ABSTRACT

The ever increasing demand for electricity in the world is a major cause of carbon dioxide (CO_2) emissions. With increasing numbers of new distribution transformers added every year, the contribution of CO_2 emission from transformer increases. It has been reported by the United Nations (UN) that almost 730 million tons/year of CO_2 emission are contributed by transformers alone. Thus, there is an urgent need to find a sustainable model to meet the demand, maintain reliability and yet reduce CO_2 emissions. By using sustainable ester fluids, a force multiplier to the existing minimum efficiency guidelines can be achieved. This combination will act as an encouragement for purchasers while defining their transformer purchasing policy by adopting sustainable transformer ratings rather than peak transformer ratings. This article quantifies how the cost of losses are reduced while simultaneously reducing CO_2 emissions.

KEYWORDS:

distribution transformers, ester fluid, sustainability, total cost of ownership, CO_2 emissions

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New technical specifications such as IEC 60076-20 on energy efficiency have been published, and many end-users and utilities have started to incorporate the loss evaluation procedure

Ester-filled distribution transformers

The sustainable model to strengthen the low voltage grid

1. Introduction

The distribution transformer is a key piece of electrical equipment installed in our electrical network but with a substantial impact on the network's overall cost, efficiency, and reliability. Selection and acquisition of distribution transformers are hence critical. Over the last 20 years, the acquisition processes for distribution transformers have moved in the right direction, with utilities becoming aware of the consequences of distribution transformer losses. New technical specifications such as IEC 60076-20 [1] on energy efficiency have been published, and many end-users (utilities) have started to incorporate the loss evaluation procedure. Contrary to this, there are still many end-users who rely on purchasing transformers based on the initial cost. When such purchase requests are made, transformer manufacturers have little incentive to design energy-efficient transformers or provide innovative solutions. With the increasing numbers of new distribution transformers added every year, the need to get the selection and acquisition of distribution transformers correct is becoming crucial. This is amplified by the fact that as we move towards new types of load such as Electric Vehicles (EV), Distributed Energy Resources (DER), the need to increase the reliability of the network will become supercritical. The question would be – how much higher sized transformer would be appropriate to maintain network reliability? Larger transformers would have higher no-load losses, as well as higher mineral oil requirements, and would need more maintenance budgets to maintain the reliability of the network. Higher losses and more mineral oil would contribute to a greater carbon footprint!

Nowadays, the reduction of Green House Gas (GHG) emissions is becoming a substantial issue due to the growing concern for global warming and climate change. Two very effective measures to reduce GHG emissions are energy efficiency and renewable energy sources. It has been reported by UN that almost 730 million tons/year of CO_2 emission are contributed by transformers alone [2]. There are now existing international policies supporting the energy efficiency of distribution transformers, such as the Minimum Energy Performance Standards (MEPS) [3]. Transformers complying with transformer MEPS have reduced losses compared

UN reports that almost 730 million tons per year of CO_2 emission are contributed worldwide by transformers alone

Ester-filled distribution transformers are a sustainable way to meet the rising electrical power demands of the low voltage network

to non-compliant high-loss transformers, with reduced energy consumed by the transmission and distribution system (technical losses / system efficiency) and, consequently, the reduced required generation of electrical energy and greenhouse gases gas emissions. Thus, the transformer selection directly affects the overall system efficiency, directly impacting the demand for electricity generation.

Traditionally, transformer sizing is performed based on two methods:

- Connected load – where all the loads connected to the transformer are assumed to be operating at full capacity, i.e., operation without any demand or diversity.
- Operating load - where all the loads connected to the transformer are assumed to be operating at actual loading i.e., operation with demand and diversity.
- The above criteria typically result in a unit selection which is operating anywhere between 20–30 % when no demand or diversity is considered and around 40–50 % of its full capacity when demand or diversity is considered.

This approach has historically served end customers well and has given the much-required reliability of the network. However, there is a growing concern that with increasing volatile loads in the Low Voltage network (LV) such as 220–240 V in many countries and 120 V in the USA, existing transformers may become overloaded sooner than they have been originally planned. As an example, the Sacramento Municipality Utility District (SMUD), with a service population of 1.4 million, has recognized 17 % or 12,000 of their transformers need replacing because of EV-related overloads, at an average estimated cost of $7,400 per transformer [4]. And that is only one municipal utility, the impacts on the entire US grid can be scaled accordingly. If the traditional method of transformer sizing is followed, the need for peak-rated transformers will proliferate to a huge extent.

Thus, there is a greater need for finding a sustainable model to meet increasing demand and yet reduce CO_2 emissions by utilizing sustainable alternatives to mineral oil. This paper presents the concept of the ester-filled distribution transformer, a sustainable way to meet the future demand of the low voltage network. Combining the advantages of sustainable natural ester in a distribution transformer would be a force multiplier to the existing minimum efficiency guidelines. This article quantifies and analyzes the impact of sustainable natural ester fluid on the economic evaluation of distribution transformers by adopting sustain-

Table 1. Metrics for energy performance of distribution transformers

Specifying maximum losses	Specifying minimum efficiency values
No-load loss and load loss at 100 % load	Efficiency at a specified loading point such as 50 %
Total loss at a specified loading point (50 % or 100 %)	Peak efficiency index (PEI)

Table 2. Energy performance standards of distribution transformers

Country	Rated frequency	Reference standard	Energy performance index
Australia and New Zealand	50 Hz	AS 2374.1.2 - 2003	Efficiency at 50 % load
Canada	60 Hz	CSA C802.1	Efficiency at 50 % load
China	50 Hz	JB/T 10317-02 GB 20052-2013	Losses at 100 % load
European Union	50 Hz	EN50588-1: 2014 EU No 548/2014	Losses at 100 % load (rating < 3150 kVA) PEI (rating > 3150 kVA)
India	50 Hz	IS 1180:2014 & GoI Gazette 2968	Losses at 50 % load and losses at 100 % load
Japan	50/60 Hz	Top Runner	Total loss at 40 % (rating ≤ 500 kVA) Total loss at 50 % (rating > 500 kVA)
USA	60 Hz	10 CFR 431	Efficiency at 50 % load
Vietnam	50 Hz	TCVN 8525:2015	Efficiency at 50 % load

able transformer ratings rather than peak transformer ratings.

There are now financial incentives also being offered to transformer manufactures under the new circularity programs such as: reduction in total weight of transformers, reduction in oil used in transformers, and establishing saved CO_2 emissions. Sustainable transformer ratings would aid the manufacturers as well.

2. Brief review of transformer efficiency programs

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.

Each approach offers certain strengths but also has some weaknesses. The categorization can be expressed as shown in Table 1.

When no-load loss and load loss are specified at 100 % load, this means that a minimum level of performance is assured, whatever the level of loading applied to the transformer. Similarly, when efficiency is specified, it allows transformer design engineers to trade-off no-load and load losses while trying to produce an optimized transformer for a specific load. However, the designed optimal loading point may not coincide with the average loading at all installation sites, resulting in lost energy savings. Table 2 shows a selected list of countries where such Minimum Energy Performance Standards have been implemented.

Since the LV distribution transformer is typically not monitored, in most situations, the expected load profile is "estimated" with quite high uncertainty with the average load value. The use of estimated average load value is typically insufficient to reach the theoretical optimum level promised by efficiency approaches. In [5], the yearly average loading of distribution transformers was reported as in Table 3.

Table 3 clearly illustrates that transformers are selected for peak ratings, and it is very crucial to look at whether selecting peak rating of transformers is beneficial in the long run or not. Also, monitoring the load of an LV distribution transformer is a key factor for expanding our LV network in a sustainable way.

The knowledge of the average load value is typically insufficient to reach the theoretical optimum level promised by efficiency approaches, actual load monitoring is the need of the hour

3. Peak rated transformers and environmental impact

Distribution transformers are one of the most significant investments utilities make, just by the sheer numbers in operation. A reported Australian utility that operates with around 150,000 distribution transformers spent in 2018 AU$60 M on replacements and AU$3 M on maintenance [6]! Minimizing the investment and increasing the utilization of the transformer is important leverage that any company can make. Using a peak-rated transformer just to handle peak loads adds higher no-load losses to the network, which is a constant cost. This implies the same amount of energy must be generated, adding to the CO_2 footprint.

While some end users prioritize the long-term advantage of reducing the total losses, others simply minimize the initial cost without long-term considerations. The most widely used technique for the long-term evaluation of distribution transformers is the Total Cost of Ownership (TCO) method [7] that is based on the following formula:

$$TCO = C_{pp}+(A\times NLL)+(B\times LL)$$

Where:

- C_{pp}: the purchase price of the transformer
- NLL and LL: transformer no-load and load loss
- A & B: loss capitalization factors ($/kW)

Distribution transformers are one of the most significant investments utilities make, just by the sheer numbers in operation

Table 3. Estimated average load of distribution transformers [5]

Country	Yearly average load factor (PU)
Australia	27 %
Canada	34 %
China	50 %
European Union	21 %
India	Unknown
Japan	22 %
USA	34 %
Indonesia	50 %
Thailand	36 %
Mexico	31 %

Using a peak-rated transformer just to handle peak loads adds higher no-load losses to the network and is a constant environmental cost

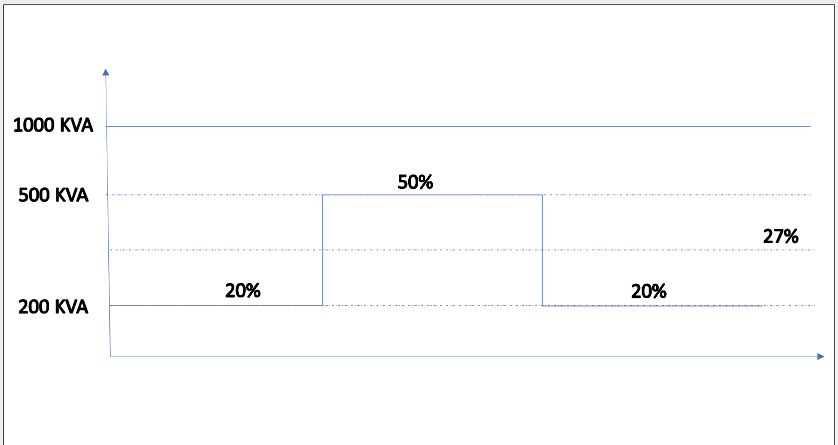

Figure 1. Peak rated transformer: illustration

Table 4. Combinations of no-load and load loss for 1000 kVA meeting MEPS efficiency limits

Values	Peak Rated 1000 kVA
Rated temperature-rise limits for mineral oil transformers	Top/average/hot spot 60/65/78 K
Rated losses #1 (NLL/LL)	900/10,500 W
Rated losses #2 (NLL/LL)	770/9,000 W
Rated losses #3 (NLL/LL)	1050/10,000 W
Rated losses #4 (NLL/LL)	693/7,600 W

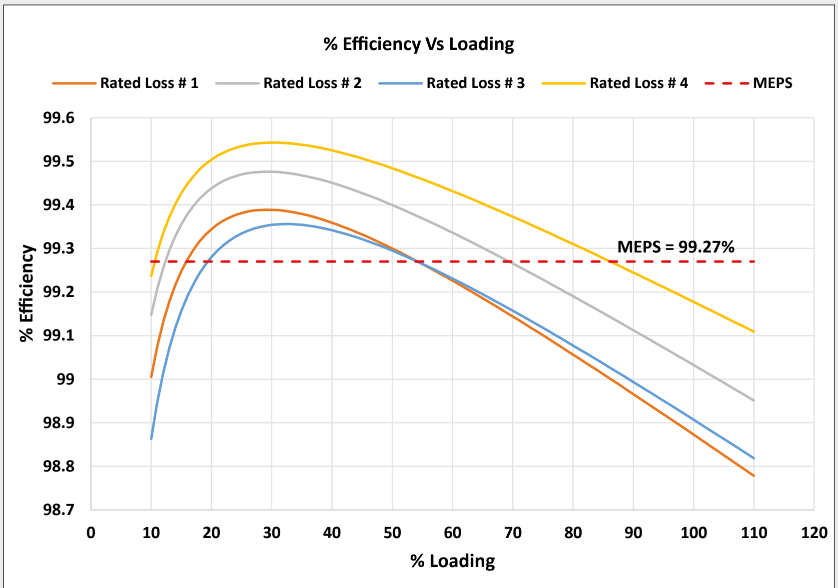

Figure 2. Efficiency vs. loading of four different designs of 1000 kVA

However, environmental costs are never considered. In many studies, it has been shown that average loading is only in the range of 20–30 %, while the peak load is in the range of 70–80 % [8]. Additional growth margin of 20–30 % is always added to ensure network reliability. This type of transformer sizing is called a "peak" rated transformer.

Let us consider a case where the peak load is 500 kVA with a base load of 200 kVA, but a peak rated transformer of 1000 kVA is used, considering maximum 50 % loading with maximum operating efficiency during the peak period. The average is around 27 %. Any actual load profile can be used instead of Figure 1.

The MEPS efficiency limit for a 1000 kVA at 50 % loading = 99.27 % as per AS 2374.1.2-2003 (R 2016) [9]. Let us consider four different transformer designs with the characteristics shown in Table 4.

Based on the efficiency vs. loading characteristics in Fig. 2 as per values in Table 4, all four designs pass the MEPS efficiency limit for a 1000 kVA at 50 % loading. Assuming a good balance on the loss capitalization and manufacturing cost, the rated losses #2 is selected. If there is no loss capitalization, rated losses #3 will be the cheapest option in terms of the purchase price.

Each kWh of a peak-rated transformer has an external cost, i.e., the environmental costs to society that are not fully reflected in the price of electricity or in the TCO formula. These externalities originate in the various types of emissions resulting from the combustion of fossil fuel to generate the extra kWh

Each kWh of a peak-rated transformer has an external cost, i.e., the environmental costs to society that are not fully reflected in the TCO formula

Table 5. Equivalent CO_2 emission / MWh calculation [10]

	Coal	Diesel	Hydro	Natural gas	Wind / solar
Fuel %	30%	19 %	20 %	21 %	10 %
G_{CO2} (kg/GJ)	94.6	74.1	0	56.1	0
G_{CH4}(kg/GJ)	0.002	0.002	0	0.003	0
G_{N2O}(kg/GJ)	0.003	0.002	0	0.001	0
η_{fuel} %	35 %	30 %	100 %	45.00 %	100 %
$J_{T\&D}$ %	8 %	8 %	8 %	8 %	8 %
GHG_{fuel}	1.068	0.975	0	0.491	0
C_{eq}	0.608 t_{CO2}/MWh				

needed to sustain peak rated no-load transformer losses. Transformer designers and owners should assume these environmental costs as these peak-rated losses directly correspond to the additional energy that must be generated by the existing generation mix of the power system of that country.

The selection of generation mix is very important in deciding the t_{CO2}/MWh and transferring that value to the environmental cost in $/MWh should be considered on a country-by-country basis

3.1 Calculation of CO_2 footprint from the operation of a transformer

According to the type of fuel (i.e., coal, diesel, natural gas, wind, etc.), gas emissions are converted into equivalent CO_2 emissions (measured in tons of equivalent CO_2 emissions) in terms of their global warming potential [10] using the formula:

$$GHG_{fuel} = (G_{CO2}+21\times G_{CH4} +310\times G_{N2O}) \times \frac{0.0036}{\eta_{fuel}\,(1 - J_{T\&D})}$$

where GHG_{fuel} is the emission factor of each fuel type in t_{CO2}/MWh, G_{CO2} is the CO_2 emission factor in kg/GJ, G_{CH4} is the CH_4 emission factor in kg/GJ, G_{N2O} is the N_2O emission factor in kg/GJ, $J_{T\&D}$ represents the transmission and distribution losses in %, and η_{fuel} is the fuel conversion efficiency in %. Considering a 70–30 % generation mix (countries like Australia, Japan, the USA), the CO_2 equivalent calculation is shown in Table 5.

The equivalent tones of CO_2 emissions per year are 0.608 t_{CO2}/MWh, considering annual average 8 % transmission and distribution losses [11] and a 70–30 generation mix [12]. The selection of generation mix is very important in deciding the t_{CO2}/MWh and should be considered on a country-by-country basis.

Considering the current cost of $50 per t_{CO2} [13], the environmental cost coefficient = 30.45 $/MWh. Utilizing the NLL and LL values for 1000 kVA, the following can be calculated as in Table 6.

Table 6. Total CO_2 emission / MWh calculation for 1000 kVA

Parameters	Value
NLL	770 W
LL	9000 W
NLL/year (kWh)	6745.2 kWh
LL/year (kWh) (at 27 % load factor)	5747.436 kWh
Total losses/year (kWh)	12492.64 kWh
Total losses/year for 30 years	374.78 MWh
Total environmental cost for 30 years* ($)	$11,412
Total CO_2 emission for 30 years (tons)	228.224 tons

*Assuming the total losses/year and environmental cost coefficient does not change over the 30-year period.

Table 7. Total CO_2 emission from BEES carbon footprint calculator: mineral oil

Category	CO_2 emission (g per 1000 L)
Raw materials	104,8184
Manufacturing	54,4363
Transportation	12,2478
Use	154,124
End of life	30,825
Sum	189,9973 = 0.00189 t_{CO2}/litre

Table 8. Total CO_2 emission for oil needed in 1000 kVA transformer

Parameters	1000 kVA
Amount of mineral oil (liters)	550 litres
Total CO_2 emission for producing oil	1.03 tons

Table 9. Total CO_2 emission for transformer lifetime for 1000 kVA [14]

Parameter	Value of CO_2 generated
Operation of transformer (losses) for 30 years	228.224 ton
Production of mineral oil (550 litres)	1.03 ton
Core steel (1200 kg) at 4kg CO_2/kg	4.8 ton
Insulation (35 kg) at 1.5 kg CO_2/kg	0.0525 ton
Winding material Al (400 kg) at 8.96 kg CO_2/kg	3.58 ton
Steel (545 kg) at 1.8 kg CO_2/kg	0.98 ton
Total CO_2 generated	238.67 ton
Total CO_2 costs	$12,000 (approx.)

Table 10. Loss capitalization factors A and B

Parameters for loss capitalization	Values	Unit
Energy cost rate for 1st year of operation	0.1	$/kWh
No of years	30	years
Interest rate	2	%
Loading	27	%
No-load loss capitalization factor "A"	19619.3	$/kW
Load loss capitalization factor "B"	1430.24	$/kW

NIST, the National Institute of Standards and Technology, calculated the amount of carbon dioxide or carbon dioxide equivalents of other gasses released into the atmosphere for naphthenic-based transformer mineral oil

3.2 CO_2 footprint calculation from transformer oil production:

NIST, the National Institute of Standards and Technology, has developed BEES® 4.0 (Building for Environmental and Economic Sustainability), which is a carbon footprint calculator. Using this tool, NIST calculated the amount of carbon dioxide or carbon dioxide equivalents of other gasses released into the atmosphere for naphthenic-based transformer mineral oil. The carbon footprint was calculated to produce a gallon of mineral oil, including carbon contributions due to crude oil extraction, refining, transportation, use, and disposal. In BEES, it is assumed that after the 30-year life of the transformer, oil can be further reconditioned and reused in another transformer.

If oil is not reclaimed, a higher value of needs to be used.

3.3 Total CO_2 for 1000 kVA transformer for 30 years

The total CO_2 emission is calculated in Table 9 utilizing emission factors from [14].

3.4 TCO including environmental costs

$$TCO=C_{pp}+(A\times NLL)+(B\times LL)+C_{env}$$

The total cost operation equation should be modified to take into account the environmental costs

Table 11. Calculated TCO for 1000 kVA transformer, with and without environmental costs

Design	No-load loss (W)	Load loss (W)	Purchase price (estimated)	TCO without C_{env}	TCO with C_{env}
1000 kVA	770	9000	$35,000	$62,980	$74,980

Table 12. Thermal class upgradation using ester fluid [17]

Oil type	Mineral oil	Mineral oil	Ester fluid	Ester fluid
Solid insulation	Kraft paper	TU paper	Kraft paper	TU paper
Max ambient temp. daily	40 °C	40 °C	40 °C	40 °C
Annual average ambient temp.	20 °C	20 °C	20 °C	20 °C
Oil temp. rise	60 K	60 K	90 K	90 K
Windings temp. rise	65 K	75 K	75 K	95 K
Hot-spot rise	78 K	90 K	90 K	110 K
Thermal class	105 °C	120 °C	120 °C	140 °C

Where:
C_{pp}: for 1000 kVA is $35,000 (the cost price varies from country to country and market to market, here the typical price for a pad-mounted transformer is assumed).

C_{env}: represents the total environmental costs calculated in Section 3.3.

Utilizing the loss capitalization formula [15], the A & B values are calculated in Table 10. The TCO for 1000 kVA transformer (without & with environmental costs) is listed in Table 11.

4. Sustainable rated transformers and environmental impact

Natural ester-filled transformers offer some distinct advantages over traditional mineral oil-filled transformers [16]. While many of the early adopters switched to natural esters because of fire safety, many end-users now realize the thermal advantages and higher thermal class of the ester fluid and insulation system to gain economic benefits. In IEC 60076-14 [17], the thermal class specification is provided, as listed in Table 12.

In most specifications, mineral oil-filled transformers (with Kraft paper) are designed with 60 K/65 K specification to limit to the hot spot temperature to 98 °C to maintain per unit life and minimize thermal degradation. However, if we look at the transformer per unit insulation life curve with the transformer the hot-spot temperature (Fig. 3), it shows that ester-filled transformers with thermally upgraded (TU) paper can maintain unit

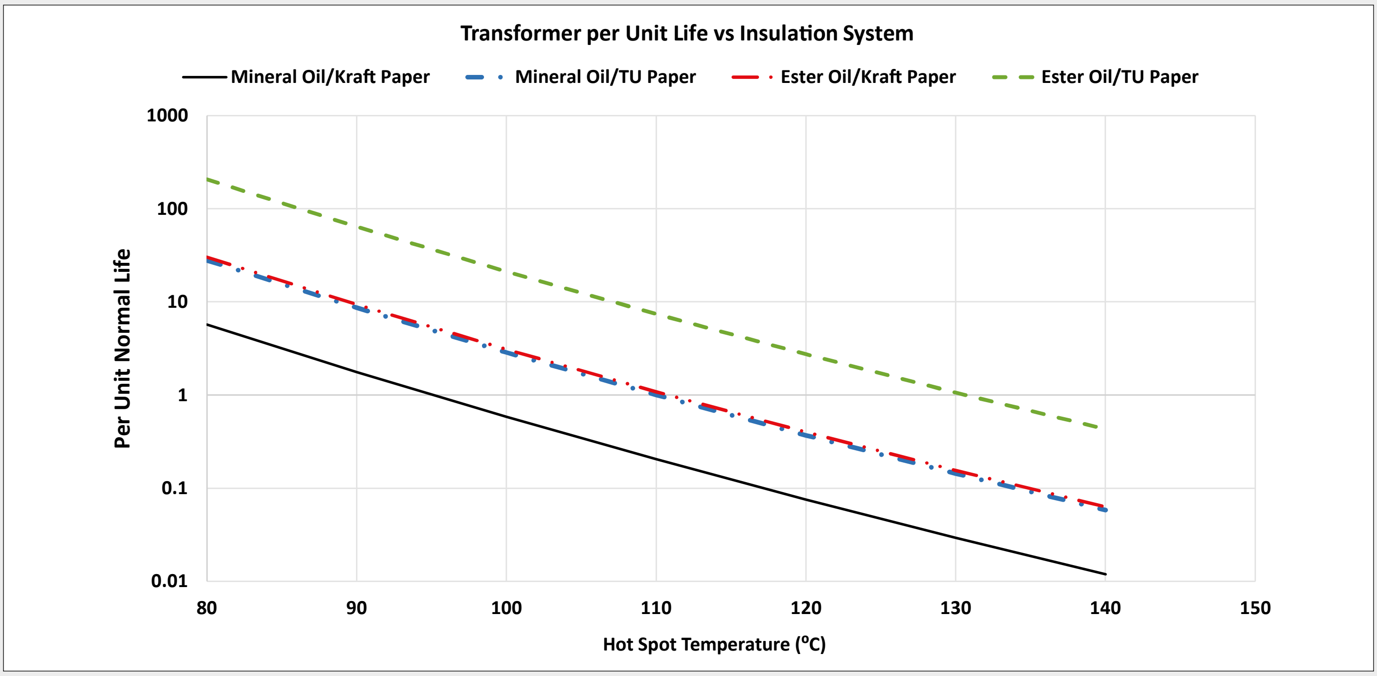

Figure 3. Transformer per unit life Vs. hot-spot temperature

Distribution transformers with a hot-spot temperature rating of 130 °C can have additional loading capability up to 30 % without additional loss of life

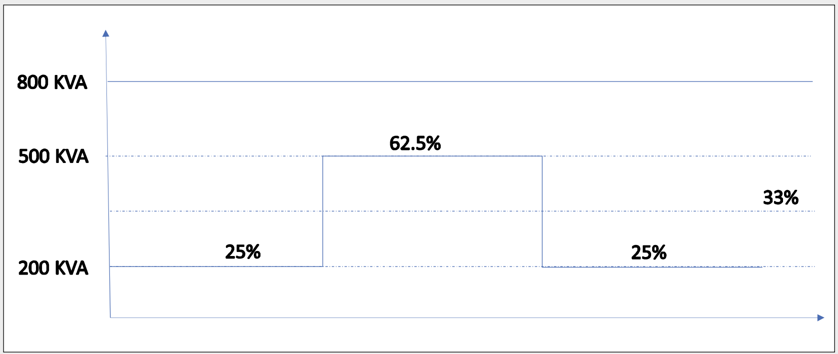

Figure 4. Sustainable rated transformer using ester fluid/TU paper: illustration

Table 13. Combinations of no-load and load loss for 800 kVA meeting MEPS efficiency limits

Values	Peak rated 800 kVA
Rated temperature rise limits	90/95/110 K
Rated losses #1 (NLL/LL)	750/8500 W
Rated losses #2 (NLL/LL)	650/6500 W
Rated losses #3 (NLL/LL)	650/7500 W
Rated losses #4 (NLL/LL)	585/6000 W

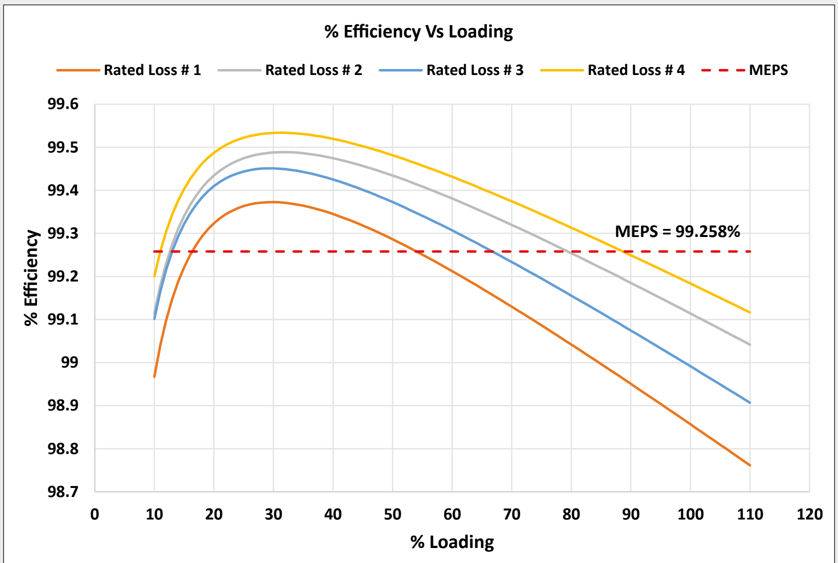

Figure 5. Efficiency vs. loading of 4 different designs of 800 kVA

life when operated at a hot-spot (and also average winding rise) temperature that is 30 °C higher than their mineral oil / kraft paper equivalents.

Higher moisture solubility limits, drying of paper by absorption of dissolved moisture with hydrolysis, and trans-esterification mechanisms support this improved life performance of cellulose insulation in natural esters, and these facts are now widely published [18]. In IEEE c57.91-2011 [19], it was estimated that, roughly, an increase by 1 % of loading accounts for 1 °C of average winding temperature rise. Thus, distribution transformers with a hot-spot temperature rating of 130 °C can have additional loading capability up to 30 % without additional loss of life, i.e., 800 kVA natural ester-filled distribution transformer can now support 1000 kVA (800 x 1.3) without any additional loss of life. This type of transformer selection is referred to as “sustainable” rated transformers (Fig. 4).

The MEPS efficiency limit for 800 kVA at 50 % loading = 99.258 % as per AS 2374.1.2-2003 (R 2016). Let us consider four different transformer designs with the following characteristics shown in Table 13.

Based on the efficiency vs. loading characteristics in Fig. 5 as per values of Table 13, all four designs pass the MEPS efficiency limit for 800 kVA at 50 % loading. Assuming a good balance on the load loss efficiency and loss capitalization, the rated losses #4 is selected. If there is no loss capitalization, rated losses #1 will be the cheapest option in terms of the purchase price.

The new specification for a sustainable transformer would have the characteristics as per Table 14.

4.1 CO_2 footprint calculation from operation of sustainable transformer

Utilizing the NLL and LL values for 800 kVA, the following can be calculated as in Table 15.

Table 14. Specification characteristics for sustainable rating transformer

	Peak rated 1000 kVA	Sustainable rated 800 kVA
Insulation	Kraft paper / mineral oil	TU paper / ester fluid
Rated temperature rise limits	60/65/78 K	90/95/110 K
Rated losses	770/9000 W	585/6000 W

NIST, the National Institute of Standards and Technology, also calculated the carbon footprint for the production of natural ester fluid, and it is 55 times lower than naphthenic-based transformer mineral oil

4.2 CO_2 footprint calculation from transformer oil production

NIST, the National Institute of Standards and Technology, also calculated the carbon footprint for the production of natural ester fluid, as listed in Table 16.

4.3 Total CO_2 for 800 kVA transformer for 30 years

Total CO_2 emission for a 800 kVA transformer's lifetime is shown in Table 17 and Table 18.

4.4 TCO including environmental costs

C_{pp}: for 800 kVA is $32,000 (considering a 15 % higher price for an ester-filled transformer than a mineral oil-filled transformer for the same rating). Utilizing the loss capitalization, the following is calculated as in Table 19.

Over the transformer lifetime, more than 30 tons of CO_2 emission can be reduced by replacing peak-rated transformers with sustainable rated transformers

Table 15. Total CO_2 emission / MWh calculation for sustainable transformer

Parameters	800 kVA
NLL	585 W
LL	6000 W
NLL/year (kWh)	5124.6 kWh
LL/year (kWh) (at 33 % load factor)	5723.78 kWh
Total losses/year (kWh)	10848.38 kWh
Total losses/year for 30 years	325.45 MWh
Total CO_2 emission for 30 years (tons)	198.18 tons

Table 16. Total CO_2 emission from BEES carbon footprint calculator: natural ester fluid

Category	CO_2 emission (g per 1000 L)
Raw materials	-381,590
Manufacturing	160,212
Transportation	71,498
Use	153,450
End of life	30,690
Sum	34,260 = 0.00003426 tCO_2/litre

Table 17. Total CO_2 emission for oil needed in transformer

Parameters	800 kVA
Amount of ester fluid (litre)	485 L
Total CO_2 emission for producing ester fluid	0.017 ton

Table 18. Total CO_2 emission for transformer lifetime: 800 kVA

Parameter	Value of CO_2 generated
Operation of transformer for 30 years	198.18 tons
Production of ester fluid (485 litres)	0.017 tons
Core steel (1030 kg) at 4 kg CO_2/kg	4.12 tons
Insulation (30 kg) at 1.5 kg CO_2/kg	0.045 tons
Winding material Al (530 kg) at 8.96 kg CO_2/kg	4.75 tons
Steel (470 kg) at 1.8 kg CO_2/kg	0.846 tons
Total CO_2 generated	208 tons
Total CO_2 costs	$10,400

Table 19. TCO comparisons – peak rated vs sustainable rated

Design	No-load loss (W)	Load loss (W)	Purchase price (estimated)	TCO without C_{env}	TCO with C_{env}
1000 kVA	770	9000	$35,000	$62,980	$74,980
800 kVA	585	6000	$32,000	$56,296	$66,700

Table 20. TCO savings earned from sustainable rated transformers

	Peak rated transformer	Sustainable rated transformer
TCO (30 years)	$75,000	$66,700
Savings	11.07 %	

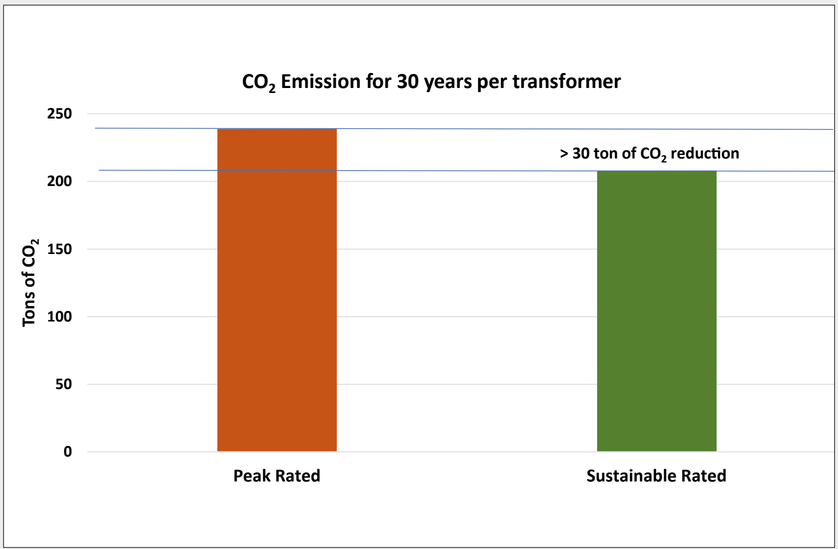

Figure 6. CO_2 emission savings over transformer lifetime: peak rated vs. sustainable rated

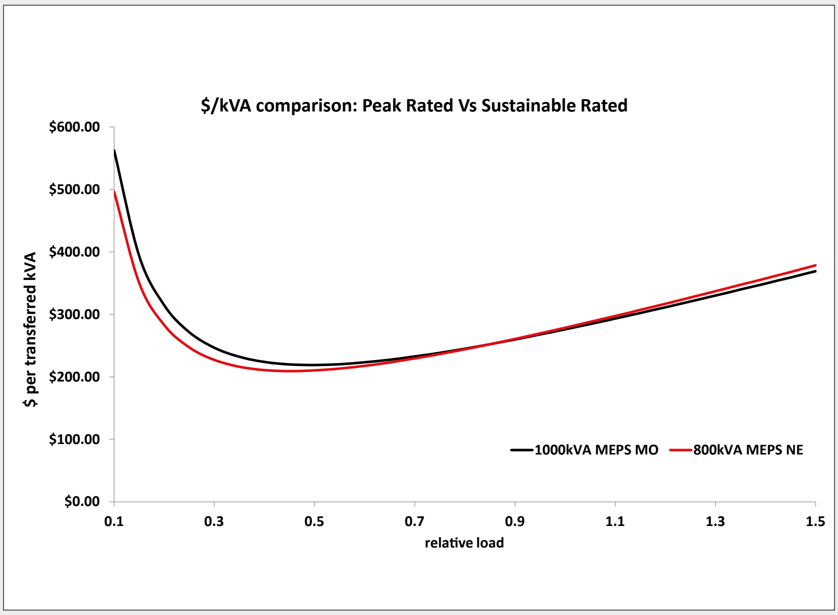

Figure 7. $ per transferred kVA over transformer lifetime: peak rated vs. sustainable rated (Table 21 values)

4.5 Savings

The following savings can be easily identified for one transformer alone:

A) CO_2 savings

Over the transformer lifetime, more than 30 tons of CO_2 emission can be reduced (Fig. 6) by replacing peak-rated transformers with sustainable rated transformers.

B) TCO savings

Over the transformer's lifetime, by replacing peak rated transformers with sustainable rated transformers, a savings of 11.07 % can be achieved (Table 20).

C) Loading ($) limits of sustainable rated transformers

The increase in average load of sustainable rated transformers depends on the designed losses, and average load of the peak rated transformers, and there is a limit to this margin. This margin can be estimated by calculating the transferred $/kVA for both 1000 kVA and 800 kVA using the following formula:

$$\frac{\$}{kVA} = \frac{C_{pp}+(A\times NLL)+(B\times LL)+Environmental\ Costs}{\%\ KVA_{peak\ rated}}$$

Using the values in Table 21, $/kVA for both 1000 kVA and 800 kVA is shown in Fig. 7.

It can be clearly seen that below 80 % load for 1000 kVA transformer, it is cheaper to operate the 800 kVA sustainable rated transformer. Thus, if intention is to operate transformers always below 50 % loading for reliability purposes, it is more

Table 21. The cross-over point determination between peak and sustainable rated transformers

Design	No-load loss (W)	Load loss (W)	Purchase price (assumed)	Energy cost rate for 1st year of operation	Discount rate	Increase in energy rate	Lifetime
1000 kVA	770	9000	$35,000	0.1 $/kWh	5%	5 %	30 years
800 kVA	585	6000	$32,000	0.1 $/kWh	5%	5 %	30 years

economical to use a sustainable rated transformer!

The cross-over point between peak and sustainable rated transformers depends on factors such as NLL, LL, A, B, t_{CO2}/MWh and must be evaluated when considering the use of sustainable rated transformers.

If we compare other designs, the cross-over point can be around 40 %, as shown in Fig 8, which is a comparison of the two designs shown in Table 22.

It is always recommended to conduct a sensitivity analysis when choosing sustainable rated transformers.

Conclusions

The carbon footprint and total cost of ownership of a peak-rated transformer can be easily reduced by combining the advantages of sustainable ester fluids. The same level of network reliability is maintained, which is the main apprehension behind the uptake of sustainable transformer ratings. With such a strategy in place, end users can reap the financial benefits of having sustainable rated transformers – an alternative design that provides a reduction in carbon footprint while operating transformers!

It is seen that the 30-year carbon emission of 238 tons per transformer (peak rated 1000 kVA) can be reduced to 208 tons, which is around 30 tons from only one transformer while using a sustainable rated 800 kVA transformer and delivering the same load. If one medium-size utility buys around 200 similar transformers per year, the potential would be 6000 tons of CO_2 reduction. If more and more end-users switch to ester-filled sustainable transformers, the potential to reduce global CO_2 emissions would be tremendous, which will help to create a stronger, greener, and more sustainable power grid.

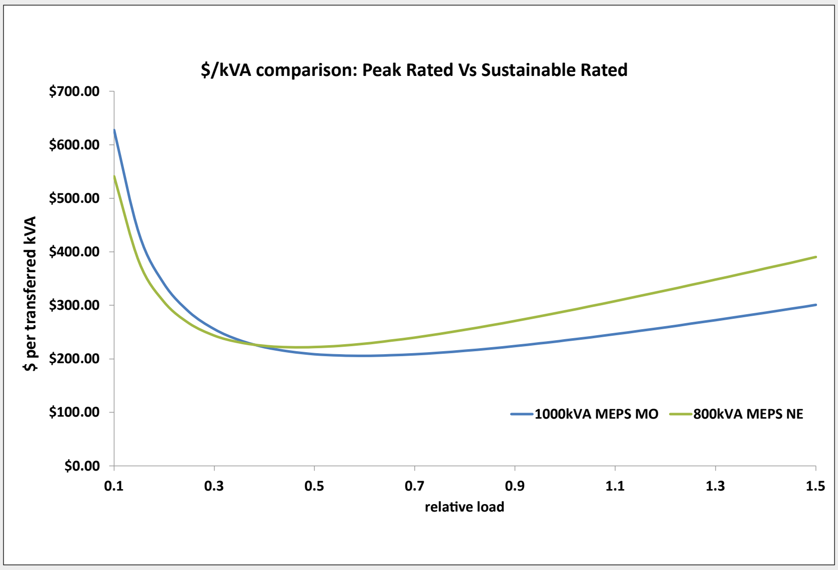

Figure 8. $ per transferred kVA over transformer lifetime: peak rated vs. sustainable rated (Table 22 values)

Table 22. The cross-over point determination between peak and sustainable rated transformers

Design	No-load loss (W)	Load loss (W)	Purchase price (assumed)	Energy cost rate for 1st year of operation	Discount rate	Increase in energy rate	Lifetime
1000 kVA	1200	8000	$35,000	0.1 $/kWh	5 %	5 %	30 years
800 kVA	870	7000	$32,000	0.1 $/kWh	5 %	5 %	30 years

End users can reap the financial benefits of having sustainable rated transformers – an alternative design that provides a reduction in carbon footprint while operating transformers

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