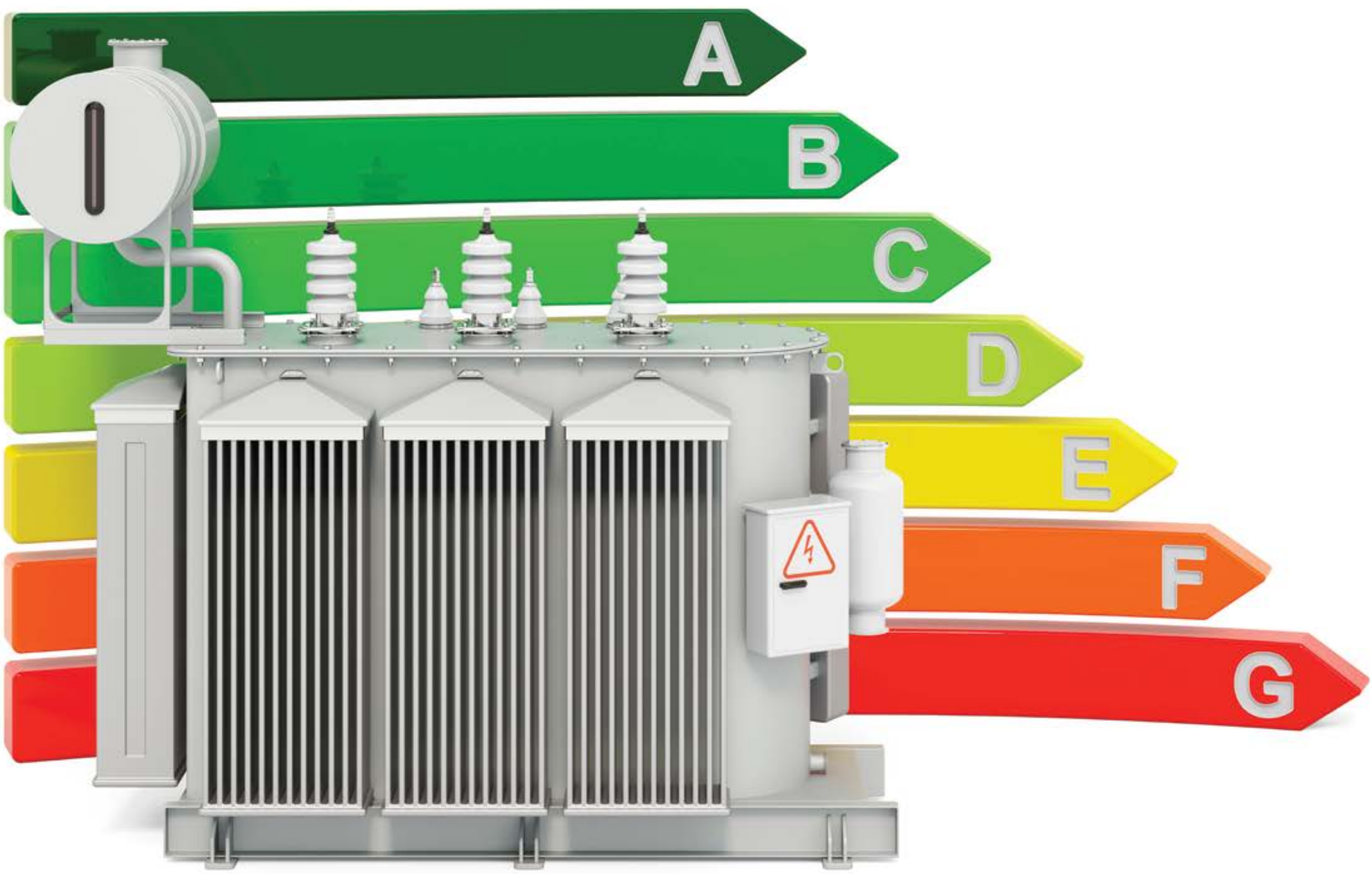

A review of distribution transformer energy efficiency metrics: in the Australian and New Zealand context

ABSTRACT

Distribution transformers play an important role in achieving the ambitious energy efficiency targets set by many countries in the world. Distribution transformers are of high value in terms of energy efficiency because of the number of installed units in each country. In this context, energy efficiency metrics have been introduced, such as efficiency at 50 % load, maximum no-load and load losses, maximum combined losses, etc. Typically, the selection of energy-efficient distribution transformer is a two-step process: a) transformers must comply with the minimum power efficiency levels (typically at 50 % load), b) selection of that transformer whose losses are economically optimal over the lifetime of the transformer.

In this article, a review of the present energy performance metrics, especially the efficiency at 50 % load is presented, paying particular attention to the Australian and New Zealand market. Alternative metrics such as no-load and load loss values and peak efficiency index are investigated.

KEYWORDS:

distribution transformers, MEPS, losses, peak efficiency index

Although distribution transformers are among the most efficient electrical devices, even slight improvements in their energy performances are highly valued

Introduction

There are two intertwined issues challenging the world today – how to meet the rising energy demand and limit its environmental impact. Governments across the world have engaged in developing regulations and policies to provide suitable policy recommendations to end-users. It has been reported in [1] that half of the world's electricity is consumed by just four products: electric motor systems, lighting, room air conditioners, and residential refrigerators. The energy is delivered to these four products using distribution transformers. Although distribution transformers are among the most efficient electrical devices, even slight improvements in their energy performances are highly valued. One such regulation is the energy-efficiency standard for distribution transformers. There are many countries in the world that have introduced metrics for assessing the energy performance of distribution transformers. They broadly fall into two main categories: 1. specifying maximum losses, 2. specifying minimum efficiency values. These are again subdivided into transformer categories – single-phase: oil- or dry-type; three-phase: oil- or dry-type, large power transformers.

In Australia, the AS 2374.1.2 standard [2] – Minimum Energy Performance Standard (MEPS) requirements for distribution transformers was introduced in 2003, applicable for transformers from 10 kVA to 2500 kVA, intended to be used on 11 kV and 22 kV networks. A report [3] published for EECA (Energy Efficiency and Conservation Authority) of New Zealand also recommended that New Zealand should proceed to implement a MEPS for distribution transformers and adopt the Australian standard AS 2374.1.2, as a New Zealand standard for distribution transformers. The main objective of introducing MEPS for distribution transformers is:

- increase overall energy efficiency by reducing electricity losses in transformers, thereby moving towards a sustainable energy future.

The introduction of specific minimum energy performance standards through transformers in 2003 represented a huge step forward in streamlining the transformer market and directing it towards energy-efficient solutions. In this article, we articulate why there is a need to relook at the existing regulations after almost 20 years of being in existence. The most common Australian requirement is that applicable distribution transformers must comply with the minimum power efficiency levels (at 50 % load) as detailed in AS 2374.1.2 standard and a common practice is to use loss capitalization values as defined in Energy Networks Association (ENA) Doc 007.

AS 2374.1.2 – efficiency at 50 % load

It can be noted that these values, while commonly used, are non-normative and risk being out of date, as underlying ener-

Minimum Energy Performance Standards policy guideline is a powerful tool, as it requires entire transformer markets to shift towards higher levels of efficiency

Table 1. Efficiency levels defined in AS 2374.1.2 for oil-immersed transformers

kVA	Minimum efficiency at 50 % loading and Unity PF	High efficiency at 50 % loading and Unity PF
25	98.28	98.50
63	98.62	98.82
100	98.76	99.00
200	98.94	99.11
315	99.04	99.19
500	99.13	99.26
750	99.21	99.32
1000	99.27	99.37
1500	99.35	99.44
2000	99.39	99.49
2500	99.40	99.50

Setting a reasonable value of minimum efficiency will be effective in improving the overall energy performance of the installed transformer population by eliminating transformers with a low efficiency

gy costs have changed over the years since publication.

There are several governmental policy guidelines or incentives around the world which support the improvement in the energy efficiency of transformers. These include:

- Minimum Energy Performance Standards (MEPS)
- Voluntary or mandatory product labelling
- Financial incentives, subsidies, and tax breaks
- Funding of demonstration projects and research activities.

Among these policy guidelines and incentives, MEPS regulation is the most powerful tool, as it requires entire transformer markets to shift towards higher levels of efficiency. In the AS 2374.1.2 standard, the energy efficiency metric used is the efficiency at 50 % load, which is calculated as:

$$\eta_{50\%} = \frac{0.5 \times S_r}{0.5 \times S_r + 0.25 \times P_{LL} + P_{NLL}} \quad (1)$$

Where S_r = rated power (kVA), P_{LL} = load loss at rated load (kW) and P_{NLL} = no-load loss (kW). The losses are specified at a rated temperature of 75 °C and frequency is at 50 Hz. For three-phase oil type distribution transformers, Table 1 illustrates the MEPS and HEPS (high efficiency) limits. It is to be noted that MEPS is mandatory while HEPS is voluntary.

Some common examples of utility specifications are listed below:

1. Transformers shall meet minimum power efficiency levels (at 50 % load) as detailed in AS 2374.1.2.
2. All transformers shall meet or exceed the minimum power efficiency levels prescribed in Table 1 of AS 2374.1.2. The Energy Efficiency and Conservation Authority of New Zealand may also impose additional requirements from time to time. Transformers with efficiencies (at 50 % load) that do not meet or exceed these levels are not acceptable.
3. The transformers must comply with AS 2374.1.2 Table 3 for "High power efficiency levels for oil-immersed transformers".
4. The manufacturer is required to guarantee that efficiency of the transformer at 50 % load will not be less than that specified in item 21, Table 3. This is a mandatory requirement. It is desirable to have the high-power efficiency of the transformer at 50 % load (HEPS) equal to or better than that specified in item 23, Table 3.
5. All transformers must meet or exceed the minimum power efficiency levels specified in Table 1 of AS 2374.1.2 – 2003 Minimum Energy Performance Standard (MEPS). Transformers with efficiencies not meeting or improving performance upon these MEPS levels are unacceptable.

Setting a reasonable value of minimum efficiency (MEPS) will be effective in improving the overall energy performance of the installed transformer population by eliminating transformers with low efficiency. A comparison of AS 2374.1.2 with world practices is listed in the next section for the sake of completeness.

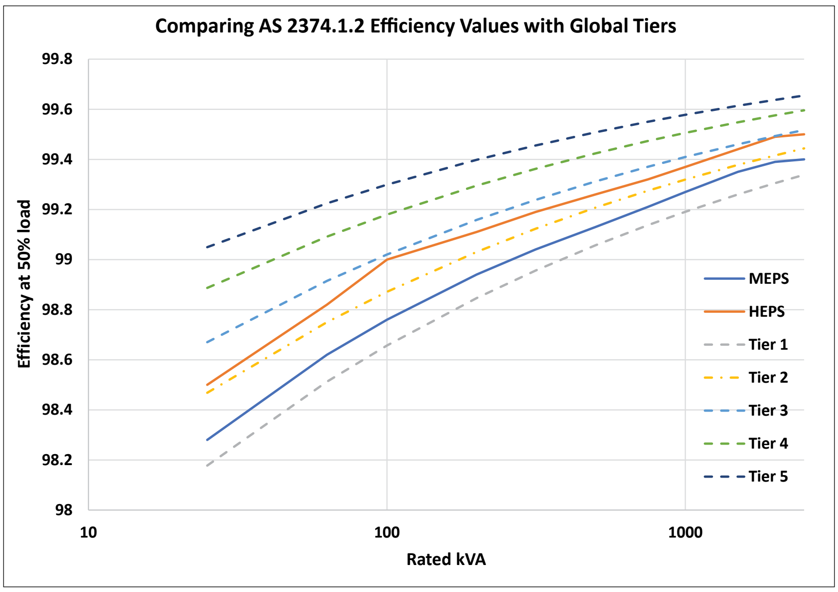

Figure 1. Comparing AS 2374.1.2 efficiencies with Tier 1 -Tier 5 for three-phase, 50 Hz oil-filled transformers

Comparing AS 2374.1.2 limits with world practices

In IEC 60076-20 [4] Annex B, a set of set equations (best-fit curves) developed from an analysis of existing world standards with 5 tiers has been listed for efficiency at 50 % loading. Tier 1 is the least efficient level, and Tier 5 is the most efficient. It can be seen from Fig. 1 that the mandatory MEPS limits in AS 2374.1.2 fall between Tier 1 and Tier 2, while voluntary HEPS limits fall between Tier 2 and Tier 3.

Loss capitalization as per ENA Doc 007

Provided that the MEPS efficiency at 50 % loading is fulfilled, the use of proper loss capitalization for purchasing transformers is essential to select a transformer with the optimal economically justified level of efficiency. It is now well recognized by many end-users that the most economical and energy-efficient transformers will arise when the Total Costs of Ownership (TCO) is evaluated, where the initial cost of the transformer plus the designed losses are considered together. Utilizing the TCO concept, savings in initial purchase costs from buying an inefficient transformer are balanced by the higher level of losses incurred, and vice versa, with increased savings in losses with a higher initial purchase price. The principles of capitalization are well explained in the literature [5]-[6].

In Australia, Energy Networks Association (ENA) Doc 007 [7] specification provides the purchaser loss capitalization values as listed in Table 2. It can be noted that these values, while commonly used, are non-normative and risk being out of date, as underlying energy costs have changed over the years since publication.

The expected load factor can be inferred from the capitalization rates as below:

$$k = \sqrt{\frac{1800}{6300}} = 53.45\% \quad (2)$$

Based on the expected load factor, the transformer design engineers can trade-off no-load and load losses while trying to produce an optimized transformer for that expected load as specified by the capitalization formula.

What happens when the designed optimal loading point does not coincide with actual transformer loading?

To illustrate this point, let us consider a 1,000 kVA transformer with the following designs as listed in Table 3:

The MEPS efficiency limit for a 1,000 kVA at 50 % loading = 99.27 % as per AS 2374.1.2-2003. The transformer efficiencies versus loading are plotted in Fig. 2. It is clear from Fig. 2 that both 1,000 kVA transformers are compliant with the MEPS requirement since both designs are acceptable as per regulations and clauses specified in the specification documents. Now let us compare the daily transformer operational losses under two specific cases:

1. Flat 50 % loading profile.
2. Actual loading profile with a peak loading of 50 % and average loading of 28 % (Fig. 3).

Provided that the MEPS efficiency at 50 % loading is fulfilled, the use of proper loss capitalization for purchasing transformers is essential to select a transformer with the optimal economically justified level of efficiency

Table 2. Loss capitalization values as per ENA Doc 007

Rating	No Load loss $/kW	Load loss $/kW
Up to and including 63 kVA	$6,300	$700
100 kVA and above	$6,300	$1,800

Table 3. Loss values for two 1000 kVA designs

Parameters	1,000 kVA	Total loss
Design 1 (NLL/LL)	1,800/7,000 W	8.8 kW
Design 2 (NLL/LL)	920/10,500 W	11.42 kW

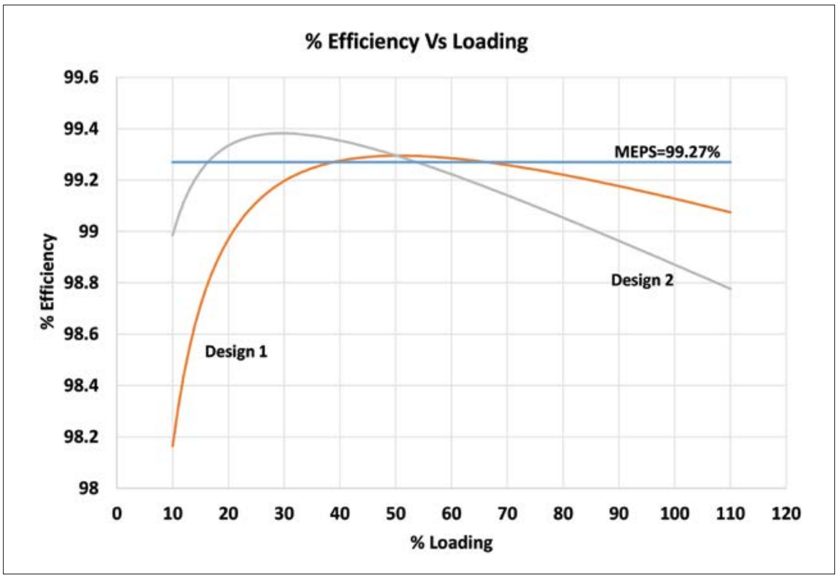

Figure 2. Efficiency vs loading of 1,000 kVA MEPS-compliant designs 1 & 2

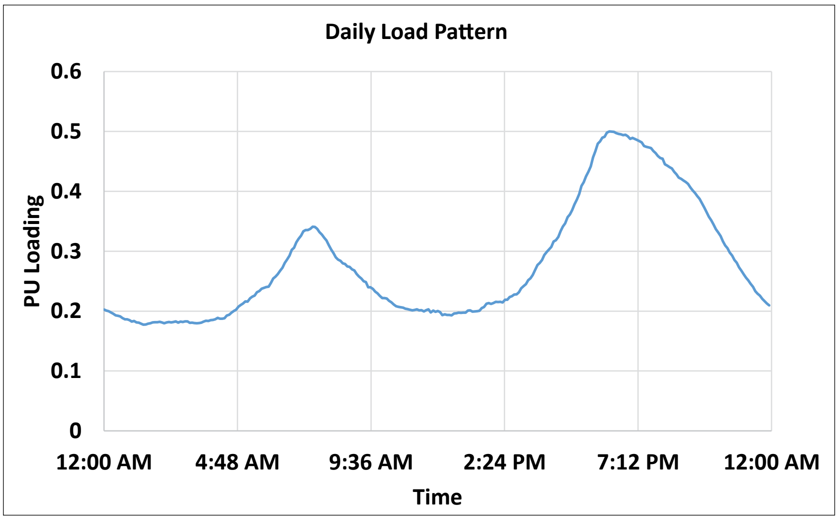

Figure 3. Daily load profile with a peak loading of 50 %

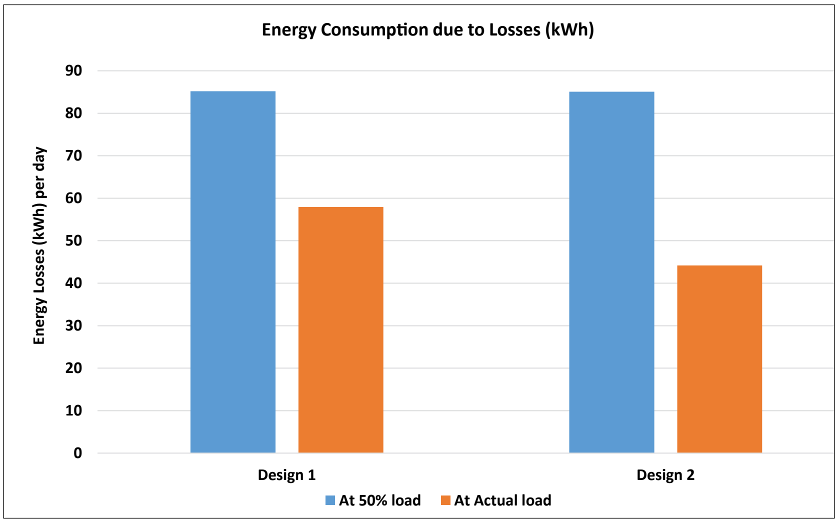

Figure 4. Daily energy consumption due to transformer losses – flat 50 % loading vs Design 1 vs Design 2

Energy losses at MEPS energy efficiency at 50 % are only meaningful and accurate when loading factors are close to 50 %, which may not be the case for users with diverse daily load profiles

From Fig. 4, the computed values are:

1. Daily transformer loss at flat 50 % load = 85 kWh
2. Daily transformer loss at actual load for Design 1 = 57.95 kWh
3. Daily transformer loss at actual load for Design 2 = 44.19 kWh

Let us compute the loss capitalized values for the two transformer designs:

A rough comparison of transformer price between the two designs can be computed as:

$$PC2 = PC1 \times \frac{NLL_1 \times LL_1}{NLL_2 \times LL_2} \tag{3}$$

$$PC1 \times \frac{1.8 \times 7}{0.92 \times 10.5} = PC1 \times (1.1{\sim}{<}1.3)$$

Based on the above calculation, the TCO for the two designs can be computed as:

$$TCO1 = PC1 + \$23{,}940$$

$$TCO2 = 1.1 \times PC1 + \$24{,}696$$

A clear contradiction can be seen where the capitalized loss cost for Design 2 is higher than Design 1 while the daily transformer operational losses are lower for Design 2 when compared to Design 1. Analogously, the total losses for Design 1 = 8.8 kW while for Design 2 = 11.42 kW, but there are greater lost energy savings with Design 1 compared to Design 2 due to the larger mismatch between the presumed load factor k and the actual load profile. Additionally, the ENA 007 values are premised on an average load of approx. 50 % (53.4 %). Hence the loss capitalization is also skewed and potentially inappropriate for the daily load profile of Fig. 3.

Table 4. Summary of oil-filled distribution transformer energy performance index

	No-load loss $	Load loss $	Total
Design 1	6,300 x 1.8	1,800 x 7	$23,940
Design 2	6,300 x 0.92	1,800 x 10.5	$24,696

If the diversity of daily load profiles and loading factors for different end-uses such as residential, commercial, and industrial applications are considered, variations in transformer operating losses with the same MEPS energy efficiency at 50 % can be easily computed. Hence, energy losses at MEPS energy efficiency at 50 % will only be meaningful and most appropriate when loading factors are close to 50 %. Similarly, the loss capitalization formula values of 'k' also need to be consistent with the load profile.

Global energy performance metrics

There are many different metrics in use for assessing the energy performance of a distribution transformer. All of them fundamentally refers to two main categories: maximum losses and minimum efficiency, as listed in Table 5 [1].

As seen from Table 5, many countries have selected efficiency at 50 % load as the energy performance index. However, typically the LV distribution transformer is not monitored. In most situations, the expected load profile is "estimated" with quite high uncertainty. Under such circumstances, the flexibility of the efficiency at 50 % index provides greater scope to be incorrectly adopted, such as selecting Design 1 instead of Design 2 when based on efficiency at 50 % and / or TCO considerations at 50 % loading.

There are many different metrics in use for assessing the energy performance of a distribution transformer, but all of them fundamentally refers to maximum losses and minimum efficiency

Table 5. Summary of oil-filled distribution transformer energy performance index

Country	Energy performance index	Standard
Australia / New Zealand	Efficiency at 50 % load	AS 2374.1.2 - 2003
Brazil	Max no-load and load losses at 100 % load	ABNT NBR 5356; 5440
Canada	Efficiency at 50 % load	CSA C802.1
China	Max no-load and load losses at 100 % load	JB/T 10317-02 GB 20052-2013
EU	Max no-load and load losses at 100 % load, PEI > 3,150 kVA	EN50588-1:2014;
India	Max total losses at 50 % and at 100 % load	IS 1180:2014 & GoI Gazette 2968
Israel	Max total losses at 100 % load	IS 5484
Japan	Total losses at 40 % or 50 % load	Top runner
Mexico	Efficiency at 50 % load	NOM-002- SEDE-1997
Korea	Efficiency at 50 % load	KS C4306, C4316 and C4317
USA	Efficiency at 50 % load	10 CFR 431
Vietnam	Efficiency at 50 % load	TCVN 8525:2015

From capitalization formulae available in AU/NZ end user specifications, it can be concluded that the transformers are very lightly loaded, which means that it makes more sense to lower the no-load losses

Importance of load factor in loss capitalization

Lower load factors increase the importance of no-load losses and decrease the importance of load losses. Consequently, it steers the transformer manufacturer to lower the no-load losses instead of decreasing the load losses and vice versa. This characteristic can be identified in the loss capitalization formula. Apart from loss capitalization specified in ENA Doc 007, we have also found other loss capitalization formulae based on our literature survey (Table 6):

Table 6. Other loss capitalization formulae based on literature survey of end user specifications in AU/NZ

SI #	Loss capitalization formula specified	Estimated loading
1	0.78 x purchase cost + $8,500 x NLL + $420 x LL	22.22 %
2	0.8 x purchase cost + $6,619 x NLL + $868 x LL (100–500 kVA)	36.21 %
	0.8 x purchase cost + $6,619 x NLL + $1153 x LL (> 500 kVA)	41.7 %
3	Purchase cost + $62,635 x NLL + $ 2,029 x LL	17.99 %
4	Purchase cost + $23,288 x NLL + $ 577 x LL	15.7 %
5	Purchase cost + $9,319 x NLL + $1184 x LL (200–500 kVA)	35.65 %
	Purchase cost + $9,319 x NLL + $1625 x LL (750–1,500 kVA)	41.7 %
6	Purchase cost + $8,300 x NLL + $ 1450 x LL	41.7 %
Average estimated loading		31 %

Table 7. No-load loss reduction methods available to transformer manufacturers

Objective	Approach	No-load loss	Load loss	Effect on price
Decrease no-load loss	Use lower-loss core materials	Lower	No change	Higher
	Better core construction techniques	Lower	No change	Same to higher
	Decrease flux density by increasing core cross-sectional area	Lower	Higher	Higher
	Decrease flux density by decreasing volts / turn	Lower	Higher	Same to higher

The main drawback of specifying no-load and load losses is that the load at which the peak efficiency occurs is fixed, and the designer has less flexibility

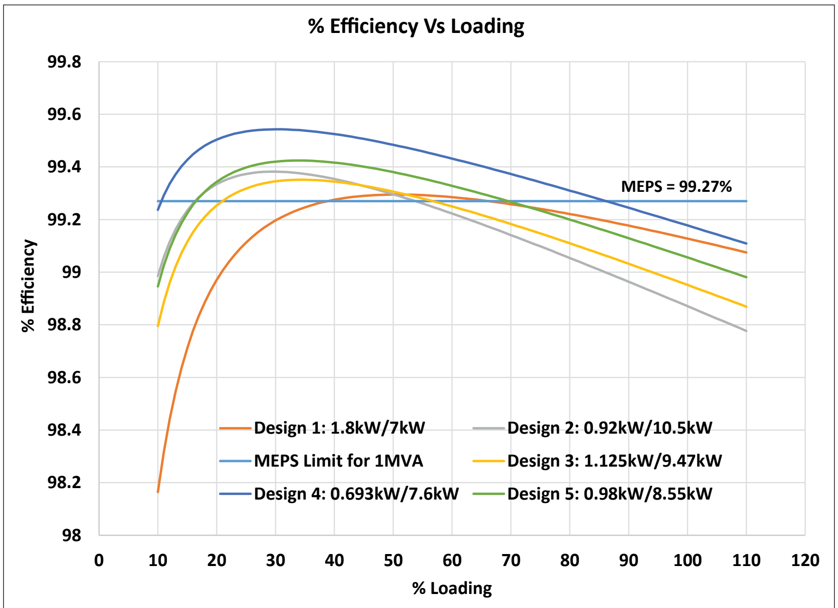

Figure 5. Transformer efficiency curves: Design 1 – Design 5

From Table 6, it can be estimated that the majority of the transformers across end-users are very lightly loaded. Under such circumstances, it is ideal for transformer manufacturers to lower the no-load loss by different methods, as listed in Table 7. Hence, it is acknowledged that specifying no-load and load losses allow for better estimation of the actual operational losses under different operating conditions, rather than simply using the efficiency at 50 % index. An example is illustrated in Table 8.

From Table 8, Fig. 5 and Fig. 3, the order of least daily operating losses are as follows – Design 4, Design 5, Design 2, Design 3 and Design 1. The main drawback

Table 8. 5 different 1000 kVA designs with NLL and LL specified

Parameters	1000 kVA	Total loss	Load where peak efficiency	Peak efficiency
Design 1 (NLL/LL)	1,800/7,000 W	8.8 kW	50.71 %	99.29 %
Design 2 (NLL/LL)	920/10,500 W	11.42 kW	29.60 %	99.38 %
Design 3 (NLL/LL)	1,125/9,470 W	10.59 kW	34.47 %	99.35 %
Design 4 (NLL/LL)	693/7,600 W	8.293 kW	30.20 %	99.54 %
Design 5 (NLL/LL)	980/8,550 W	9.53 kW	33.86 %	99.42 %

of specifying no-load and load losses is that the load at which the peak efficiency occurs is fixed, and the designer has less flexibility. However, this is a better method than only using efficiency at 50 % load.

Can PEI be used for distribution transformers?

In IEC 60076-20 [4], another metric – peak efficiency index (PEI) was introduced. The use of PEI provides scope for further reduction in losses as it allows the transformer to be designed to match the load, either minimizing copper or iron losses as appropriate. This is typically achieved by specifying the minimum PEI with load and no-load loss capitalization values.

Using this PEI method, peak efficiency for all the designs is the same, whereas the load at which the peak efficiency occurs can be adjusted according to the loss capitalization values. Table 10 lists four different 1,000 kVA designs meeting PEI requirements. From Table 10 and Fig. 7, we can conclude that the use of fixed losses for distribution transformers is sub-optimal, and efficiency (overall energy consumption minimized) could be further improved using PEI. The conclusion is that there is still a potential to increase the efficiency of transformers using PEI by altering the methods described in AS 2374.1.2, even if MEPS or HEPS at 50 % is not met!

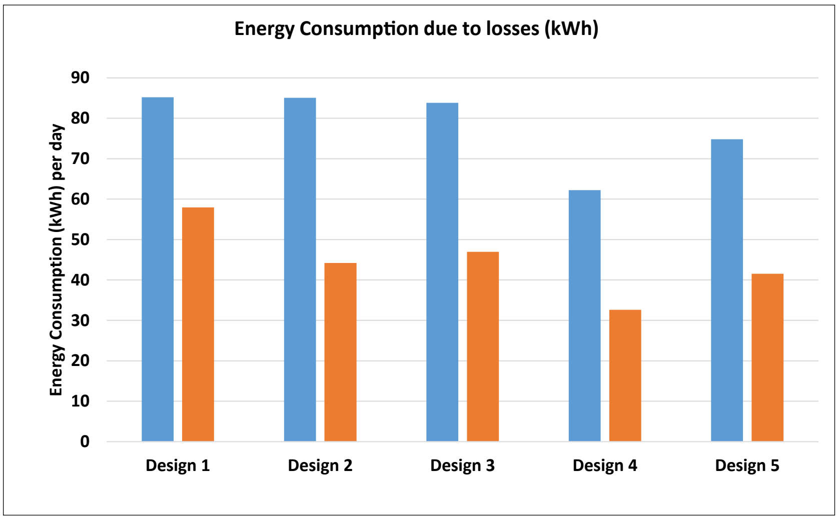

Figure 6. Daily transformer losses comparison – 5 different designs with NLL/LL specified (load profile of Fig. 3)

Table 9. PEI values defined in IEC 60076-20 (Table 2, HV <= 24kV)

kVA	PEI Level 1	PEI Level 2
500	99.330 %	99.465 %
630	99.373 %	99.500 %
1000	99.431 %	99.541 %
1600	99.488 %	99.550 %
2000	99.495 %	99.558 %
2500	99.504 %	99.568 %
3150	99.506 %	99.572 %

There is a potential to increase the efficiency of transformers by considering PEI as an alternate metric

Table 10. Four different 1,000 kVA designed for PEI requirements

Parameters	1,000 kVA	Total loss	Load where peak efficiency	Peak efficiency
Design 1 (NLL/LL)	770/10,500 W	11.27 kW	27.1 %	99.433 %
Design 2 (NLL/LL)	1,150/7,000 W	8.15 kW	40.5 %	99.433 %
Design 3 (NLL/LL)	1,800/4,450 W	6.25 kW	63.6 %	99.433 %
Design 4 (NLL/LL)	1,340/6,000 W	7.34 kW	47.3 %	99.433 %

Conclusions

Based on the analysis presented in this article, it is recommended that the AS 2374.1.2: 2003 standard should be updated to facilitate the assessment under new metrics, such as: peak efficiency index, or using different specifications – low no-load losses for lightly loaded transformers and low load losses for highly loaded transformers. Policymakers are trying to influence transformer specifications by introducing specific rules on minimum transformer efficiency, but if the specification process is not in line with the intended operational usage, optimal selection of transformer is not possible. The following steps are recommended while updating the AS 2374.1.2:2003 standard:

1. Consideration and inclusion of the effects of different load profiles into the MEPS assessment, explanation and understanding of the effect and importance of coordinating the load profile with the desired efficiency.
2. Consideration and consensus of the most appropriate assessment method: fixed losses or PEI plus loading factor, which gives the opportunity to improve the realized efficiency at the actual load profile.

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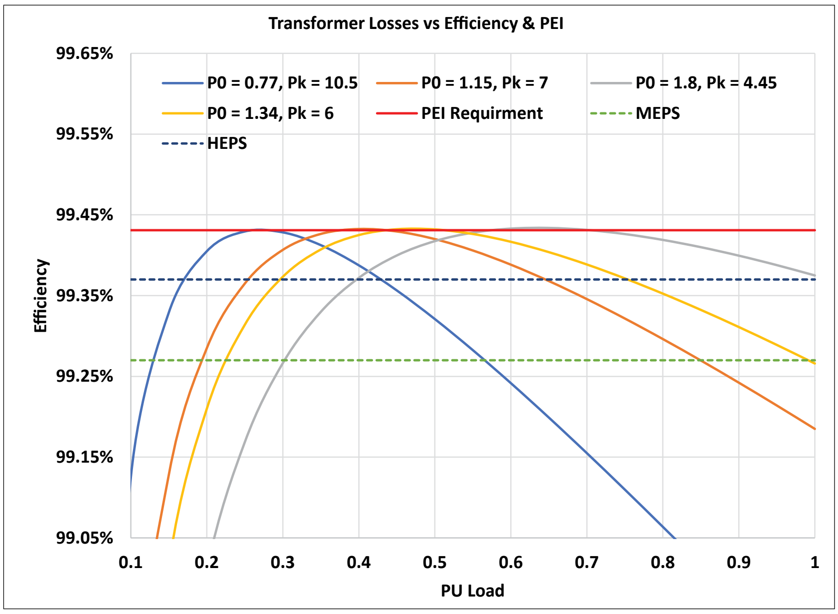

Figure 7. Transformer efficiency curves meeting PEI (Level 1) for 1,000 kVA

Authors

Dr. Bhaba P. Das is the Lead Digital Business Developer for Transformers Business Line, HUB (Asia- Pacific, Middle East and Africa), Hitachi Energy, based in Singapore. He is part of the Application Engineering Team and spearheads the digital transformation efforts of transformers in the Asia Pacific region. Prior to Hitachi Energy, he worked as the R&D engineer for a major transformer manufacturer in New Zealand. He was awarded the Young Engineer of the Year 2017 by the Electricity Engineers Association of New Zealand for his work on the design and development of smart distribution transformers, fibre optics-based sensors for transformers, and diagnostic software for fleet condition monitoring. He is a Senior Member of IEEE and Young Professional of IEC. He completed his PhD in Electrical Engineering from the University of Canterbury, New Zealand.

Rob Milledge, based in Sydney, Australia, graduated from the University of NSW with 1st Class Honours and University Medal.

He has been involved with Power Transformer design since 1974, starting as an Electrical Design Engineer progressing to Engineering Management in 1995 with direct engineering design and manufacturing experience for units up to 1,125 MVA and 550 kV since 1979.

Since 2001, Mr. Milledge has been involved in both Customer and factory technical support, including tender and order designs to 765 kV, alternate opportunity assessment, Customer design review and FAT Support throughout the Asia Pacific Region. This also included technology transfer and implementation programs for various factories.

Following a period within the company's Global "Top Gun" Design Team, he is focusing on his Application Engineering role for the Asia Pacific Region applying his extensive power transformer knowledge to Customer technical support, training and technical co-ordination with factories.

Mr. Milledge is also the current Chair of the EL008 Power Transformers Committee of Standards Australia and a member of the Cigre Committee APA2 Panel.