA rating represents the rated input to the transformer – how much power is being supplied to a particular unit. When rated as the output (i.e., the IEEE method), the power rating *excludes* the core and coil losses when the transformer is operating, whereas for the input capacity (i.e., the IEC method), the power rating includes the transformer's losses. In essence, the total losses represent the difference between the two kVA rating conventions, as shown in the table below. To provide a worked example showing the difference in kVA rating, the losses associated with the European BoBk level for three different kVA ratings are shown in the following table. The kVA value shown for IEEE is the rating that an IEC rated transformer would have if it were re-rated as an IEEE transformer. The magnitude of the percentage difference in kVA ratings decreases as the kVA ratings increase because the losses are also decreasing as a proportion of kVA capacity.

Table 3-1. Illustrative Comparison of kVA Ratings at Full Load, IEC and IEEE

kVA_{IEC}	Core Loss (Bo, Watts)	Coil Loss (Bk, Watts)	kVA rating in Watts	kVA_{IEC}	kVA_{IEEE}	% Difference in kVA ratings
50	190	1250	50,000	50.0	48.6	2.9%
400	930	4900	400,000	400.0	394.2	1.5%
2000	3150	21,000	2,000,000	2000.0	1975.9	1.2%

For the purposes of the comparison in this report, we will convert the IEEE kVA ratings to the IEC method, as the IEC test method is more common among the countries that are active on distribution transformer efficiency requirements. The method selected also has an impact on how losses are treated in the efficiency metric. Efficiency is, broadly speaking, a measurement of power out divided by power in. However, the way that efficiency is calculated differs slightly between IEC and IEEE. This difference stems from a difference in how transformers are rated – that is, the power capacity of a transformer. In IEC, the equation is based on the input power, while for IEEE, the equation is based on output power, as shown in the following equations:

$$IEC\ Definition\ Efficiency = \frac{(Power\ Input - Losses)}{(Power\ Input)}$$

$$IEEE\ Definition\ Efficiency = \frac{Power\ Output}{(Power\ Output + Losses)}$$

Where:

Power Output and *Power Input* are measured in Watts and are calculated by multiplying the kVA rating of the transformer (IEEE or IEC method) by the per unit load (e.g., 50% of rated nameplate);

Losses represents the sum of core and coil losses at the per unit load point; where *core loss* is the power loss in the core at rated voltage and *coil losses* are the square of the *per unit load* times the coil losses at rated capacity.

Per unit load is the decimal equivalent of the percentage of rated load supplied by the transformer, such as 0.50 for 50% of rated capacity.

Although these two equations may appear to be different on first review, as long as the kVA rating is consistent (i.e., based on input or output), the two equations will yield exactly the same numerical efficiency value. To illustrate this calculation, consider the 50 kVA model from the above Table 3-1, which is calculating the percentage efficiency at full-load:

Table 3-2. Illustrative Comparison of kVA Rating Conventions, IEC and IEEE

Item	IEC Method	IEEE Method
kVA Rating	50 kVA	48.6 kVA
Core Losses	0.190 kilowatts	0.190 kilowatts
Coil Losses	1.250 kilowatts	1.250 kilowatts
Efficiency	= (kVA – losses) / kVA	= kVA / (kVA + losses)
Equation	= (50 – (0.190 + 1.250))/50	= 48.6 / (48.6 + (0.190 + 1.250)
Result (%)	97.12%	97.12%

There are, in addition, some stray losses that occur in the transformer tank due to eddy current loss, for example, but these are usually very small compared to the core and coil losses and can be ignored for the purposes of this calculation. Thus, the only conversion necessary is a conversion of kVA ratings based on either input or output of the transformer, and then the efficiency equation used will yield comparable and consistent results.

In the various country programmes, there are a variety of performance metrics used such as separate maximum levels of core and coil losses as well as a minimum percentage efficiency which is specified at a per unit load point. In Annex A and B, the normalisation methods used to create comparable values from the different economies is provided.

4 Comparison of Distribution Transformer Efficiency Programmes

When comparing the levels of ambition between the various programmes, one of the problems is the wide diversity of metrics used. There are maximum watts of core and coil losses (at a defined loading point), percentage efficiency at different loading points and an exponential equation that is based on the transformer power rating. There are also differences in the operating frequency of distribution transformers and differences in how the transformer capacity is rated, where the IEC defines the transformer on the basis of input (i.e., including losses of the distribution transformer) while IEEE define it on the basis of output (i.e., excluding losses).

For the measurement of losses, most economies around the world have regulatory and/or voluntary programmes promoting energy-efficient distribution transformers based on IEC 60076. In some cases, there are slight (local) modifications that have been made due to specific or unique requirements, however for the most part, the standards are consistent. The economies that fall into the group using or based on IEC 60076 are: Australia, Brazil, China, European Union, India, Israel, Japan, Korea, New Zealand and Vietnam. The two major economies who deviate from using IEC are the United States and Canada. The US is using its own test standard that was adopted in 2006 by DOE in close consultation with manufacturers and other stakeholders. The US test standard is largely based on IEEE C57.12.90-1993 and C57.12.91-1993 (using IEEE C57.12.00-1993 as an additional reference source). Canada has adopted the most recent voluntary industry testing standard, NEMA TP 2-2005 which is similar to the same IEEE standards and is consistent with the US DOE test method.

The two sections in this chapter present the levels of ambition associated with the liquid-filled and dry-type distribution transformer efficiency programmes. The level of ambition is presented as a percentage efficiency at 50% of rated load, 50Hz network frequency and using the IEC definition of a kVA rating (i.e., based on power input). The procedure followed in converting some of the countries for normalisation in order to compare them is provided in Annexes A and B of this report.

4.1 Liquid-Filled Distribution Transformer Efficiency Programmes

The following table provides a summary of the liquid-filled distribution transformer efficiency programmes presented in this report. This table presents the country / economy, the scope of transformers covered, the requirements, whether it is mandatory or not, and the standard or regulation referenced.

Table 4-1. Summary of Coverage of Liquid-Filled Distribution Transformer Programmes

Country	Transformers	Indicative Requirements	Mandatory?	Standard / Regulation
Australia / New Zealand	1 phase: 10-50 kVA 3 phase: 25-2500 kVA Voltage: 11 and 22 kV	Efficiency at 50% load	Yes, since April 2004	AS2374.1.2-2003
Brazil	1 phase: 5 to 100 kVA 3 phase: 15 to 300 kVA Voltage: 15, 24.2 & 36.2kV	Max watts core and coil losses at 100% load	Yes, current regulation	ABNT NBR 5356
Canada	1 phase: 10-833 kVA 3 phase: 15-3000 kVA	Efficiency at 50% load	No, voluntary since 2000	CSA C802.1
China	1 phase: 5-160 kVA 3 phase: 30-1600 kVA	Maximum core and coil losses at 100% load	Yes	JB/T 10317-02 GB 20052-2013
European Union	3 phase: 50-2500 kVA; Voltage: 24 and 36kV (draft: 3 phase: 25-3150 kVA)	Maximum core and coil losses at 100% load	No (draft MEPS in review)	EN50464-1:2007
India	3 phase: 16-200 kVA for labelling	Maximum W losses at 50% and 100% loading	No, but utility required to purchase 3-Star	IS 1180
Israel	100-2500 kVA Voltage: 22kV or 33kV	Maximum W losses 100%	Yes, 2011	IS 5484
Japan	1 phase: 5-500 kVA 3 phase: 10-2000 kVA both 50 and 60 Hz	<500 kVA: 40% >500 kVA: 50%	Yes, March 2008; updated 2013	Top Runner
Korea	1 phase 10-100 kVA; 1 and 3 phase; 3.3-6.6kV, 100-3000 kVA 1 and 3 phase; 22.9kV, 100-3000 kVA & 10-3000 kVA	Efficiency at 50% load	Yes, July 2012	KS C4306; C4316 and C4317
Mexico	1 phase: 5-167 kVA 3 phase: 15-500 kVA Voltage: 15, 25 and 34.5 kV	Efficiency at 50% load	Yes, 1999	NOM-002-SEDE-1997
USA	1 phase: 10-833 kVA 3 phase: 15-2500	Efficiency at 50% load	Yes, Jan 2010; new Jan 2016	10 CFR 431
Vietnam	25-2500 kVA, 0.4-35kV	Efficiency	Yes, Jan 2013	TCVN 8525:2010

4.1.1 Comparison of Liquid-Filled Three-Phase Distribution Transformers

The following figure presents a comparison of the various programmes for liquid-filled three-phase distribution transformers. These data have been normalised to all show 50% loading, 50Hz operation and using the IEC definition of kVA ratings. For the USA, the transformers have also had their load losses corrected to 75C, making them consistent with the IEC reference temperature. This figure consists of mandatory, minimum level performance requirements (i.e., MEPS) from the countries listed in the table above. That is, programmes like the high-efficiency performance levels from Australia, Israel and Korea are not included in this graph. For the countries shown, the highest efficiency curve for the smaller kVA ratings (up to about 200kVA) is the US DOE MEPS level published in 2013, which will take effect in January 2016. Above 200kVA, the Japanese Top Runner scheme has slightly higher efficiency requirements. The two low efficiency curves in the graph are the Korean and the Brazilian MEPS. At the smaller kVA ratings (i.e., 25-45 kVA) the European Commission's Draft Tier 1 MEPS that take effect in 2015 approach the Brazilian level at 25kVA.

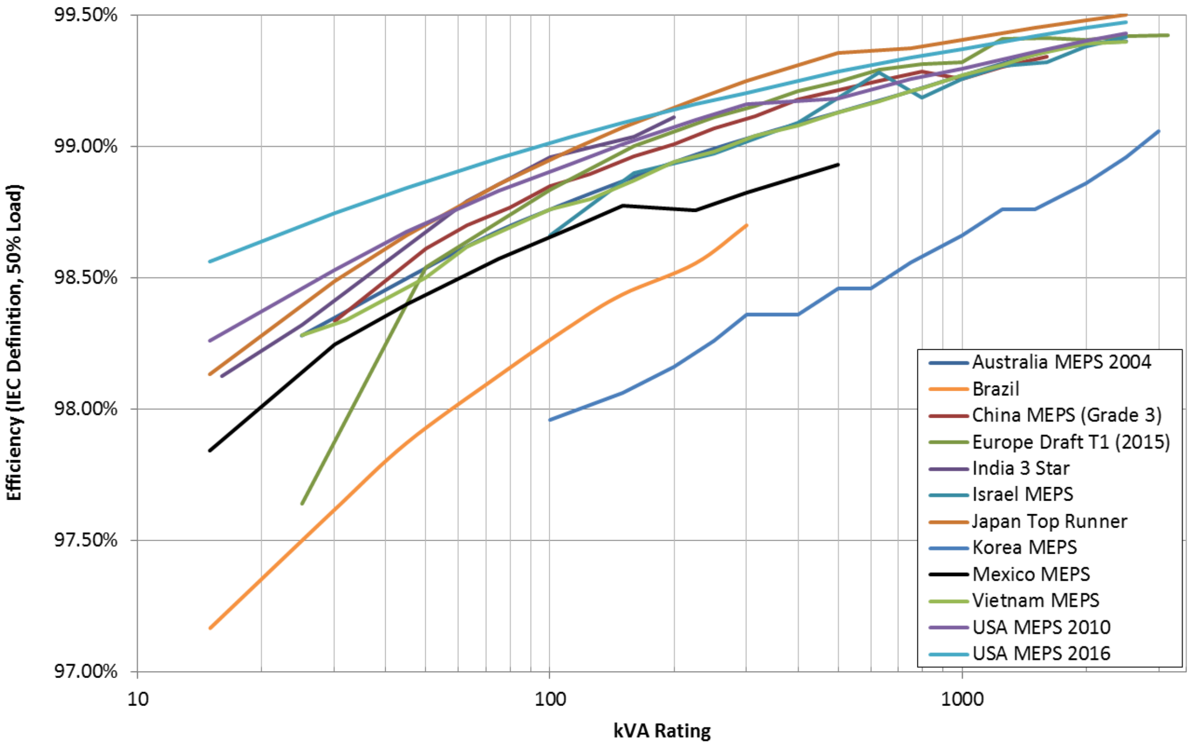

Figure 4-1. Efficiency at 50% Load for Three-Phase Liquid-Filled Transformers

As discussed above, these curves are primarily based on MEPS requirements. The curves generally show that all the countries are clustered together within approximately 0.5% on the efficiency scale at any given kVA rating. However, Korea's MEPS level is lower than the levels adopted in the other countries.

Looking at some of the individual country curves, it would appear that some of the requirements have anomalies in how they treat losses, such as Israel's step-down in efficiency at 800 kVA and Mexico at 200 kVA. The shape of these two curves is unexpected because transformers tend to increase in efficiency at higher kVA ratings. Therefore to have an efficiency level decrease while the kVA rating is increasing runs counter to the physics of transformer design.

To take a more detailed look at the comparison of requirements between the countries, two figures were prepared looking at the requirements of a 100kVA and a 1000kVA transformer across the countries profiled in this diagram. The following figure presents the 100 kVA three-phase liquid-filled transformer requirements. In this graph, as with the earlier one, all the efficiency requirements have been normalised to be comparable – 50% loading, 50Hz operation, using the IEC definition of kVA rating and efficiency. Note that the red bar farthest to the right is the "MaxTech" design for this rating published by the US DOE. This is not a regulatory requirement but rather illustrates the technical limit for energy-efficiency of a wound 100 kVA liquid-filled distribution transformer at 50Hz and 50% loading.

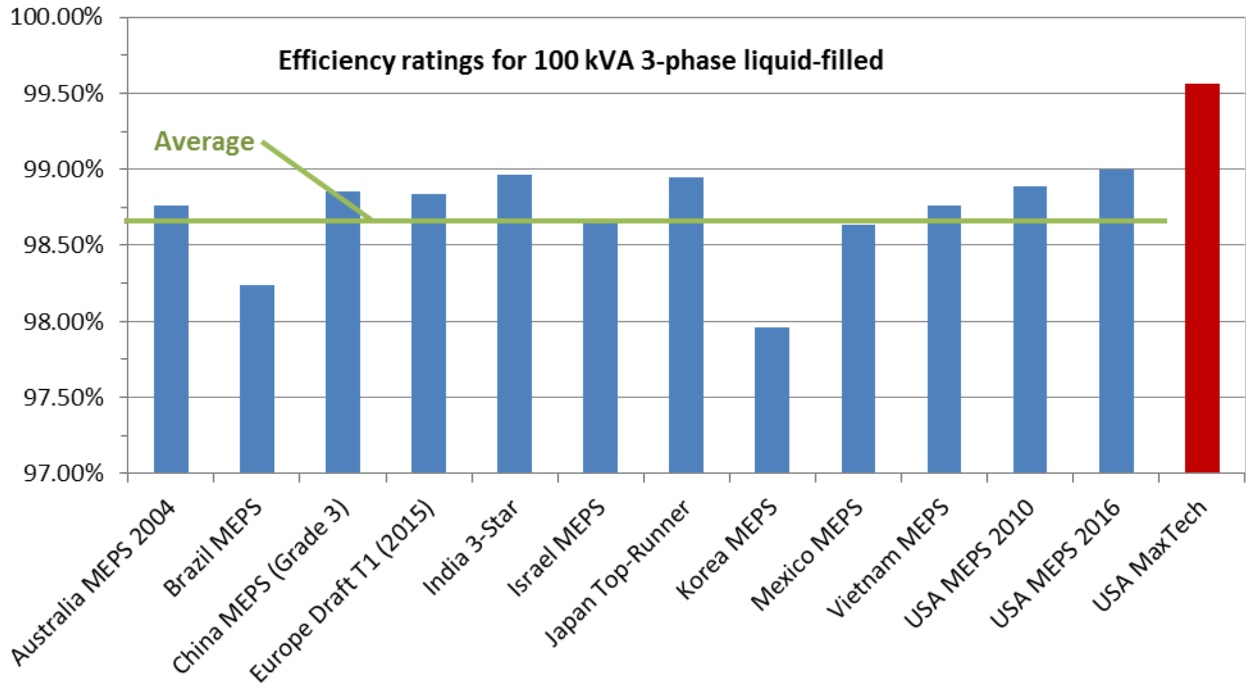

Figure 4-2. Efficiency at 50% Load for 100 kVA Three-Phase Liquid-Filled Transformers

In this figure, a green line has been drawn at 98.71% which represents the simple average of all the blue bars for this 100 kVA transformer. The range of values is from 97.96% for Korea to 99.00% for the US DOE MEPS that will take effect in January 2016. This range represents a difference of 1.04% in efficiency from the lowest to the highest required performance.

Looking at a larger kVA rating, there is less variability between the lowest and the highest values. The following figure presents the range of efficiency requirements for a 1000 kVA three-phase liquid-filled transformer, normalised for the comparison to 50Hz, 50% loading and the IEC definition of kVA rating and efficiency. Brazil, India and Mexico do not cover liquid-filled distribution transformers as large as 1000 kVA, so these countries do not have any performance levels appearing in the figure.

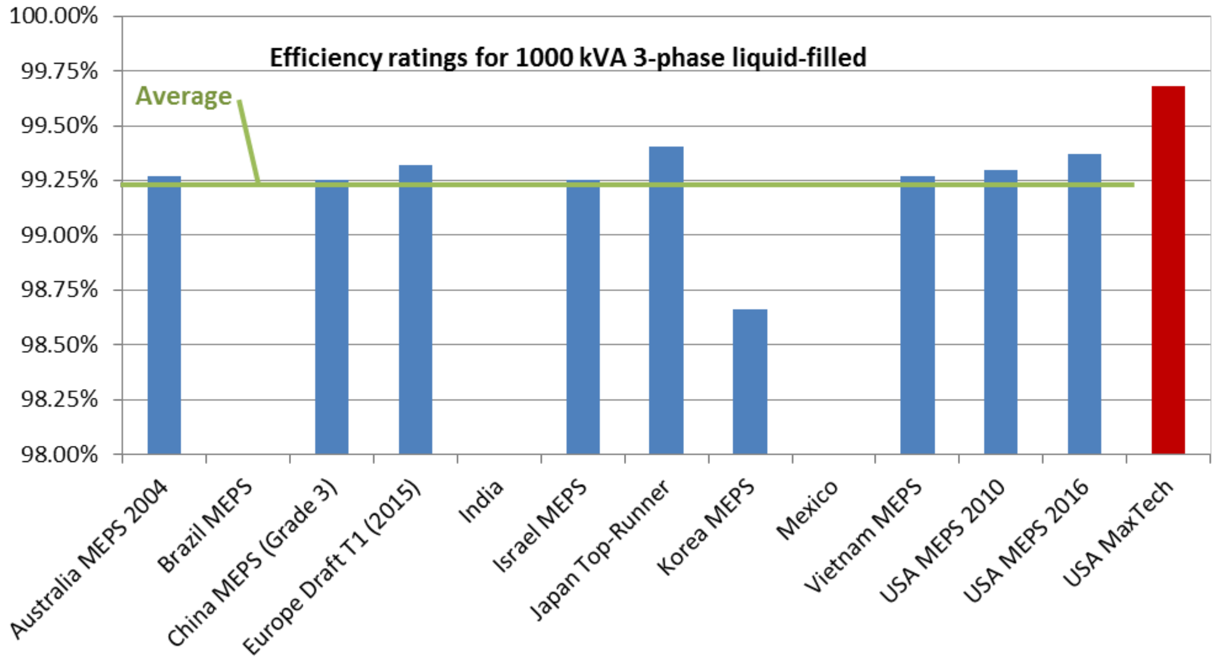

Figure 4-3. Efficiency at 50% Load for 1000 kVA Three-Phase Liquid-Filled Transformers

In this figure, a green line has been drawn at 99.23% which represents the simple average of all the blue bars for this 1000 kVA transformer. The range of values is from 98.66% for Korea to 99.41% for Japan's (draft) new Top-Runner programme requirements. This range of efficiency values is indeed smaller than the 100 kVA, spanning just 0.75% for the 1000 kVA rating. However, if Korea is excluded from the comparison, the difference between the highest and lowest efficiency is only 0.15% between the remaining countries.

As is visible in Figure 4-1 and the above two histograms, the differences in efficiency requirements between the various programmes gets smaller at the larger kVA ratings. The differences in the smaller kVA ratings are, for example, approximately 1.0% at 50 kVA but less than 0.2% at 2500 kVA.

The following figure presents the *high efficiency* curves for the various economies, normalised for 50% loading, 50Hz, IEC definition of kVA and efficiency and temperature correction for the US data. This figure includes the European Commission's draft Tier 2 level for 2020, the 5-star labelled designs for India, and the high efficiency performance level in Australia, Israel and Korea. The US DOE 2016 regulation is also included, as well as the 'max tech' performance level and Japan's Top Runner scheme.

In this figure, it is clear to see that the ambition associated with Korea's high efficiency models are more in line with the high efficiency targets and labelling schemes elsewhere in the world. And, although India's programme only extends to 200 kVA, the five-star rating is one of the most ambitious programmes globally up to that kVA rating. In 2011, Australia proposed a new high-efficiency performance level (HEPL), which is shown as a black line in the following figure. The proposed HEPL for Australia is in line with the draft European Commission's regulation scheduled to take effect in 2020 (Tier 2). The European

Commission's Tier 2 regulation – while in keeping with the more ambitious programmes around the world for the majority of the covered kVA ratings has a much lower requirement for the small kVA ratings, i.e., less than 50 kVA. The European Commission's Tier 2 thus cuts across several programmes and has a comparatively low efficiency for 25kVA transformers. China's Grade 1 standard is for amorphous transformers, and is one of the most ambitious in the world.

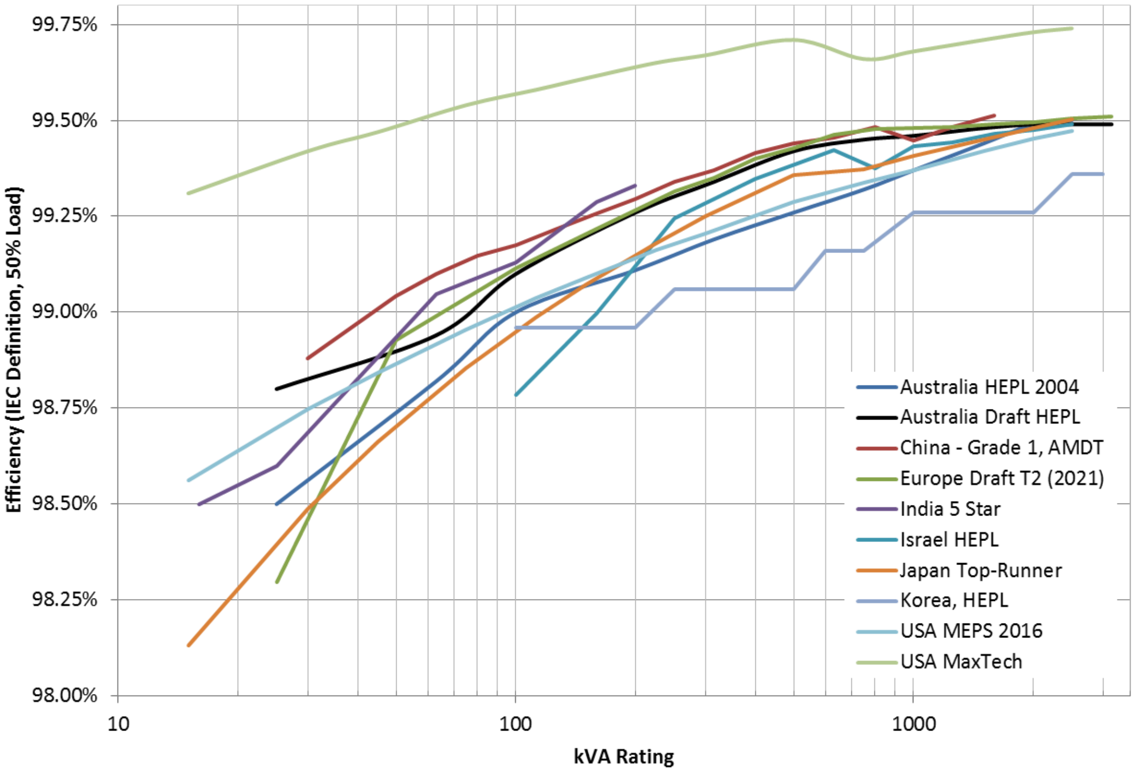

Figure 4-4. High Efficiency Programmes for Three-Phase Liquid-Filled Transformers

The following table presents a comparison between the normalised[9] percentage efficiency levels for the different kVA ratings across the programmes. As is clearly illustrated by this table, there are traditions and different practices around the preferred kVA ratings in different parts of the world, therefore the tables of maximum losses and efficiency presented in the regulations do not all correspond to the same set of kVA ratings. However, efficiency values transformers can only be compared for the same kVA rating because efficiency scales with size. Also, although there are gaps in the table, this does not necessarily mean that those ratings would not be regulated in that market. Instead, it simply means the kVA rating is not one of the preferred ratings in that country or economy.

[9] The values shown in this table may be adjusted from their original values in order to ensure their comparability with the other countries / economies. The efficiency values shown here are representative of distribution transformers operating at 50% loading, 50Hz frequency and the IEC definition of kVA rating and efficiency.

Table 4-2. Comparison of MEPS Requirements for Three Phase Liquid-Filled Transformers

kVA	Australia MEPS (2004)	Brazil MEPS	China MEPS–Grade 3	Europe Tier 1 2015 (Draft)	Europe Tier 2 2021 (Draft)	India – 3 stars	Israel - MEPS	Japan Top-Runner	Korea – MEPS for 22kV-LV	Mexico MEPS	Vietnam - MEPS	USA - MEPS 2010	USA – MEPS 2016
15		97.17						98.13		97.84		98.26	98.56
16						98.13							
25	98.28			97.64	98.30	98.32					98.28		
30		97.62	98.33					98.49		98.25		98.53	98.75
45		97.87						98.66		98.40		98.68	98.84
50			98.61	98.54	98.93						98.50		
63	98.62		98.70			98.79					98.62		
75		98.13						98.86		98.57		98.83	98.96
80			98.77										
100	98.76		98.85	98.84	99.12	98.96	98.66		97.96		98.76		
112.5		98.32						98.99		98.69		98.93	99.04
125			98.90								98.80		
150		98.44						99.07	98.06	98.78		99.01	99.09
160			98.96	99.00	99.22	99.04	98.90				98.87		
200	98.94		99.01			99.11			98.16		98.94		
225		98.55						99.18		98.76		99.10	99.16
250			99.07	99.11	99.31		98.97		98.26		98.98		
300		98.70						99.25	98.36	98.82		99.16	99.20
315	99.04		99.12	99.15	99.35						99.04		
400			99.18	99.21	99.40		99.09		98.36		99.08		
500	99.13		99.21	99.25	99.43			99.36	98.46	98.93	99.13	99.18	99.29
600									98.46				
630			99.25	99.29	99.46		99.28				99.17		
750	99.21							99.37	98.56		99.21	99.26	99.34
800			99.29	99.31	99.48		99.19				99.22		
1000	99.27		99.26	99.32	99.48		99.26	99.41	98.66		99.27	99.30	99.37
1250			99.30	99.41	99.48		99.31		98.76		99.31		
1500	99.35							99.45	98.76		99.35	99.36	99.42
1600			99.34	99.41	99.49		99.32				99.36		
2000	99.39			99.41	99.49		99.38	99.48	98.86		99.39	99.40	99.45
2500	99.40			99.42	99.50		99.41	99.50	98.96		99.40	99.43	99.47
3000									99.06				
3150				99.42	99.51								

Note: The efficiency values shown here are representative of distribution transformers operating at 50% loading, 50Hz frequency and the IEC definition of kVA rating and efficiency. USA levels are corrected for 75C winding temperature.

From this table some of the national similarities can be identified, for example Australia and Vietnam have the same efficiency requirements, although Vietnam provides more preferred kVA ratings in their efficiency tables. The draft European Commission’s Tier 1 level that takes effect in 2015 appears to be approximately the same level as the USA MEPS level that took effect in 2010. The Korean MEPS are the lowest for all of the kVA ratings in the table, as was observed from the previous diagrams. The most ambitious MEPS requirements shown in this table are shared between the United States MEPS 2016 level (which has been adopted) at lower kVA ratings and the draft European Commission’s Tier 2 levels for 2020 and draft Japanese Top-Runner levels at the higher kVA ratings.

4.1.2 Comparison of Liquid-Filled Single-Phase Distribution Transformers

The following figure presents a comparison of the various programmes for liquid-filled single-phase distribution transformers. These data have been normalised to all show 50% loading, 50Hz operation and using the IEC definition of kVA ratings. . For the USA, the transformers have also had their load losses corrected to 75C, making them consistent with the IEC reference temperature. This figure consists of all the efficiency programmes on single-phase liquid-filled transformers, both MEPS and high-efficiency labelling programmes as well. This graph also includes the US DOE "MaxTech" level (a bright green line at the top) which depicts the maximum technologically feasible efficiency level for these units.

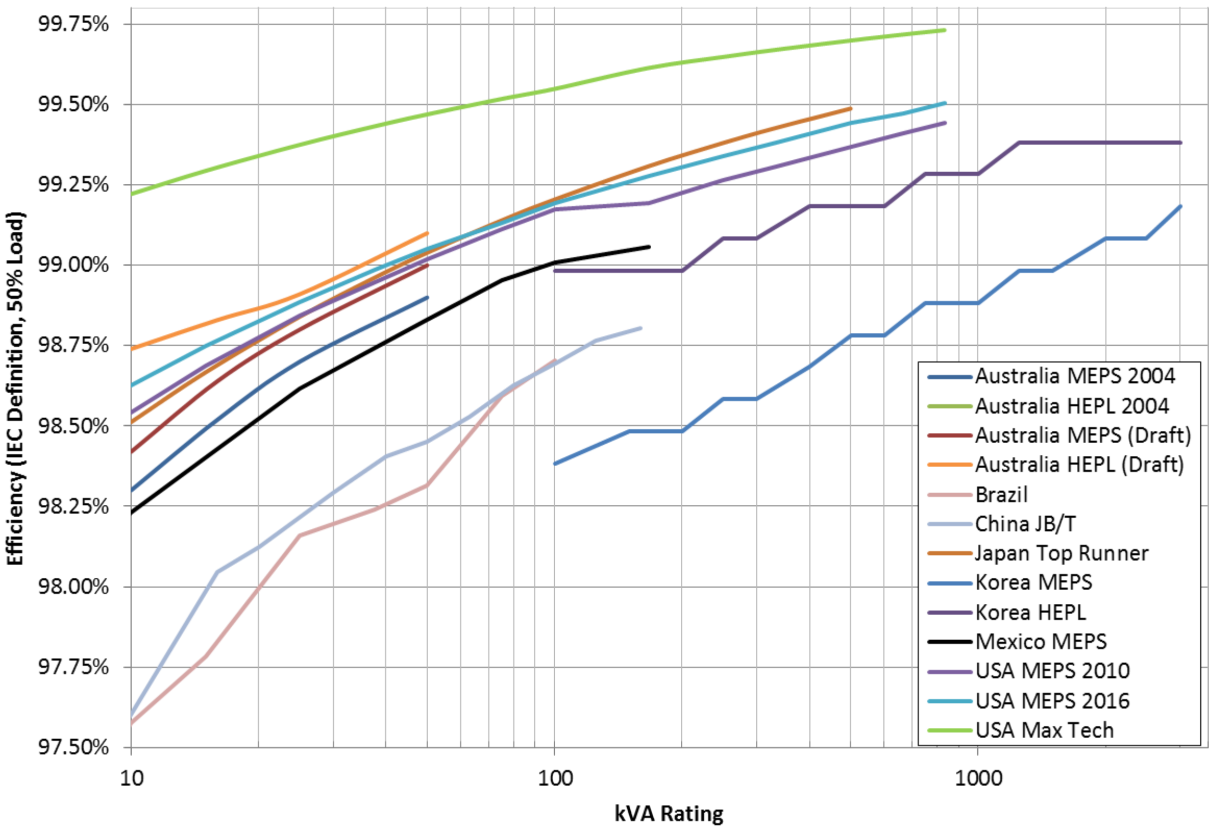

Figure 4-5. Efficiency at 50% Load for Single-Phase Liquid-Filled Transformers

In the above graph of single-phase liquid-filled transformers, there are three programmes that have high efficiency levels. The US DOE MEPS levels that take effect in January 2016 are the most ambitious of the MEPS programmes, and are the highest efficiency between 50 and 70kVA. Below 50kVA, Australia's draft high efficiency performance levels are the most ambitious, and above 70kVA, Japan's Top Runner scheme is the most efficient up to about 500 kVA. The US MEPS are then the most efficient again, through 833 kVA, the highest regulated rating in the USA for single-phase liquid-filled. The requirements for Brazil, China's JB/T (industry) standard and Korea's MEPS levels (which start at 100 kVA) are the lowest of those analysed, however, Korea's HEPL efficiency levels are more in line with the other programmes around the world, and have nearly the same value as Mexico at 100 kVA.

The curves generally show that all the countries are clustered between 1.0 to 1.5% of each other on the efficiency scale at any given kVA rating.

To take a more detailed look at the comparison of requirements between the countries, a comparison of the requirements was prepared for a 50 kVA single-phase liquid-filled distribution transformer. In this graph, as with the earlier one, all the efficiency requirements have been normalised to be comparable – 50% loading, 50Hz operation, using the IEC definition of kVA rating and efficiency. Note that the red bar farthest to the right is the “MaxTech” design for this rating published by the US DOE. This is not a regulatory requirement but rather illustrates the technical limit for energy-efficiency.

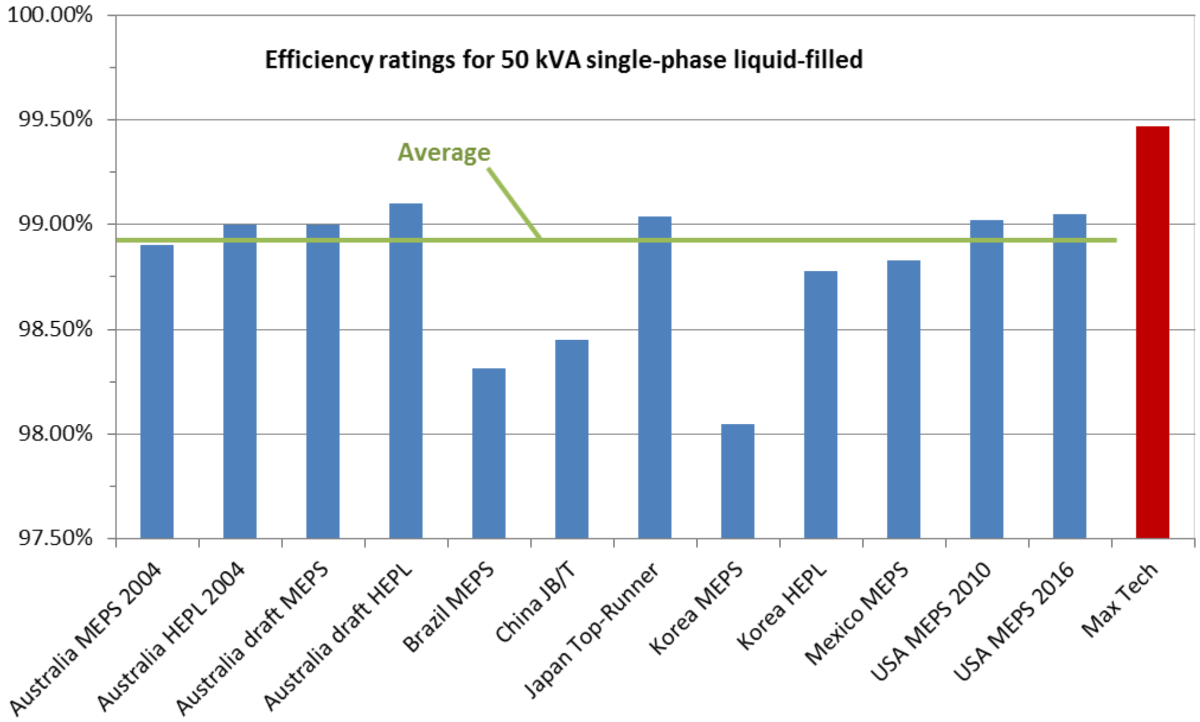

Figure 4-6. Efficiency at 50% Load for 50 kVA Single-Phase Liquid-Filled Transformers

In this figure, a green line has been drawn at 98.79% which represents the simple average of all the blue bars for this 50 kVA transformer. The range of values is from 98.05% for Korea to 99.10% for Australia’s HEPS level. The US DOE MEPS level that takes effect in 2016 is 99.05%. This range represents a difference of 1.05% in efficiency from the lowest to the highest required performance.

The following table presents a comparison between the normalised[10] percentage efficiency levels for the different kVA ratings across the programmes. As is clearly illustrated by this

[10] The values shown in this table may be adjusted from their original values in order to ensure their comparability with the other countries / economies. The efficiency values shown here are representative of

table, there are traditions and different practices around the preferred kVA ratings in different parts of the world, therefore the tables of maximum losses and efficiency presented in the regulations do not all correspond to the same set of kVA ratings. However, transformer efficiency values can only be compared for the same kVA rating because efficiency scales with size. Also, although there are gaps in the table, this does not necessarily mean that those ratings would not be regulated in that market. Instead, it simply means the kVA rating is not one of the preferred ratings in that country or economy.

Table 4-3. Comparison of MEPS Requirements for Single Phase Liquid-Filled Transformers

kVA	Australia MEPS 2004	Australia HEPL 2004	Australia Draft MEPS	Australia Draft HEPL	Brazil MEPS	China JB/T	Japan Top-Runner	Korea MEPS	Korea HEPL	Mexico MEPS	USA MEPS 2010	USA MEPS 2016
5					96.85	97.15				97.80		
10	98.30	98.42	98.42	98.74	97.58	97.60	98.51			98.23	98.54	98.63
15					97.78		98.67			98.40	98.69	98.75
16	98.52	98.64	98.64	98.83		98.05						
20						98.13						
25	98.70	98.80	98.80	98.91	98.16		98.84			98.62	98.84	98.88
30						98.29						
37.5					98.24		98.96			98.74	98.95	98.99
40						98.41						
50	98.90	99.00	99.00	99.10	98.32	98.45	99.04			98.83	99.02	99.05
63						98.53						
75					98.59		99.14			98.95	99.11	99.13
80						98.63						
100					98.70	98.70	99.20	98.38	98.98	99.01	99.17	99.19
125						98.76						
150								98.48	98.98			
160						98.80						
167							99.31			99.06	99.19	99.28
200								98.48	98.98			
250							99.38	98.58	99.08		99.27	99.34
300								98.58	99.08			
333							99.43				99.31	99.38
400								98.68	99.18			
500							99.49	98.78	99.18		99.37	99.44
600								98.78	99.18			
667											99.41	99.47
750								98.88	99.28			
833											99.44	99.50
1000								98.88	99.28			
1250								98.98	99.38			
1500								98.98	99.38			
2000								99.08	99.38			
2500								99.08	99.38			
3000								99.18	99.38			

Note: The efficiency values shown here are representative of distribution transformers operating at 50% loading, 50Hz frequency and the IEC definition of kVA rating and efficiency. USA levels are corrected for 75C winding temperature.

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distribution transformers operating at 50% loading, 50Hz frequency and the IEC definition of kVA rating and efficiency.

From this table some of the national similarities can be identified, for example the Japanese Top-Runner programme has values that are similar to those of Mexico; and the US 2010 MEPS are close to those of the draft Australian standard now proposed. The Korean and the Brazilian MEPS are the lowest in the table along with the Chinese industry standard. That said, the High Efficiency Performance Level (HEPL) for Korea is approaching that of the US 2010 MEPS levels. As stated earlier, the most ambitious MEPS requirements shown in this table is that of the United States MEPS 2016 level (which has been adopted), and the Japanese Top-Runner and Australian HEPL levels meet or exceed the US DOE values at different kVA ratings (although neither are MEPS).

4.2 Comparison of Dry-Type Efficiency Programmes

The following table provides a summary of the dry-type distribution transformer efficiency programmes presented in this report. This table presents the country / economy, the scope of transformers covered, the requirements, whether it is mandatory or not, and the standard or regulation referenced. Brazil, India, Mexico and Vietnam are not shown because they do not have programmes in dry-type transformers.

Table 4-4. Summary of Coverage of Dry-Type Distribution Transformer Programmes

	Phases	Requirement	Mandatory	Standard / Regulation
Australia	1 phase: 10-50 kVA 3 phase: 25-2500 kVA; Voltage: 11 and 22kV	Efficiency at 50% load	Yes, April 2004	AS2374.1.2-2003
Canada	1 phase: 15-833 kVA 3 phase: 15-7500 kVA Voltages: 20-45, >45-95; >95-199kV BIL	35% loading for low voltage (1.2kV) and 50% for >1.2kV	Yes, April 2012	C802.2-12/ Canada Gazette Part II
China	3 phase: 30-2500 kVA; Class B, F and H.	Maximum core and coil losses at 100% load	Yes	GB 20052-2013
European Union	3 phase: 100-3150 kVA ≤12kV, 17.5 and 24kV, ≤36 kV (draft: 3 phase: 50-3150 kVA)	Maximum core and coil losses at 100% load	No (draft MEPS in review)	EN50464-1:2011
Israel	100-2500 kVA Voltage: 22kV or 33kV	Maximum W losses 100%	Yes, 2011	IS 5484
Japan	1 phase: 5-500 kVA 3 phase: 10-2000 kVA both 50 and 60 Hz	<500 kVA: 40% >500 kVA: 50%	Yes, March 2008; updated 2013	Top Runner
Korea	1 and 3 phase; 3.3-6.6kV, 50-3000 kVA 1 and 3 phase; 22.9kV, 50-3000 kVA	Efficiency at 50% load	Yes, July 2012	KS C4311
USA	1 phase, LV, 25-333 kVA 3 phase, LV, 30-1000 kVA 1 phase, MV, 15-833 kVA 3 phase, MV, 15-2500 kVA MV: 20-45kV, 46-95, >96kV BIL	35% loading for low voltage (LV) (<600V) and 50% for medium voltage (MV)	Yes, Jan 2010; new Jan 2016	10 CFR 431

4.2.1 Comparison of Dry-Type Three-Phase Distribution Transformers

The figure below offers a comparison of the energy-efficiency programmes reviewed for medium-voltage dry-type distribution transformers. These data have been normalised to show 50% loading, 50Hz operation and using the IEC definition of kVA ratings and efficiency. Due to the impact of insulation on the performance of a dry-type transformer, when preparing this comparison, transformers with similar primary voltages and insulation ratings were included to the greatest extent possible. Brazil, India, Mexico and Vietnam do not have efficiency programmes for dry-type transformers, therefore these countries are not included in this section of the report.

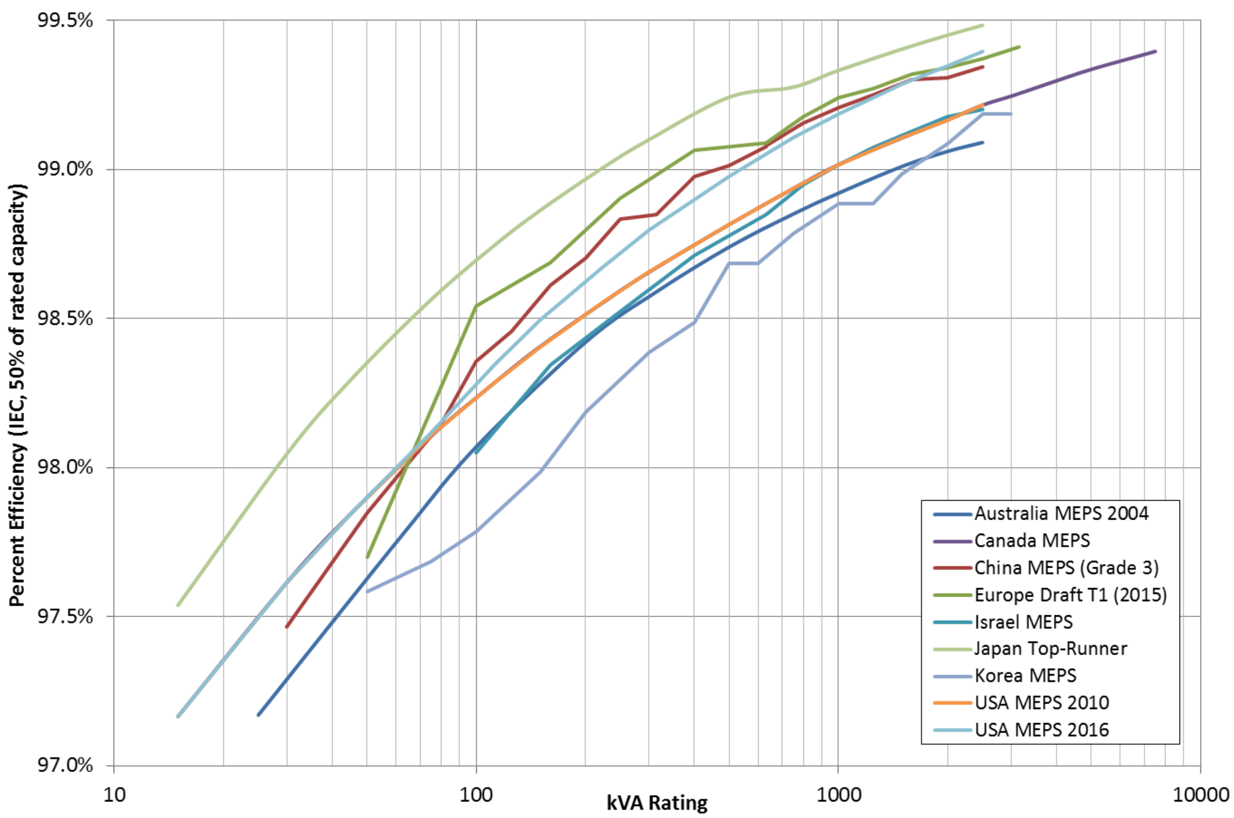

Figure 4-7. Efficiency Programmes at 50% Load for Three-Phase Dry-Type Transformers

Note: For Canada, the dry-type MEPS regulations extend to 7500 kVA.

These efficiency curves are for three-phase dry-type medium-voltage distribution transformers with a primary voltage around 24kV. The curves generally show that all the countries are clustered together within approximately 0.5% on the efficiency scale at any given kVA rating. The slope of the curves is generally consistent as well, although the European Commission's draft Tier 1 appears to have a steeper slope in the kVA ratings below 100 kVA because of its comparatively low efficiency 50 kVA unit. Korea has the lowest MEPS requirements in dry-type, as is the case with liquid-filled, however Korea's level of ambition is not as low on the dry-type relative to the other countries as it is for the liquid-filled. The highest level of ambition in MEPS in the above graph is the Japanese Top Runner programme. The new US DOE MEPS that take effect in 2016 are approximately in the middle of all the curves presented. And, although difficult to see due to the superposition of lines, the Canadian, Israeli and US DOE 2010 MEPS are all approximately the same.

In the following figure, a more detailed comparison of 100 kVA three-phase dry-type transformers is presented. This graph shows the requirements associated with this particular kVA rating for each of the economies analysed. In this graph, as with the earlier one, all the efficiency requirements have been normalised to be comparable – 50% loading, 50Hz operation, using the IEC definition of kVA rating and efficiency. Note that the red bar farthest to the right is the "MaxTech" design for this rating published by the US DOE. This is not a regulatory requirement but rather illustrates the technical limit for energy-efficiency of a 100 kVA dry-type distribution transformer at 50Hz and 50% loading.

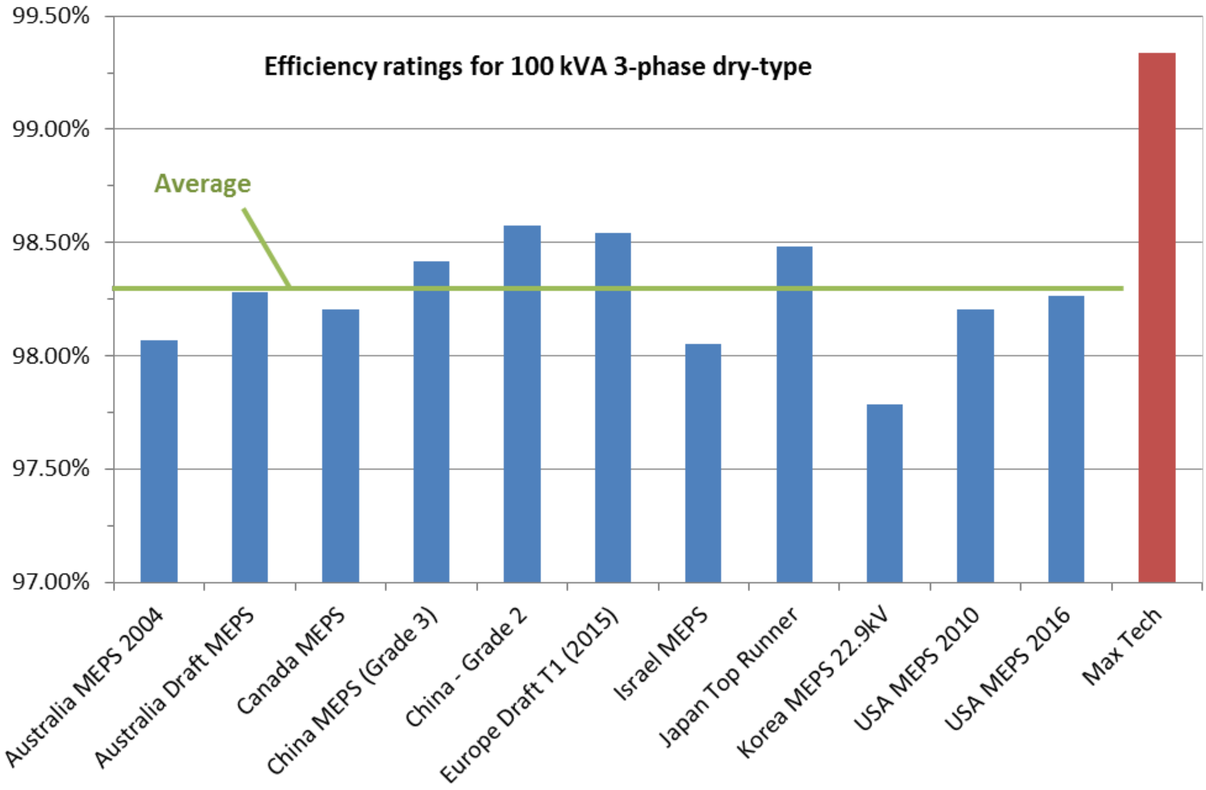

Figure 4-8. Efficiency at 50% Load for 100 kVA Three-Phase Dry-Type Transformers

In this figure, a green line has been drawn at 98.26% which represents the simple average of all the blue bars for this 100 kVA transformer. The range of values is from 97.79% for Korea to 98.58% for the draft European Commission's Tier 1 regulation taking effect in 2015. This range represents a difference of 0.79% in efficiency from the lowest to the highest required performance.

Looking at a larger kVA rating, there is less variability between the lowest and the highest values. The following figure presents the range of efficiency requirements for a 1000 kVA three-phase dry-type transformer, normalised for the comparison to 50Hz, 50% loading and the IEC definition of kVA rating and efficiency.

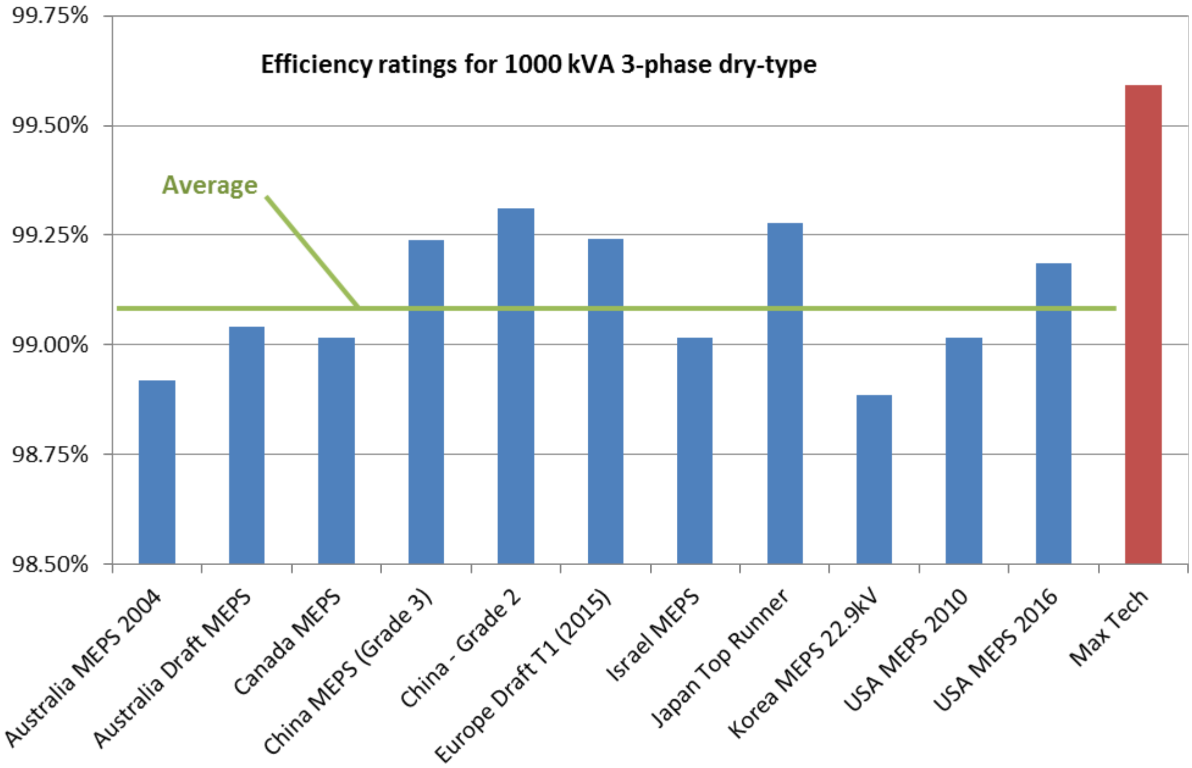

Figure 4-9. Efficiency at 50% Load for 1000 kVA Three-Phase Dry-Type Transformers

In this figure, a green line has been drawn at 99.10% which represents the simple average of all the blue bars for this 1000 kVA transformer. The range of values is from 98.89% for Korea to 99.31% for China – Grade 2, Cold-Rolled Grain Oriented (CRGO) steel. This range of efficiency values is roughly half the range of efficiencies at 100 kVA, spanning just 0.43% at 1000 kVA rating.

As is visible in Figure 4-7 and the above two histograms, the differences in efficiency level requirements between the various programmes gets smaller at the larger kVA ratings. The differences in the smaller kVA ratings are, for example, approximately 0.7% at 50 kVA and narrowing to about 0.4% at 2500 kVA.

The following figure presents the *high efficiency* curves for the various economies, normalised for 50% loading, 50Hz, IEC definition of kVA and efficiency. This figure includes the European Commission's draft Tier 2 level for 2021, the high efficiency performance level in Australia, Israel, and Korea. The US DOE 2016 regulation is included, as well as Japan's Top Runner scheme and China's Grade 1 Amorphous levels. Finally, the USDOE's MaxTech levels are also included for reference.

In this figure, the ambition associated with China's Grade 1 – amorphous core transformers is the most ambitious, followed by Korea's high efficiency performance level. The Japanese Top-Runner scheme next, and is closely aligned with Korea between 200 and 1000 kVA. In 2011, Australia proposed a new high-efficiency performance level, which is shown as an orange line in the following figure. The proposed HEPL for Australia is broadly in line with the draft European Commission's regulation proposed to take effect in 2021 (Tier 2).

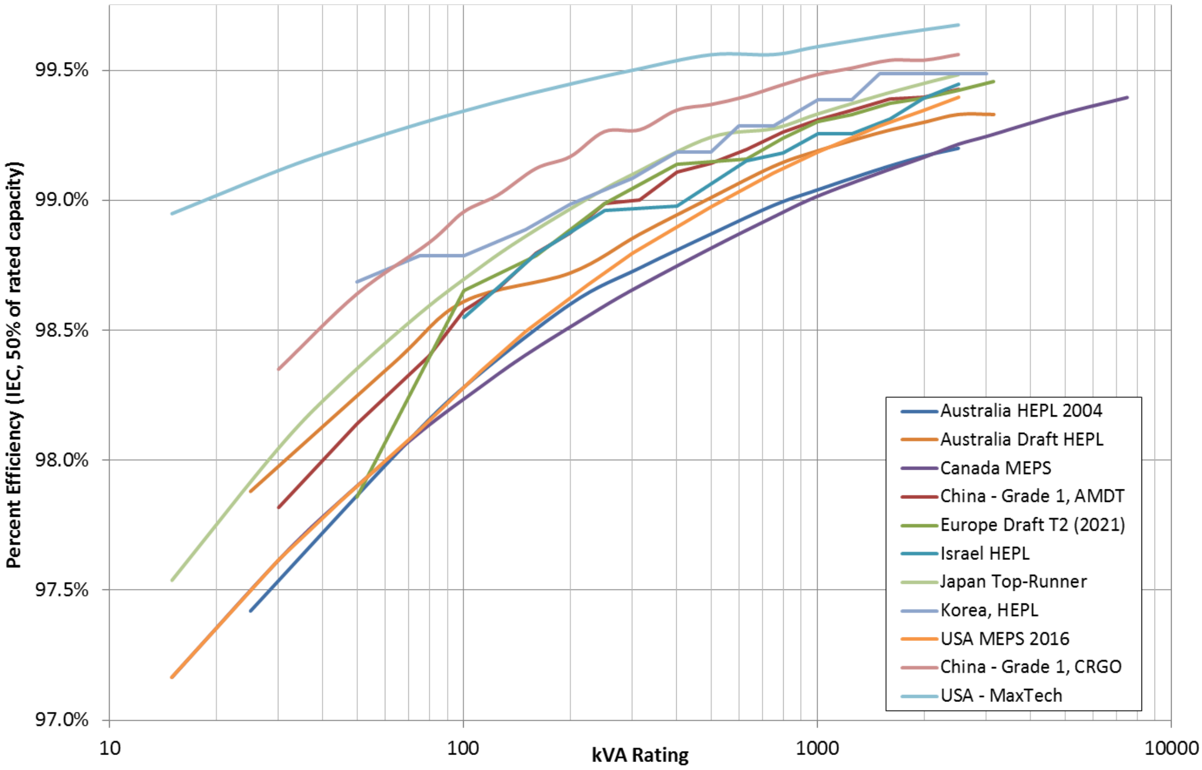

Figure 4-10. High Efficiency Programmes for Three-Phase Dry-Type Transformers

The following table presents a comparison between the normalised[11] percentage efficiency levels for the different kVA ratings across the dry-type transformer programmes. As is clearly illustrated by this table, there are traditions and different practices around the preferred kVA ratings in different parts of the world, therefore the tables of maximum losses and efficiency presented in the regulations do not all correspond to the same set of kVA ratings. However, efficiency values transformers can only be compared for the same kVA rating because efficiency scales with size. Also, although there are gaps in the table, this does not necessarily mean that those ratings would not be regulated in that market. Instead, it simply means the kVA rating is not one of the preferred ratings in that country / economy. The efficiency values presented in the table below are based on the IEC definition of efficiency at 50% loading and adjusted for 50Hz operation.

[11] The values shown in this table may be adjusted from their original values in order to ensure their comparability with the other countries / economies. The efficiency values shown here are representative of distribution transformers operating at 50% loading, 50Hz frequency and the IEC definition of kVA rating and efficiency.

Table 4-5. Comparison of MEPS Requirements for Three-Phase Dry-Type Transformers

Three Phase	Australia MEPS 2004	Australia Draft MEPS	Canada MEPS	China MEPS (Grade 3)	China Grade 2	Europe Tier 1 2015 (draft)	Israel MEPS	Japan Top-Runner 50Hz	Korea MEPS	Korea HEPL	USA MEPS 2010	USA MEPS 2016
15			97.17					96.97			97.17	97.17
25	97.17	97.42										
30			97.62	97.55	97.82			97.64			97.62	97.62
45			97.85					97.97			97.85	97.85
50				97.92	98.14	97.70			97.59	98.69		
63	97.78	98.01										
75			98.11					98.32	97.69	98.79	98.11	98.12
80				98.21	98.40							
100	98.07	98.28		98.42	98.58	98.54	98.05	98.48	97.79	98.79	98.20	98.27
113			98.29					98.55			98.29	98.35
125				98.51	98.66							
150			98.41					98.70	97.99	98.89	98.41	98.50
160				98.66	98.80	98.69	98.34					
200	98.42	98.60		98.75	98.87				98.19	98.99		
225			98.56					98.88			98.56	98.68
250				98.87	98.99	98.90	98.52					
300			98.66					98.99	98.39	99.09	98.66	98.80
315	98.59	98.74		98.89	99.00							
400				99.01	99.11	99.06	98.71		98.49	99.19		
500	98.74	98.87	98.82	99.05	99.14			99.16	98.69	99.19	98.82	98.98
600									98.69	99.29		
630				99.11	99.19	99.09	98.85					
750	98.85	98.98	98.94					99.22	98.79	99.29	98.94	99.11
800				99.19	99.26	99.18	98.95					
1000	98.92	99.04	99.02	99.24	99.31	99.24	99.02	99.28	98.89	99.39	99.02	99.19
1250				99.28	99.35	99.27	99.07		98.89	99.39		
1500	99.01	99.12	99.11					99.35	98.99	99.49	99.11	99.29
1600				99.33	99.39	99.32	99.13					
2000	99.06	99.17	99.17	99.33	99.39	99.34	99.18	99.40	99.09	99.49	99.17	99.35
2500	99.09	99.20	99.22	99.37	99.43	99.37	99.20	99.44	99.19	99.49	99.22	99.40
3000			99.25						99.19	99.49		
3150		99.20				99.41						
3750			99.29									
5000			99.34									
7500			99.40									

From this table some of the national similarities are evident, for example Canada and the US MEPS 2010 are aligned, and European Commission's Draft Tier 1 is approximately equivalent to the Chinese Grade 2 level. The Korean MEPS are the lowest in the table, however the Korean high-efficiency levels are among the highest. Korea's high-efficiency levels and the draft new Japanese Top-Runner programme have the highest levels for three-phase dry-type distribution transformers.

4.2.2 Comparison of Dry-Type Single-Phase Distribution Transformers

The figure below offers a comparison of the energy-efficiency programmes reviewed for single-phase medium-voltage dry-type distribution transformers. These data have been normalised to show 50% loading, 50Hz operation and using the IEC definition of kVA ratings and efficiency. Due to the impact of insulation on the performance of a dry-type transformer, when preparing this comparison, transformers with similar primary voltages and insulation ratings were included to the greatest extent possible. The only countries that have single-phase dry-type programmes from those profiled in this study are Australia, Canada, Japan, Korea and the USA. The figure below therefore presents all the data from the various efficiency-programmes in these five countries. Please note that the Canadian and US MEPS curves are exactly the same (super-imposed in the graph).

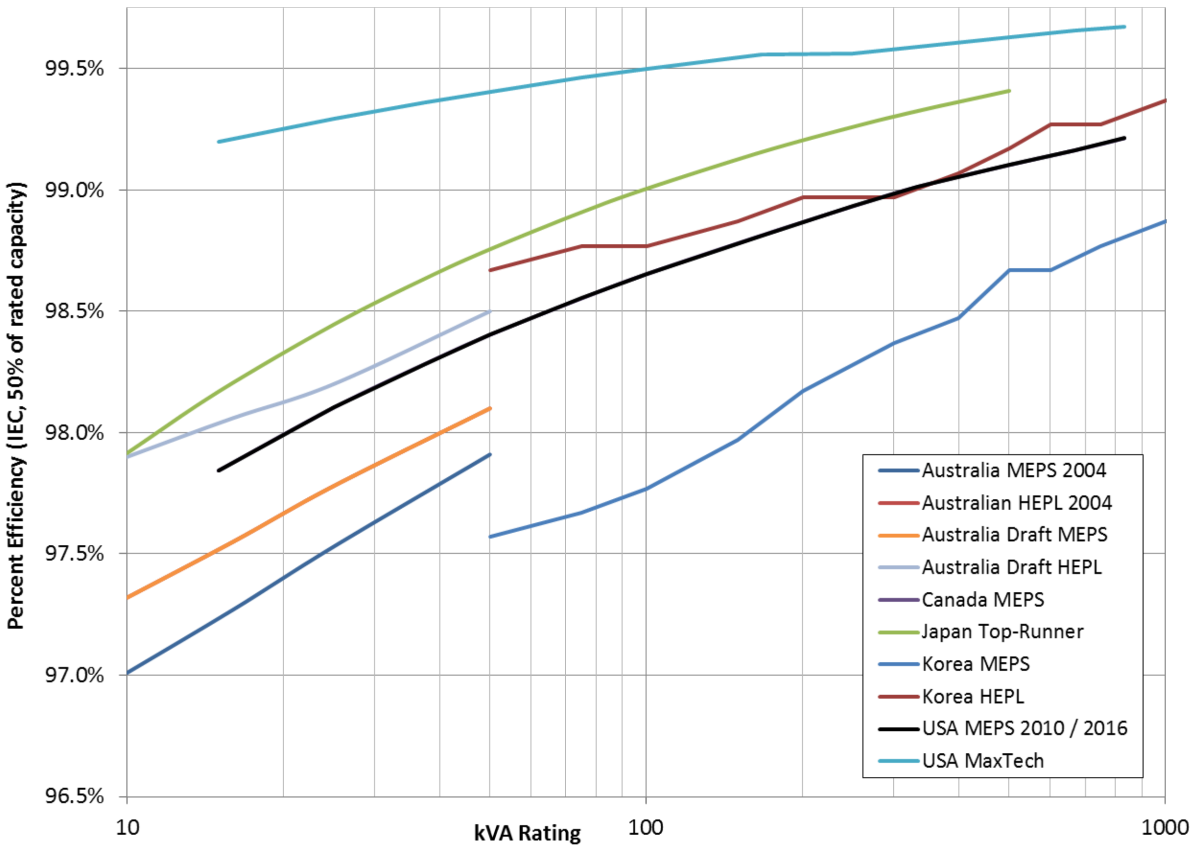

Figure 4-11. Efficiency Programmes at 50% Load for Single-Phase Dry-Type Transformers

These efficiency curves are for single-phase dry-type medium-voltage distribution transformers with a primary voltage around 24kV. There is some more variation in the requirements, with efficiency values for the MEPS programmes ranging from 1% to 1.5% for the different kVA ratings. Korea's MEPS levels are the lowest of those analysed, however their high efficiency levels are above or in-line with the US DOE MEPS levels for 2010 and 2016 (there was no change to these requirements in the new US 2016 MEPS level). The MaxTech level published by DOE is also shown on this graph as a blue line at the very top.

This level represents the maximum technologically feasible efficiency level for these kVA ratings, not taking into account the transformer cost or size.

In the following figure, a more detailed analysis of 50 kVA single-phase dry-type transformers is presented. This graph shows the requirements associated with this particular kVA rating for each of the economies analysed. In this graph, as with the earlier one, all the efficiency requirements have been normalised to be comparable – 50% loading, 50Hz operation, using the IEC definition of kVA rating and efficiency.

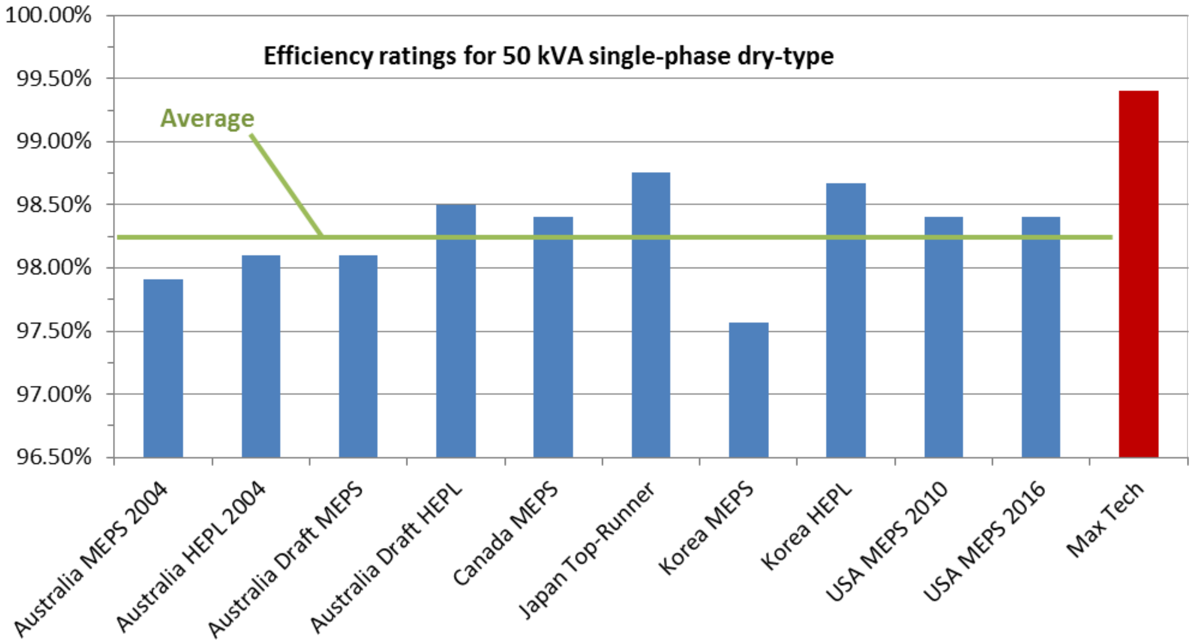

Figure 4-12. Efficiency at 50% Load for 50 kVA Single-Phase Dry-Type Transformers

In this figure, a green line has been drawn at 98.28% which represents the simple average of all the blue bars for this 50 kVA transformer. The range of values is from 97.57% for Korea to 98.76% for the draft European Commission's Draft Tier 1 regulation proposed to take effect in 2015. This range represents a difference of 1.19% in efficiency from the lowest to the highest required performance.

The following table presents a comparison between the normalised[12] percentage efficiency levels for the different kVA ratings across the single-phase dry-type transformer programmes. As is clearly illustrated by this table, there are traditions and different practices around the preferred kVA ratings in different parts of the world, therefore the tables of maximum losses and efficiency presented in the regulations do not all correspond to the same set of kVA ratings. However, efficiency values transformers can only be

[12] The values shown in this table may be adjusted from their original values in order to ensure their comparability with the other countries / economies. The efficiency values shown here are representative of distribution transformers operating at 50% loading, 50Hz frequency and the IEC definition of kVA rating and efficiency.

compared for the same kVA rating because efficiency scales with size. Also, although there are gaps in the table, this does not necessarily mean that those ratings would not be regulated in that market. Instead, it simply means the kVA rating is not one of the preferred ratings in that country / economy. The efficiency values presented in the table below are based on the IEC definition of efficiency at 50% loading and adjusted for 50Hz operation.

Table 4-6. Comparison of MEPS Requirements for Single-Phase Dry-Type Transformers

Single Phase	Australia MEPS 2004	Australia HEPL 2004	Australia Draft MEPS	Australia Draft HEPL	Canada MEPS	Japan Top-Runner	Korea MEPS	Korea HEPL	USA MEPS 2010	USA MEPS 2016	USA Max Tech
10	97.01	97.32	97.32	97.90		97.92					
15					97.84	98.17			97.84	97.84	99.20
16	97.27	97.55	97.55	98.06							
25	97.53	97.78	97.78	98.20	98.10	98.45			98.10	98.10	99.29
37.5					98.28	98.64			98.28	98.28	99.36
50	97.91	98.10	98.10	98.50	98.40	98.76	97.57	98.67	98.40	98.40	99.41
75					98.55	98.91	97.67	98.77	98.55	98.55	99.46
100					98.65	99.00	97.77	98.77	98.65	98.65	99.50
150							97.97	98.87			
167					98.81	99.16			98.81	98.81	99.56
200							98.17	98.97			
250					98.93	99.26			98.93	98.93	99.56
300							98.37	98.97			
333					99.01	99.33			99.01	99.01	99.59
400							98.47	99.07			
500					99.10	99.41	98.67	99.17	99.10	99.10	99.63
600							98.67	99.27			
667					99.16				99.16	99.16	99.66
750							98.77	99.27			
833					99.21				99.21	99.21	99.67
1000							98.87	99.37			
1250							98.87	99.37			
1500							98.97	99.47			
2000							99.07	99.47			
2500							99.17	99.47			
3000							99.17	99.47			

From this table some of the national similarities are evident, for example Canada and the US MEPS 2010 and 2016 are the same. The Korean MEPS are the lowest in the table, however the Korean high-efficiency levels are among the higher levels found in the analysis. The draft new Japanese Top-Runner programme has the highest levels of ambition for single-phase dry-type distribution transformers.

Annex A. Efficiency Conversion Calculations

This Annex provides an explanation of the steps followed in normalising the national energy performance metrics for distribution transformers into a set of measured percentage efficiency at 50% loading on a 50Hz system using the IEC definition of efficiency. There were three main adjustments that were made to the energy performance metrics, described in the text that follows. For the US liquid-filled transformers, a correction to the reference temperature for the windings was also made, which is discussed in section A.4.

A.1 KVA Rating and Percentage Efficiency

As discussed in Chapter 4, there are different ways of rating the power handling capacity of a distribution transformer. In countries applying IEEE standards (generally North America), the kVA power rating of the transformer is defined as the rated capacity at the output of the device – that is, it represents the available capacity at the loading point. However, in other parts of the world employing IEC standards, the kVA rating represents the rated input to the transformer – how much power is being supplied to a particular unit. When rated as the output (i.e., the IEEE method), the power rating *excludes* the core and coil losses when the transformer is operating, whereas for the input capacity (i.e., the IEC method), the power rating *includes* those losses.

For this analysis, most of the countries adopt the IEC methodology for rating transformers, therefore, those that are based on the IEEE approach will be adjusted to kVA ratings that reflect their IEC equivalent. So, for example, a transformer rated 50 kVA by the IEEE would have a slightly higher kVA rating (i.e., approximately 51.5 kVA) under the IEC rating definition. In this way, the plots generated for comparison will all reflect the IEC approach.

The definition of efficiency is also linked to this difference between IEC and IEEE. Efficiency is, broadly speaking, a measurement of power out divided by power in. However, the way that efficiency is calculated differs slightly, as shown below. In IEC, the equation is based on power input whereas for IEEE, it is based on the output power, as shown in the following equations:

$$IEC\ Definition\ Efficiency = \frac{(Power\ Input - Losses)}{(Power\ Input)}$$

$$IEEE\ Definition\ Efficiency = \frac{Power\ Output}{(Power\ Output + Losses)}$$

Where:

Power Output and *Power Input* are measured in Watts and are calculated by multiplying the kVA rating of the transformer (IEEE or IEC method) by the per unit load (e.g., 50% of rated nameplate);

Losses represents the sum of core and coil losses at the per unit load point; where *core loss* is the power loss in the core at rated voltage and *coil losses* are the square of the per unit load times the coil losses at rated capacity.

Per unit load is the decimal equivalent of the percentage of rated load supplied by the transformer, such as 0.35 for 35% or 0.50 for 50% of rated capacity.

The percentage efficiency reported in the comparisons in this report will be the IEC method, as that is more universal in the global distribution transformer market.

A.2 Frequency Conversion

The performance of distribution transformers will not be the same and is not comparable when operated on electricity systems with different fundamental frequencies. Therefore, an adjustment from one operating frequency to another must be made when comparing the performance of a transformer.

Transformer efficiencies are slightly lower for 50Hz transformers because at lower frequencies, the iron magnetic core “saturates” more easily, so you need more core material and copper, which makes the transformer slightly larger and more expensive and increases losses. However, that said, at higher frequencies, the magnetic core will have higher losses due to the eddy currents induced in the core steel laminations. This can be reduced by making the core into thin plates, but thinner laminations are more expensive on a material and assembly basis.

The team has looked at the conversion in efficiency between 50Hz and 60Hz transformers in two ways. The first comparison is based on the relationship between the losses required in Japan’s Top Runner programme, as Japan has both 50Hz and 60Hz sections of its grid working separately. The second comparison is based on an empirical approach, taking into account material performance under the different electrical frequencies.

This is due to the fact that a straight-forward conversion is not possible since a transformer company would either design a distribution transformer to operate at 60Hz or 50Hz, but not both. Therefore, to convert the requirements from one frequency to the other without taking into account re-design would not be appropriate.

Approach #1: Comparison of Japanese Top Runner Requirements
Japan operates its national electrical networks based on both 50Hz and 60Hz. The Top Runner programme was designed to establish an equivalent performance requirement nationally, including both the 50Hz and 60Hz systems. By comparing the equations that were developed and taking the average of the difference between them, a multiplier can be developed that shows the performance difference between transformers designed for 50Hz and those designed for 60Hz in the same national market. The difference in performance is small, however it does find that the 50Hz units are slightly less efficient than the 60Hz units.

The figure below illustrates the curves associated with the requirements of oil-filled distribution transformers.

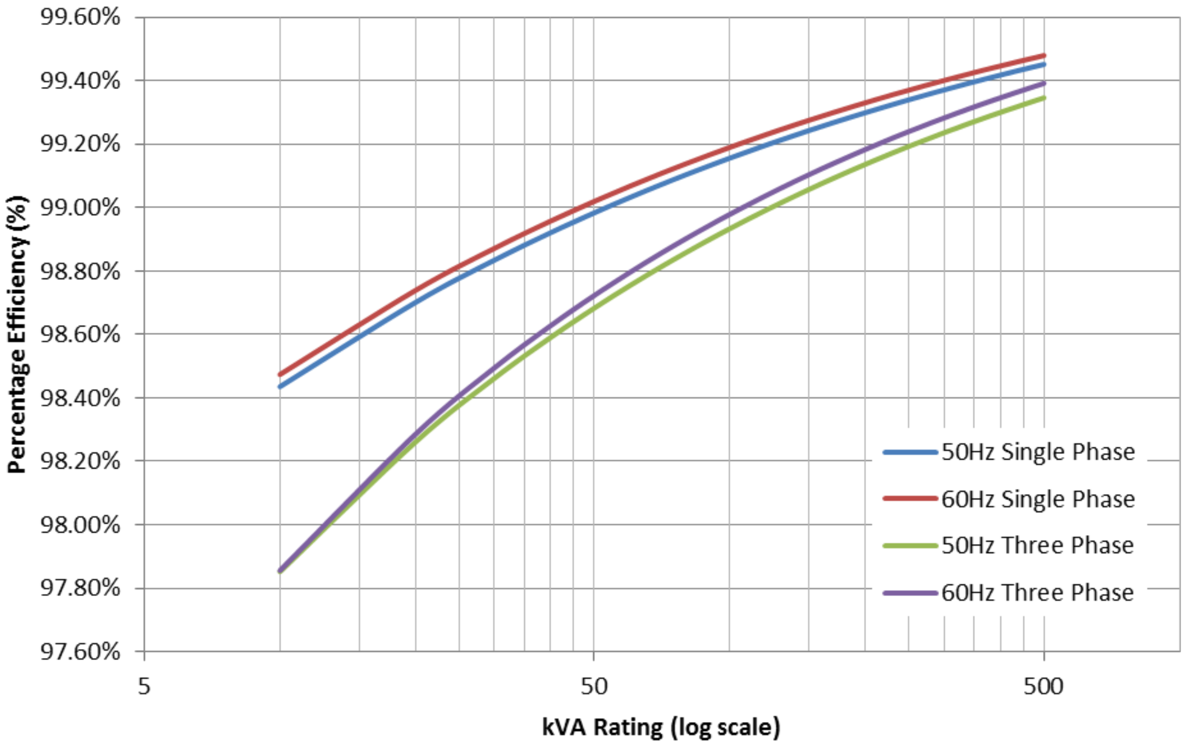

Figure A-1. Plot of Japanese Top Runner Requirements for Liquid-Filled Transformers

The Top Runner programme has similar requirements for dry-type transformers (cast coil), and now there are two new proposed updates – one with more ambition than the other. Overall, there are six different product groups from three different levels of ambition (one is the existing Top Runner programme and the other two are the proposed updates under consideration). The table below shows the ratio of 50Hz transformers of the same kVA rating to 60Hz transformers, effectively creating the 'normalisation' factor for converting from 60Hz efficiency requirements to their equivalent in a 50Hz market for comparison.

Change % efficiency	Phase	kVA Rating	Top Runner (50/60Hz)	Proposal 1 (50/60Hz)	Proposal 2 (50/60Hz)
Oil-filled	Single	All	0.99960	0.99969	0.99969
	Three	<= 500 KVA	0.99939	0.99955	0.99959
	Three	> 500 KVA	0.99971	0.99957	0.99955
Dry-Type	Single	All	1.00002	0.99981	0.99983
	Three	<= 500 KVA	1.00032	1.00008	1.00005
	Three	> 500 KVA	1.00005	0.99986	0.99985

The conversion factor for oil-filled transformers is 0.99959 and for dry-type transformers is 0.99999. These values are multiplied by the 60Hz efficiency values at 50% loading to convert them to the equivalent performance at 50Hz.

Approach #2: Comparison Based on Material Performance at 50 and 60 Hz
In this approach, a comparison is derived based around the difference in core steel performance at 50Hz and 60Hz. The following illustrates some of the complexities involved in achieving a precise comparison of power efficiencies. The total core loss (C) of a transformer is composed of hysteresis (H) and eddy current (E) losses as follows:

$C = H + E = (k_1 B_m^{1.8} f) + (k_2 B_m^2 f^2)$ Watts Equation A.1

Where B_m is peak magnetic flux density in the core (Tesla)
f is the power frequency (Hz)
k_1 and k_2 are constants of the core material and configuration

Using the transformer design equation, the interdependencies of the various design parameters can be seen:

$V = 4.44 \times B_m ANf$, Equation A.2

Where V = winding voltage
A = core cross-section area
N = number of winding turns
B_m = peak magnetic flux density in the core (Tesla)

Depending on the kVA rating and the operating frequency, these values may all differ in any transformer. However, for the same core material in a transformer, it can be assumed that the peak flux density B_m will be chosen by the designer to ensure maximum possible magnetic field in the core without taking the transformer to saturation. Given that assumption, then we have the proportionality:

$V \alpha ANf$

This means that for the same voltage and power rating of a transformer design, and with a change of frequency from 50 Hz to 60 Hz, the required AN will have to decrease by a factor of 60/50, or 1.2. This will mean either a lower number of winding turns (N) or smaller core cross-sectional area (A), or a combination of both. These changes will have some impact on core loss and hence on transformer efficiency, particularly if the area A decreases with the same flux density in use. And while the total core loss (C) given above will increase at the higher frequency, it will be partly compensated for by having a smaller core cross-sectional area required at 60 Hz.

However, if the transformer design has the same AN and power rating, then the voltage will increase with the frequency (f) as below:

$V \alpha f$

Again the core loss C will increase with frequency according to the core loss equation, with hysteresis losses scaling with frequency and eddy currents scaling with the frequency squared. However, in this case, the higher voltage for the same rating will mean a lower current in the winding and the copper loss (i.e., I^2R) will then decrease and compensate to some extent for the increase in core loss.

Given the above considerations it can be seen that the comparison of 50 Hz and 60 Hz transformer losses for the same notional rating of transformer is very complex and, given the variation in design between 50 and 60 Hz, extremely difficult to do accurately. However a very simplistic approach can be used to give some general estimate of the relative losses in the core at the different frequencies by simply using the equation 1 above and making some simplifying assumptions, including:

- Identical kVA rating;
- Identical voltage;
- Identical number of winding turns (N) or smaller core cross-sectional area (A);
- Assume that the copper loss is the same at 50 and 60 Hz (not totally valid as the stray loss part of the copper loss will increase at the higher frequency);
- Assume that peak efficiency is at 50% loading, where the core loss C and the copper loss (W) are equal (50% loading is used as the MEPS defining point in some countries); and
- Assume that total core loss is equally divided between hysteresis and eddy current losses.

It is then possible to perform very simple calculations with these assumptions, using for example, transformer efficiency at maximum efficiency loading (taken to be 50%). From this efficiency and loading and the assumptions, the hysteresis losses (H) and eddy current losses (E) in the core can be calculated, and equation A.1 used to determine how the calculated loss components will vary when frequency is changed. This can then be used with the (assumed unchanged) copper loss to determine the efficiency at the new operating frequency.

The following is a worked example of this conversion. Using the case of a 500 kVA three-phase transformer with efficiency of 99.29% at 50% load and unity power factor, we get the following:

kVA rating = 500 kVA which converts to 250 kW at 50% loading
Efficiency = 0.9929 = 250 kW / [250 kW + L], where L is the total loss
Solving for L, we find L = 1.788 kW and, with equal winding and core losses,
Calculate the core loss C = 1.788/2 = 0.894kW,
Assuming equal H and E losses, we have, H = E = 0.894/2 = 0.447kW at 60 Hz

Then, scaling down H and E at the lower frequency of 50 Hz
$H_{50} = 0.447 \times (50/60) = 0.373$ kW
$E_{50} = 0.447 \times (50/60)^2 = 0.310$ kW

Thus the total core loss at 50Hz would be C_{50} = 0.373 + 0.310 = 0.683 kW
And therefore, L_{50} = 0.894 + 0.683 = 1.577 kW
And the efficiency at 50 Hz = 250 kW / (250 kW +1.577) = 99.37%
Note that the efficiency at 60 Hz was 99.29%

So the ratio of 50/60Hz for efficiency is 1.00084, meaning the reported efficiency can be converted from 50 to 60 Hz by dividing by this ratio of efficiency values.

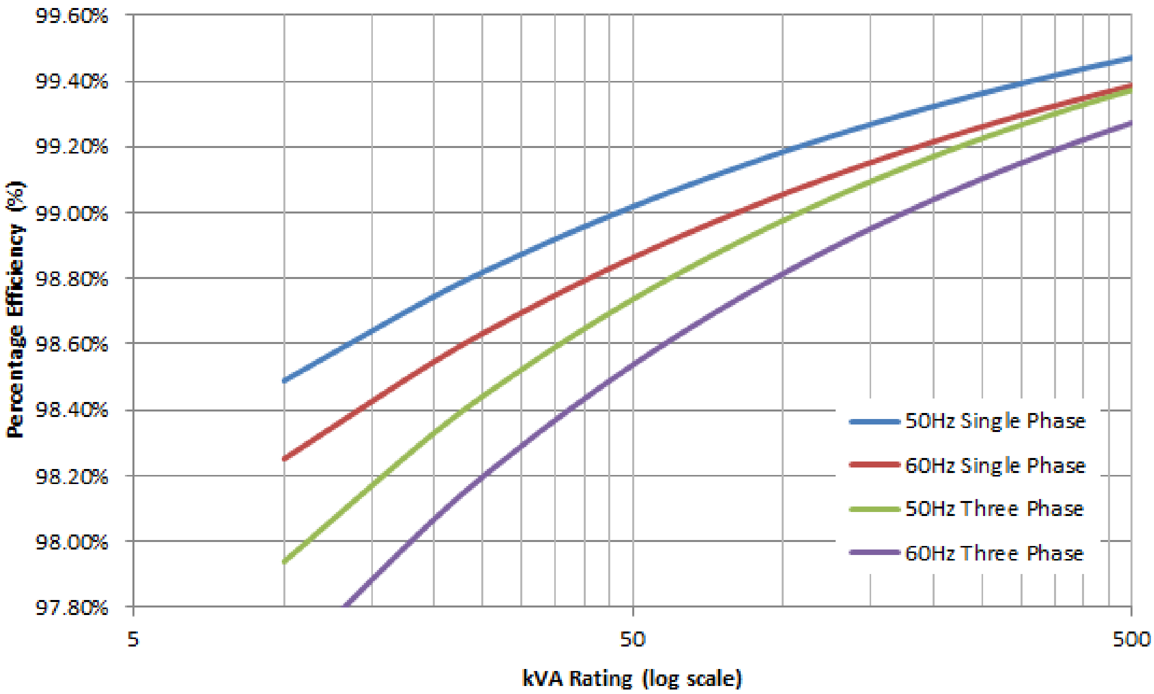

Figure A-2. Frequency Conversion Plot of Calculation for Liquid-Filled Transformers

Comparing this graph to the earlier plot of the Japanese Top Runner programme, it finds that the results are inverted. In this approach, the 50Hz transformers are found to be inherently more efficient than the 60Hz because of the impacts on the core loss components – the hysteresis and eddy current losses. However, in the Top Runner programme, the government has set targets that expect a slightly more efficient performance for most of the 60Hz designs (there are some cast-coil 60Hz designs that are less efficient than the 50Hz designs in Japan’s Top Runner).

The efficiency ratings of the transformers are found to be slightly higher or slightly lower than the other frequency depending on which approach is taken. In the mathematical approach, several underlying assumptions had to be made about the design in order for the conversion calculation to work – however, if a manufacturer were creating a design for one frequency or the other, they would make optimising adjustments to these properties, creating the best performance for a given frequency. In other words, a design created to operate at 60Hz may be able to be operated at 50Hz, but in reality, a design engineer would make changes to the dimensions and other properties when creating a 50Hz design, so these assumptions made in the calculation method to convert losses between the two different frequencies may not be representative of practice. Instead, the engineers would make changes in the dimensions and other aspects of the transformer design to improve the overall performance of the transformer.

For this reason, the conversion that will be applied for this study will be the Japanese Top Runner conversion, which represents a small adjustment to the losses, but which does reflect otherwise equivalent expected performance values at both frequencies in the same country, under the same programme, with the same objective.

A.3 Maximum Losses to Percentage Efficiency

Many countries regulate transformers by establishing maximum values of loss (in Watts) of core losses and of coil losses at full load (i.e., rated capacity). Other countries regulate transformers through a percentage efficiency requirement at a specified loading point. Having a percentage efficiency rather than maximum losses provides more flexibility in the design process, enabling manufacturers to provide a greater variety of designs and be more responsive to the needs of utilities.

Efficiency is a measure of the power consumed by a transformer, and it is determined in part by the sum of the core losses and coil losses experienced by the transformer. The efficiency of a transformer varies across the range of loading points that a transformer may experience in its lifetime. The measured efficiency of a transformer operating at 80% of rated load (where coil losses are likely to dominate) will probably be different to the efficiency of a transformer operating at 20% of rated load (where core losses are likely to dominate). The figure below shows the efficiency curve relative to the watts of core and coil loss. This figure shows that the efficiency curve varies over the loading points, with its peak occurring where the core losses are equal to the coil losses.

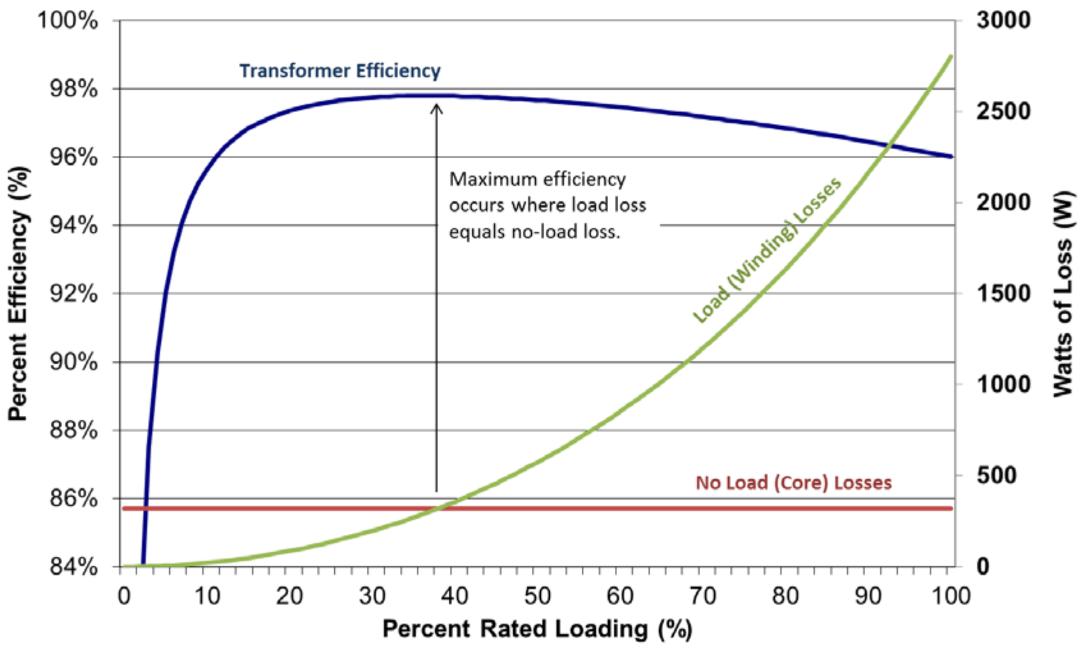

Figure A-3. Illustration of Relationship Between Losses and Efficiency

Maximum losses can readily be converted into a percentage efficiency at a specified loading point (50% for this report) by applying the IEC formula for percentage efficiency. The equation that can be used is given below:

$$IEC\ Definition\ Efficiency = \frac{(Power\ Input - Losses)}{(Power\ Input)}$$

Expands to be:

$$IEC\ Definition\ Efficiency = \frac{(Load_{PU} \times S_{kVA}) - NL - LL)}{(Load_{PU} \times S_{kVA})}$$

Where:

$Load_{PU}$ – represents the per unit loading experienced by the transformer (usually as a percentage, such as 40%, 50% or 80% load. For normalisation purposes in this report, 50% is used.

S_{kVA} – represents the kVA rating of the transformer, such as 50kVA, 100KVA or 2500kVA.

NL – represents the kilowatts of loss in the core of the transformer (to be consistent with the units in the power input calculation).

LL – represents the kilowatts of loss in the winding (i.e., coil) of the transformer.

This equation and approach is used in countries where the maximum losses are given, and these are converted to an IEC-based percentage efficiency at 50% of rated load.

A.4 Temperature Correction for US Liquid-Filled Transformers

As discussed in the Part 2 report, load losses are incurred in the windings of distribution transformers. The load losses are a directly proportional to the resistance of the windings multiplied by the square of the current – in other words, = R x i^2 .

However, resistance of the winding material is not constant – it varies with the temperature of the winding – increasing the resistance as the temperature increases. Therefore, the reference temperature at which the coil losses are reported are important, and should be equal (or very close) to ensure comparability of the results. In our review of the test methods used around the world, it was found that there is a 20°C difference in the reference temperature of the windings for the liquid-filled distribution transformer test methods between the United States and the IEC test method. The US DOE adopted its test procedure final rule in 2006, and uses a reference temperature in the windings of 55°C. The IEC, on the other hand, uses a reference temperature of 75°C. Since most of the countries in the world reference the IEC test method and reference temperatures, we applied a temperature correction to the US DOE requirements to make them comparable to the other economies.

By increasing the reference temperature for the measurement of load losses from 55°C to 75°C, this has the effect of slightly increasing the losses associated with the US levels, which causes the percentage efficiency levels to be reduced slightly. The equation below shows the calculation that was applied to the US DOE liquid-filled transformer levels:

Temperature Correction Factor from 55°C to 75°C:

$$= \frac{235 + T}{235 + t}$$

Where:

T is temperature at which the losses are to be guaranteed; and
t is temperature at which the losses are measured.

So plugging in the values for the two temperatures to this equation, (235+75) / (235+55) = 1.06896551724138. This temperature correction factor was then multiplied by the watts of load loss for the US DOE regulations, to adjust the load losses from a reference temperature of 55°C to 75°C.

Annex B. Efficiency Conversion Calculations Applied to Countries

This Annex provides an explanation of the calculations applied (if any) following the normalisation factors associated with each of the countries. There were three main adjustments that were made to the energy performance metrics, described in the text that follows.

B.1 Australia and New Zealand

The performance metric for Australia and New Zealand are presented as percentage efficiency at 50% loading, and they are designed to operate at 50Hz. Therefore, there were no normalisation adjustments made to the efficiency requirements published by Australia and New Zealand.

Table B.1 Summary of Conversions for Australia and New Zealand

Normalisation Factors	Actions Taken
kVA Rating	None – already uses IEC definition of kVA
System Frequency	None – already 50Hz system.
Losses to per cent Efficiency	None – already at 50% load

B.2 Brazil

The Brazilian draft efficiency requirements for dry-type transformers follow the IEC methodology, and therefore are based on the IEC definition of a kVA rating. The requirements are presented as maximum losses in the core and coil at 100% loading. These transformers are designed to operate on a 60Hz system.

Table B.2 Summary of Conversions for Brazil

Normalisation Factors	Actions Taken
kVA Rating	None – already uses IEC definition of kVA
System Frequency	Adjusted from 60Hz to 50Hz.
Losses to per cent Efficiency	Adjusted from maximum losses to 50% load.

B.3 Canada

The Canadian voluntary standard for liquid-filled distribution transformers and the mandatory standard for dry-type distribution transformers are both a percentage efficiency at 50% of rated load on a 60Hz system. The kVA rating being used in Canada is based on the output of the transformer (i.e., the IEEE method), so the kVA ratings must be increased slightly to reflect the IEC definition.

Table B.3 Summary of Conversions for Canada

Normalisation Factors	Actions Taken
kVA Rating	Adjusted from IEEE to IEC.
System Frequency	Adjusted from 60Hz to 50Hz.
Losses to per cent Efficiency	Already at 50% load.

B.4 China

The Chinese mandatory requirements on distribution transformers apply to both liquid-filled and dry-type, and are based on the IEC standards. The requirements are published in tables that prescribe the maximum losses of core and coil losses (at 100% of rated load). China's electrical grid operates at 50Hz. Thus, the only conversion necessary with the Chinese regulations is to take the maximum losses and convert them into percentage efficiency at 50% of rated capacity.

Table B.4 Summary of Conversions for China

Normalisation Factors	Actions Taken
kVA Rating	Already uses IEC method.
System Frequency	Operates at 50Hz.
Losses to per cent Efficiency	Convert the maximum losses to per cent efficiency.

B.5 European Union

The European Union has voluntary requirements that apply to both liquid-filled and dry-type, and are based on the IEC standards. The requirements are published in a series of tables that set-out the maximum losses of core and coil losses (at 100% of rated load). European Union's electrical grid operates at 50Hz, and so the only conversion necessary with the European Commission's proposed regulations is to take the maximum losses and convert them into a percentage efficiency at 50% of rated capacity.

Table B.5 Summary of Conversions for European Commission's Proposal

Normalisation Factors	Actions Taken
kVA Rating	Already uses IEC method.
System Frequency	Operates at 50Hz.
Losses to per cent Efficiency	Convert the maximum losses to per cent efficiency.

B.6 India

India has mandatory labelling scheme that applies to certain liquid-filled distribution transformers. The labelling scheme has a series of maximum losses at 50% and 100% of rated load, and a corresponding number of stars that relate to those maximum losses. The kVA ratings are based on the IEC system and the electrical grid in India already operates at 50Hz. The only issue that remains for normalising these labelling levels for comparison is to convert the maximum losses at 50% of rated load into a percentage efficiency at 50%.

Table B.6 Summary of Conversions for India

Normalisation Factors	Actions Taken
kVA Rating	Already uses IEC method.
System Frequency	Operates at 50Hz.
Losses to per cent Efficiency	Convert the watts of maximum loss at 50% load into per cent efficiency.

B.7 Israel

Israel has mandatory efficiency requirements for distribution transformers covering both liquid-filled and dry-type units. The kVA ratings are based on the IEC system and the electrical grid in Israel operates at 50Hz, so no adjustments are required to these parameters. The only requirement that requires normalisation is to convert the maximum losses at 100% of rated load into a percentage efficiency at 50%.

Table B.7 Summary of Conversions for Israel

Normalisation Factors	Actions Taken
kVA Rating	Already uses IEC method.
System Frequency	Operates at 50Hz.
Losses to per cent Efficiency	Convert the watts of maximum losses at 100% load into per cent efficiency at 50%.

B.8 Japan

Japan runs the Top Runner scheme for distribution transformers covering both liquid-filled and dry-type units. Top Runner establishes equations that provide the maximum total losses for a transformer at 40% load (for ratings ≤500 kVA) or 50% load (for ratings >500 kVA). Japan's testing standards are based on the IEC system, therefore the kVA ratings will also be based on the power input rather than output. Part of the electrical grid in Japan operates at 50Hz, and the Top Runner scheme has requirements for those transformers, so no conversion of those parameters is required. The only issue is that for kVA ratings less than or equal to 500 kVA, the losses are set for 40% of rated nameplate load rather than 50%. So it was assumed that the maximum efficiency of these units (where core losses = coil losses) occurs at 40% loading, then the coil loss was adjusted for 50% loading, and the efficiency was recalculated for those same models at 50% loading. For kVA ratings of 501 kVA and larger, the maximum losses are based on a different equation which uses 50% of rated nameplate capacity as its basis for the calculation.

Table B.8 Summary of Conversions for Japan

Normalisation Factors	Actions Taken
kVA Rating	Already uses IEC method.
System Frequency	Selected a Top-Runner equation that provides maximum total losses on the 50Hz network.
Losses to per cent Efficiency	Has efficiency at 40% load for ≤500 kVA which was corrected to 50% loading by assuming core loss = coil loss at 40% load. Has 50% loading for >501 kVA.

B.9 Korea

Korea has mandatory efficiency requirements for distribution transformers covering both liquid-filled and dry-type units. Korea follows the IEC standards, and therefore the kVA ratings are based on the IEC system. The electrical grid in Korea operates at 60Hz, so a small adjustment must be made to all the efficiency values to convert them to 50Hz. The percentage efficiency values in Korea are already given at 50% of rated nameplate, so no adjustment is required.

Table B.9 Summary of Conversions for Korea

Normalisation Factors	Actions Taken
kVA Rating	Already uses IEC method.
System Frequency	Convert from 60Hz to 50Hz equivalent.
Losses to per cent Efficiency	Already presents efficiency based on 50% load.

B.10 Mexico

Mexico has a mandatory efficiency requirement for liquid-filled distribution transformers. Mexico follows the NEMA and IEEE approach, therefore the kVA ratings needs to be corrected to the IEC rating (slightly higher). The Mexican electricity grid operates at 60Hz, therefore all the efficiency values need to be converted to 50Hz. Finally, the efficiency level and the wattages presented are at 100% of rated nameplate capacity, higher than the 50%, so an adjustment is necessary.

Table B.10 Summary of Conversions for Mexico

Normalisation Factors	Actions Taken
kVA Rating	Must be converted to IEC definition.
System Frequency	Convert from 60Hz to 50Hz equivalent.
Losses to per cent Efficiency	Convert from 100% of rated capacity to 50% loading.

B.11 United States of America

The US has mandatory efficiency requirement on all types of distribution transformers – liquid filled, low-voltage dry-type and medium-voltage dry-type. The US programme covers transformers from 15 through 2500 kVA, with primary voltages less than 35kV. The US follows the NEMA and IEEE approach to defining kVA ratings, therefore the kVA ratings needs to be corrected to the IEC rating (slightly higher). The US electricity grid operates at 60Hz, therefore all the efficiency values need to be converted to 50Hz. The efficiency level and the wattages presented are already at 50% of rated nameplate capacity, obviating the need to make an adjustment based on the loading point. Finally, for the liquid-filled distribution transformers, the load losses were adjusted from 55°C to 75°C, to ensure a comparable reference temperature is used in the graphs (see section A.4 in this report).

Table B.11 Summary of Conversions for United States of America

Normalisation Factors	Actions Taken
kVA Rating	Must be converted to IEC definition.
System Frequency	Convert from 60Hz to 50Hz equivalent.
Losses to per cent Efficiency	No change – already 50% of rated load.
Temperature Correction	Liquid-filled load losses adjusted from 55°C to 75°C.

B.12 Vietnam

Vietnam has mandatory efficiency requirement on liquid filled distribution transformers. The Vietnamese programme covers transformers from 25 through 2500 kVA, with primary voltages less than 35kV. Vietnam follows the IEC testing standards, therefore the kVA ratings will be based on the input capacity. The national system frequency is 50Hz and the losses are presented at 50% of rated capacity. Therefore, no adjustment to the Vietnamese requirements is necessary.

Table B.12 Summary of Conversions for Vietnam

Normalisation Factors	Actions Taken
kVA Rating	Already uses the IEC definition.
System Frequency	Already based on 50Hz equivalent.
Losses to per cent Efficiency	Already based on 50% loading.