The manufacturers and users have defined lists of no-load losses and load-losses for transformers a long time ago in regard to the capability of raw material and design aspect

Optimization of transformers efficiency

Cost optimization and reduction of CO_2 emission

1. Introduction

The targets of the 20/20/20 program from European Union countries has led to review of all transformers' performances.

The 2020 climate package is a set of binding legislation which ensure the EU meets its climate and energy targets for the year 2020.

The package sets three key targets:

- 20 % cut in greenhouse gas emissions (from 1990 levels)
- 20 % of EU energy should come from renewables
- 20 % improvement in energy efficiency

The targets were set by EU leaders in 2007 and enacted in legislation in 2009. They are also headline targets of the Europe 2020 strategy for smart, sustainable, and inclusive growth.

The EU has taken action in several areas to meet the targets and transformers are a part of the Commission Regulation requirements (EC) No 548/2014 of 21 May 2014 and amendment of 2019 [1] on implementing Directive 2009/125/EC of the European Parliament and of the Council concerning small, medium and large power transformers.

Starting with July 1, 2015, transformers have to fulfil minimum energy efficiency requirements. The next milestone in the improvement of their performance will be happening in 2021. The resulting energy savings have been estimated at 16 TWh per year from 2020 onwards, which corresponds to 3.7 Mt of avoided CO_2 emissions. This is equivalent to saving half of the annual electricity consumption of Denmark (32 TWh) per year.

ABSTRACT

Following the first article published in July concerning the optimisation of total cost using the PEI for large power transformers [4], this article is related to optimization of the total cost of medium power transformers use after they have had their losses fixed by the regulation.

KEYWORDS

eco-design, efficiency, losses, CO_2 emission, total owner cost, PEI

A ratio between load losses and no-load losses which leads to optimum efficiency is approximately 8 to 10 and it was established long time ago

This review of performance done by the amendment adopted in 2019 has also shown the way in which the specification of transformers which were done are economically crucial for the user in regard to money saved or lost.

The range of transformers in the European countries is divided into 2 families; one are repetitive transformers in general, with a nominal power less than 3,15 MVA where the standardization of the components is relevant in terms of cost and another without repetitive transformers (without series) where the standardization components are not possible nor relevant. Therefore, it has been chosen to have fixed losses for transformer that have a rated power less than 3,15 MVA and have identical components. Those transformers have the optimum price for the users.

After a long study, the European Commission with main stakeholders or their representatives (TD Europe for the manufacturers, ENTSO for utilities, CENELEC for standardisation bodies, etc.) have decided to fix 2 levels of efficiency corresponding to 2 levels of losses for the transformers below 3,15 MVA first being TIER 1 level from 2015 and the second (with even lower losses) being TIER in 2021.

The following tables are defined for step down or step up transformers with one winding with $U_m \le 24$ kV and the other one with $U_m \le 3{,}6$ kV. Table 1 is for liquid immersed transformers and table 2 for dry-type transformers. For other levels of voltage or different special transformers these levels are corrected.

Table 1. Losses level for liquid immersed transformers

Rated power	TIER 1 P0	TIER 1 Pk	TIER 2 P0	TIER 2 Pk
kVA	W	W	W	W
≤ 25	70	900	63	600
50	90	1100	81	750
100	145	1750	130	1250
160	210	2350	189	1750
250	300	3250	270	2350
315	360	3900	324	2800
400	430	4600	387	3250
500	510	5500	459	3900
630	600	6500	540	4600
800	650	8400	585	6000
1000	770	10500	693	7600
1250	950	11000	855	9500
1600	1200	14000	1080	12000
2000	1450	18000	1305	15000
2500	1750	22000	1575	18500
3150	2200	27500	1980	23000

Table 2. Losses levels for dry-type transformers

Rated power	TIER 1 Pk	TIER 1 P0	TIER 2 Pk	TIER 2 P0
kVA	W	W	W	W
≤ 50	1500	200	1700	180
100	1800	280	2050	252
160	2600	400	2900	360
250	3400	520	3800	468
400	4500	750	5500	675
630	7100	1100	7600	990
800	8000	1300	8000	1170
1000	9000	1550	9000	1395
1250	11000	1800	11000	1620
1600	13000	2200	13000	1980
2000	16000	2600	16000	2340
2500	19000	3100	19000	2790
3150	22000	3800	22000	3420

In the table, the level of no-load losses is called P0 and the level of load losses is called Pk.

The TIER 1 gives a level of losses applicable in 2015 and the TIER 2 gives a level of losses applicable in 2021.

2. How the level of losses has been chosen?

The manufacturers and users have defined lists of no-load losses and load-losses for transformers a long time ago. The list for dry type is different than the list of immersed transformers because the structure of dry type (needs more important electrical distances and more surface to cool) results in bigger transformers therefore, it is not physically possible to reach the same level of losses.

These lists were done in regard to the capability of raw material and design aspect. In fact, the structure of the transformers demands the ratio between the no-load losses and load losses for both physical and economic reasons. A ratio of approximately 8 to 10 between load losses and no-load losses was established long time ago for the aforementioned reasons. That led to optimum efficiency with a load factor in between 0,3 and 0,35. The load factor in this case is the square root of the ratio of no-load losses and load losses.

The efficiency of transformers is given with the reference to the IEC standard by using the formula:

$$\textit{Efficiency} = \textit{Rated power} \times \textit{Kfactor} - (\textit{No-load losses} + \textit{Load losses} \times \textit{Kfactor}) / (\textit{Rated power} \times \textit{Kfactor}) \quad (3.1)$$

Year after year, the European electrotechnical committees of each country member have defined levels of losses that we will call standardized losses. These values have been defined with the help of manufacturers and users and have been decreased with the improvement of the raw materials (magnetic steel, insulation, copper, etc.) and design.

The levels of losses for the regulation have been chosen by eliminating the worst lists that existed in the standardised losses and only more efficient values were kept for the TIER 1. The EN 50464-S1(2007) [2] gave 4 lists of load losses (Dk to Ak) and 5 lists of no-load losses (E0 to A0) for immersed transformers with a variation of roughly 100 % between the best and the worst lists. Standardisation working groups chose to give the letter A to the lowest losses and the last letter in the alphabet for the highest losses. The study done by the European Commission showed that economic reasons lead researchers to choose, initially, a soft reduction for load-losses (middle of the current list) by choosing the case Ck and Bk and strong reduction for no-load losses by taking the best list of no load-losses by choosing A0.

The EN 50541(2011) [3] gave 2 lists of load losses (Bk to Ak) and 3 lists of no-load losses (C0 to A0) for dry type transformers with a variation of roughly 10 % and 30 % between the best and the worse lists respectively. The study done by the Commission also showed that economic reasons lead researchers to initially choose to use the Bk list for smaller transformers and Ak list for larger transformers for load-losses and the best A0 list for no-load losses. At this time, the choice for the TIER 1 regarding the dry type transformers are more ambitious than those of the immersed type.

For the TIER 2, the best value of load losses (Ak) and the reduction of 10 % as the best level of no-load losses (A0-10 %) has been chosen for liquid immersed transformers. For dry type, the level of load losses was improved for smaller transformers by removing the Ak list and using the list A0 with 10 % reduction (A0-10 %). These changes were possible thanks to the improvement of the magnetic steel performance that became more and more efficient. Magnetic steel manufacturers improved grain orientation and reduced sheet thickness, reducing unit losses by 2. It is noted that with the material used today it will be difficult to significantly reduce the loss values again for both immersed and dry type transformers. Some improvements in the technology of the transformers will still improve the energy efficiency, but in practice, only the improvement in the performance of magnetic steel will allow a larger and global improvement in transformer efficiency.

Reduction of losses was possible thanks to the improvement of the magnetic steel performance, such as improved grain orientation and reduced sheet thickness, reducing unit losses by 2

3. What is the impact of the rated power choice according to the average user's consumption?

Each customer has different needs in terms of energy consumption. This consumption is variable, but it is possible to calculate the load equivalent with a simple method and to evaluate the long-term trend of consumption. The important thing is to determine the average load of transformer for the coming years in order to make the best economic choice given the price of transformer and the price of energy consumed by transformer.

The transformers are sized for average load in kVA and can accept some temporary overload that can be compensated by underload without degradation of the life duration of the transformers. The first consideration when the user buys transformers can be to buy a transformer that is close to the average load forecasted by its consumption and consider that the temporary overload will be possible for the transformers and will be compensated by the underload. Such a consideration will not be a good one because of the cost of the energy consumed by the transformers themselves with the load losses that increase quickly with the square of the load. To illustrate this fact, we have chosen the following example.

In the example, we have considered an average load of 400 kW with cos φ =1 and the calculation has been done on a TIER 2 400 kVA transformer. Several other examples are shown to explain this issue.

The data taken to make this calculation is a life duration of 40 years with a cost of 0,15€ / kWh and an interest rate of 2 %. The values taken for the calculation are usual values. The time is the usual time of use and the cost of kWh taken is close to the average cost of the kWh in the EU. It should be noted that the higher the cost of electricity is, the longer the duration of use of the transformer is, the higher the TCO (total cost of ownership) is.

Figure 1 shows the cost of energy consumed for a TIER 2 400 kVA liquid

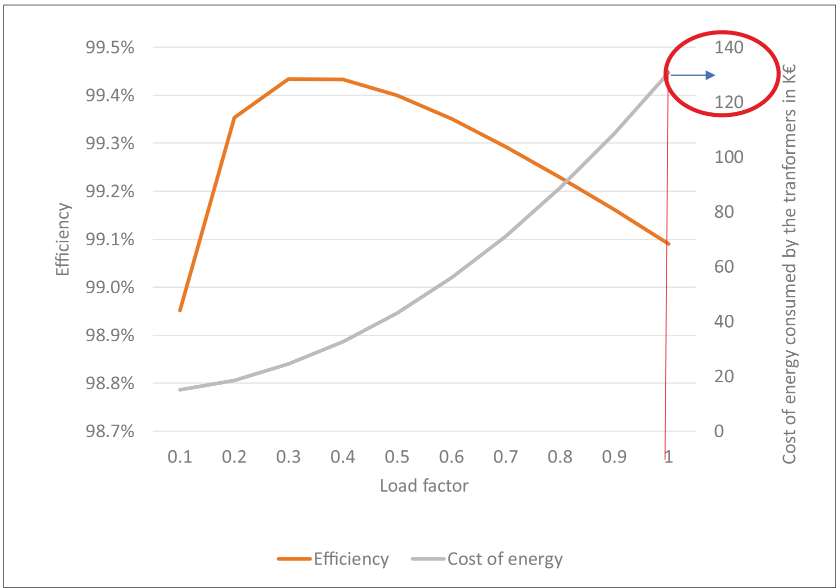

Figure 1. Cost of energy consumed by the transformer f (load fctor)

Improvements in the technology of transformers will improve the energy efficiency, but in practice, only the improvement in the performance of magnetic steel will allow a larger and global improvement of efficiency

immersed transformer loaded on average at 400 kW at cos φ=1 equivalent to 400 kVA.

In this case the load factor is obviously 1.

The level of losses given by the regulation for no-load losses is 387 W and for load-losses 3250 W.

On this curve, the peak efficiency for this transformer is around 0,345 (square root of the ratio of no-load losses divided by load losses) and the cost of use for a period of 40 years is €130,000.

The price of the transformer in this case represent less than 10 % of the cost of energy consumed.

Figure 2 shows the cost of energy consumed for TIER 2 800 kVA liquid immersed transformer loaded on average at 400 kW at cos φ=1 equivalent to 400 kVA.

In this case, the load factor considered is 0,5 corresponding to 400 / 800 kVA.

On this curve, the peak efficiency for this transformer is around 0,31 (585 W for no-load losses and 6000 W for load-losses) and the cost of use for a period of 40 years is €75,000.

This shows that it is better to buy a higher rated power transformer for this use because that will lead to a saving of €55,000 (130-75) in terms of energy cost. It is true that the price of the 800 kVA transformer is higher that a 400 kVA one but the price of the transformer is representing less than 15 % of the total cost of use and definitively, the user has the interest in buying a higher rated power transformer. Do this rated power represent the optimum total cost for user (TCO Total cost for owner)?

A third calculation has been done to try and find the optimum cost.

Figure 3 shows the cost of energy consumed for a TIER 2 1600 kVA liquid immersed transformer loaded on aver-

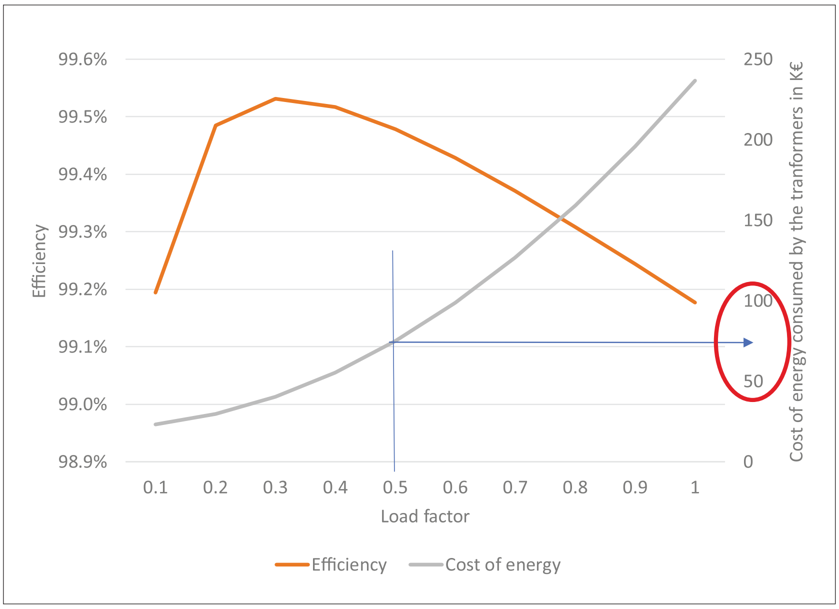

Figure 2. Cost of energy consumed by the transformer f (load factor)

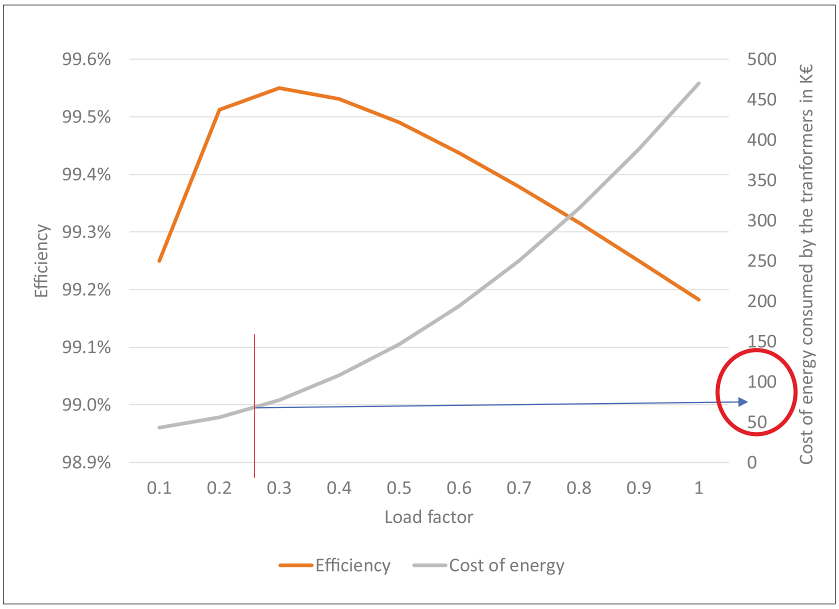

Figure 3. Cost of energy consumed by the transformer f (load factor)

It is important to determine the average load of transformer for the coming years in order to make the best economic choice given the price of transformer and the price of energy consumed by transformer

As the price of the transformer is representing only a fraction of the total cost of use, the user has the interest in buying a higher rated power transformer

age at 400 kW at cos φ=1 equivalent to 400 kVA.

In this case, the load factor considered is 0,25 corresponding to 400 / 1600 kVA.

On this curve, the peak efficiency for this transformer is 0,3 and the cost of use for a period of 40 years is €66,000.

That show it is better to select a higher rated power transformer for this use because that will lead to a saving of €64,000 (130-66) in terms of energy cost. It is true that the price of the 1600 kVA transformer is higher that a 400 kVA, but the price of the transformer represents less than 25 % of the total cost.

In this case, a more accurate study has to be conducted because the saving between, for example, a 800 kVA and a 1600 kVA is only €11,000 (75-66). The cost of the transformer has to be taken into account to determine what is the best choice for the optimum TCO.

The table below shows the cost difference between the 3 different cases mentioned before with an energy cost of 0,15€ / kWh, 40 years life duration and an interest rate of 2 %.

4. What is the optimum cost of use?

Figure 4 represents the difference of cost of use for liquid immersed transformers according to the rated power bought by the user and shows what the optimum is.

The price of the transformer increases with the rated power and the total cost (use + price of transformer) must be considered. The curve shows that the optimum, in terms of saving energy, is the 1250 kVA transformer with a saving of €65,000 when compared to the 400 kVA transformer.

According to the price of the transformer made by the suppliers, the optimum for this application, 400 kW cos φ=1, is to buy 1000 kVA transformer. With the difference in cost of use with the 800 kVA transformer being more than €6000, this difference is less that the cost difference between an 800 kVA transformer and 1000 kVA transformer.

These different case studies show that choosing a transformer with a ratio between the rated power of transformer and the average of energy consumption of around 2.5 gives, in most of the cases, the best compromise for the user in term of TCO.

5. What is the impact of choosing between TIER 1 and TIER 2?

A study done by European Commission has shown that a TIER 2 transformer is always cheaper that a TIER 1 transformer in terms of cost of use regardless of the choice of the rated power for an average load. Only in particular cases with high dimensions or weight constraints should the optimization be decided upon with more accuracy.

Substations are generally standardized in terms of dimensions for a maximum rated power such as, for example, 630 kVA. If, in the past, the sizing of these substations was made with the transformer dimensions of the time, difficulties may arise when one needs to install new transformers. Substation floors in some countries can also be limited to 2500 kg and this makes it necessary to optimize other 1000 kVA devices.

Calculation has been done to show the difference between TIER 1 trans-

Table 3. Total cost of use for 40 years for a load of 400 kW at cos φ=1 with different rated power

Rated power kVA	Load factor	No-load losses W	Load losses W	Cost of use k€
400	1	387	3250	130
800	0,5	585	6000	75
1600	0,25	1080	12000	66

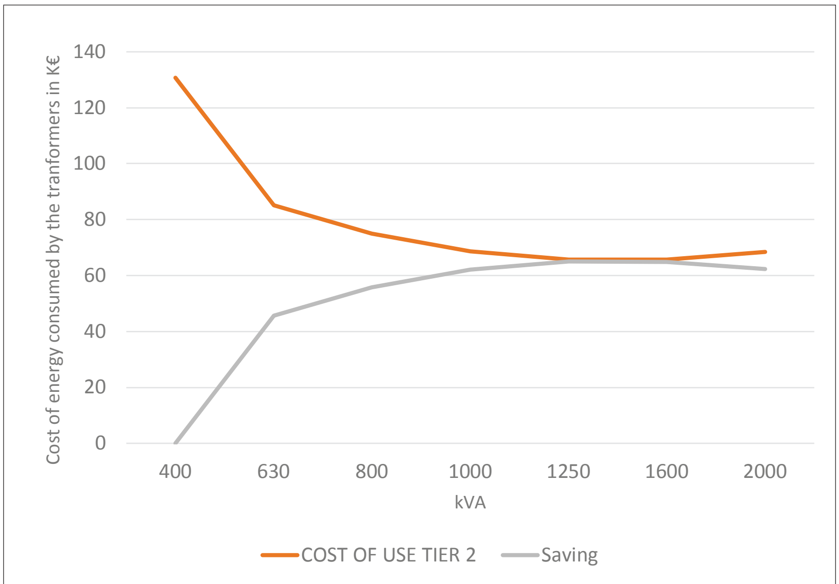

Figure 4. Cost of use of T2 transformer for load of 400 kW at cos φ=1

Case studies show that choosing a transformer with a ratio between its rated power and the average of energy consumption of around 2.5 gives, in most cases, the best compromise for the user in term of TCO

formers and TIER 2 transformers for the same application – 400 kW at cos *φ*=1.

Figure 5 shows that this cost difference, for liquid immersed transformers, is always higher than €5000 for a period of 40 years which justifies the decision to buy TIER 2 transformer.

Conclusion

To optimize the cost of the use of transformers, users must be aware of energy consumption. Therefore, they must order transformers with a rated power vastly superior to their average energy consumption forecasted for the long term.

For any European country, the no-load losses and load losses are defined for the transformers for at least up until 2025 as the future revision of the regulation will start in 2023 and at this moment nobody knows if it will be possible and economically reasonable to again improve the efficiency of the transformers. The user should make a choice according to the level of losses defined for 2021 (TIER 2).

If the lifetime expectancy is 40 years and the cost of energy is around 0,15€ / kWh then the rated power chosen must be at least 2,5 time higher that the average energy consumption to obtain the cheapest total owner shift cost. Large CO_2 emission reduction will be made during the life span of the transformer alongside the already mentioned money saved for the user and the owner.

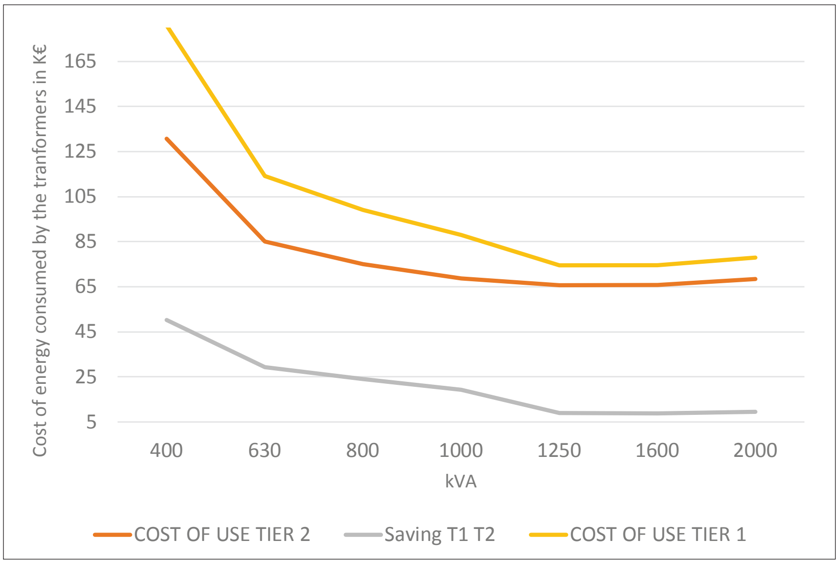

Figure 5. Difference of cost of use for TIER 2 transformer for a load of 400 kW at cos *φ*=1

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