MITIGATION OF LOCK-IN EFFECT FOR COMPACT SUBSTATIONS WITH TRANSFORMERS MEETING FUTURE EU EFFICIENCY REGULATIONS

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ABSTRACT

The subject addressed is a technical challenge faced by transformer manufacturers and users related to the possibility of replacing distribution transformers after new European regulation on transformer efficiency comes into force in 2021 (Tier 2 of Commission Regulation 548/2014). The Tier 2 will further reduce losses allowed for new distribution transformers to be installed in Europe.

The solution evaluated in the article is based on actual loading of transformers in rural substations (25-30%). Rarely are these transformers loaded to a higher loading and utilize their nameplate capacity. Therefore, it could be proposed to specify a reduced power rating for new units. The proposed de-rated transformers using insulation of higher thermal class would have sufficient capacity to supply the typical power demand. The use of higher class insulation materials in those transformers would allow safe overloading. It could also reduce Total Ownership Cost (TOC). The article introduces newly available innovative insulation material and analyses aspects of this new transformer solution vs. conventional transformer design.

INTRODUCTION

The subject addressed in this article is a technical challenge faced by transformer manufacturers and users related to the possibility of replacing distribution transformers after the new strict requirements of European regulation on efficiency in transformers come into force in 2021 (Tier 2 of European Commission Regulation 548/2014 [1]).

The Tier 2 of the Regulation will further reduce losses allowed for new distribution transformers to be installed in Europe (for small distribution transformers change of loss levels from current A_0/C_k down to A_0-10%/A_k). Typically, it means that all new transformers using traditional materials would have to be slightly larger in size for reducing the losses in transformer cores and windings. This raises a concern for existing installations ("brownfield") where there is no additional space for installing larger equipment. In certain types of installations, the space for distribution transformers was designed tightly even for the currently available distribution transformers. This situation is called a "lock-in effect". It has been raised to the attention of the European Commission (EC) during consultations on Tier 2 of the Regulation.

One example is a compact kiosk substation like the one shown in Fig. 1. Installing a new transformer with lower losses and larger physical size could require the replacement of the entire substation or its modification, if that is even possible. This would imply a higher cost to the user than just replacement of the transformer itself. Similar concerns could apply to some installations in buildings or industrial sites.

DE-RATED TRANSFORMER WITH INSULATION SYSTEM OF HIGHER THERMAL CLASS

The solution proposed is based on the analysis of actual loading of transformers in typical rural compact substations in France. It shows that typical loading of distribution transformers is approximately 25-30% of transformer's nameplate power rating. Only rarely are these transformers loaded to a higher load, and required to utilize their full nameplate capacity. Therefore, it could be

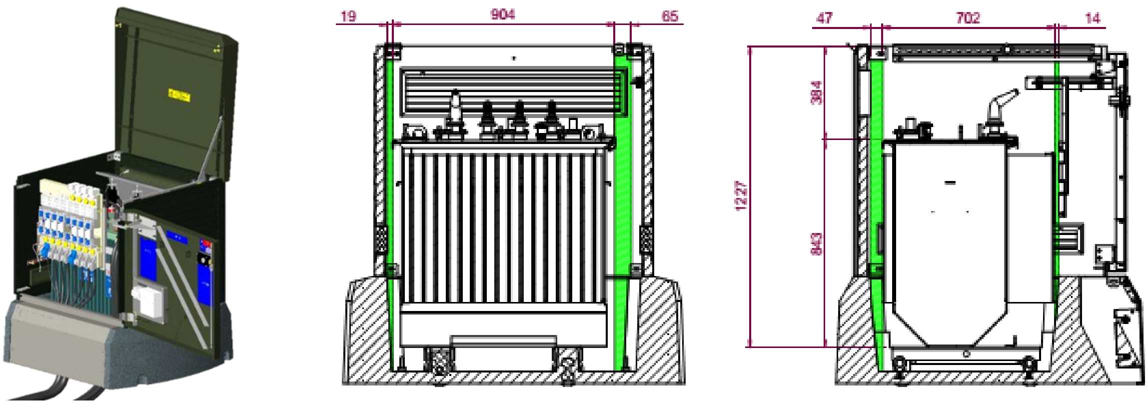

Figure 1. Compact substation – tailored size of a transformer not allowing for replacement with a larger unit

proposed to specify a reduced power rating for new transformers. This would allow **reducing the physical size of transformers while still meeting the EU efficiency regulation.**

The proposed de-rated transformers would use insulation materials of higher thermal class than the conventional design and **would be well suited to supply the typical power demand. Plus, they would have the capability of supplying greater than nameplate power output temporarily.** The use of higher class insulation materials in those transformers would allow safe overloading the transformers without impacting their reliability or expected lifetime.

Comparison of dimensions

Tables 1 and 2 show example comparisons of transformers designed with different insulation systems and power ratings. Comparisons are based on design calculations made by Cahors.

Table 1. Comparison of dimensions: conventional transformer P_i = 160 kVA vs. de-rated transformer with higher class insulation system P_{i-1} = 125 kVA

	P_i=160 kVA EC Tier 1 A_0/C_k	P_i=160 kVA EC Tier 2 A_0-10%/A_k	P_{i-1}=125 kVA EC Tier 2 A_0-10%/A_k
L (mm)	904	**995!**	**940**
W (mm)	702	**772!**	**720**
H (mm)	1152	1160	1200
M (kg)	785	1005	870

Table 2. Comparison of dimensions: conventional transformer P_i = 250 kVA vs. de-rated transformer with higher class insulation system P_{i-1} = 200 kVA

	P_i=250 kVA EC Tier 1 A_0/C_k	P_i=250 kVA EC Tier 2 A_0-10%/A_k	P_{i-1}=200 kVA EC Tier 2 A_0-10%/A_k
L (mm)	1072	1180	1110
W (mm)	748	**830!**	**770**
H (mm)	1270	1270	1270
M (kg)	990	1250	1100

Transformers of rated power P_i are designed with conventional insulation system based on cellulose insulation and mineral oil. Transformers with reduced power P_{i-1} are designed as per IEC/EN 60076-14 [2] using high temperature insulation systems based on cellulose paper enhanced with aramid. Ester liquid is used as cooling medium.

For the 160 kVA transformer, the change of loss requirements from Tier 1 to Tier 2 would increase the length and the width of the transformer beyond acceptable limits for the installation in the compact kiosk substation. To accommodate for that, costly (and time consuming) expansion of the substation size could be needed, or complete replacement of the substation with a new one, that would allow more space for the new transformer. Instead of that, a transformer of 125 kVA could be proposed. It would fit the space available allowing immediate quick replacement of the equipment.

With the transformer having smaller physical size the environmental impacts would be reduced vs. the conventional Tier 2 - 160 kVA solution since less raw materials would be required for manufacturing. (Although, the transformer would be a bit larger than the original Tier 1 unit.) Additionally, the biodegradable green liquid would further contribute to environmental benefits.

Loading

The typical load of rural compact substations in Europe is approximately 25% of their nameplate power so the expected load on the subject transformer would be approximately 40 kVA. Hence, the 125 kVA unit would be sufficient to supply the typical power load. If higher loading is needed during operation of the transformer, the unit could be easily overloaded to the original 160 kVA. The insulation system based on alternative materials would allow for this overloading or even beyond without impact on transformer reliability or long-term life expectancy. The calculated life expectancy of the proposed solution is in fact improved vs. the conventional design. This aspect will be discussed further in next sections of this article.

Transformer Cost

Tables 3 and 4 present example comparisons of transformer cost, depending on the design solution chosen (calculations by Cahors). Two sizes of distribution transformers are analysed: 160 kVA de-rated to 125 kVA, and 400 kVA de-rated to 315 kVA.

Table 3. Cost comparison for transformer 160 kVA and unit de-rated to 125 kVA (TPC transformer as per IEC/EN 60076-13 and EN 50588-1)

	160 kVA EC Tier 1 A_0/C_k	160 kVA EC Tier 2 A_0-10%/A_k	125 kVA EC Tier 2 A_0-10%/A_k
Purchase price (with mineral oil)	100%	**128%**	-
Purchase price (with ester liquid)	109%	**138%**	**128%**
TOC @ 40 kVA, 25% of 160 kVA (with ester liquid)	TOC_{160}	**TOC_{160}+10%**	**TOC_{160}+4%**

Table 4. Cost comparison for transformer 400 kVA and unit de-rated to 315 kVA (transformer as per EN 50588-1)

	400 kVA EC Tier 1 A_0/C_k	400 kVA EC Tier 2 A_0-10%/A_k	315 kVA EC Tier 2 A_0-10%/A_k
Purchase price (with mineral oil)	100%	**135%**	-
Purchase price (with ester liquid)	112%	**147%**	**137%**
TOC @ 100 kVA, 25% of 400 kVA (with ester liquid)	TOC_{400}	**TOC_{400}+7%**	**TOC_{160}+3%**

It is obvious that the transformers with higher acceptable losses as per Tier 1 of the EC Regulation are the cheapest solutions. The loss reduction required by the Tier 2 requirement increases the unit cost significantly, up to 28-35% depending on the rating of the transformer. This is typically related to the use of larger conductors for reducing winding losses or the use of larger core cross section for reducing the core losses. Alternate ways to decrease losses are by using a higher grade of core steel, or copper could replace aluminum in the windings, both of which contribute to an additional cost increase.

If the end user prefers the use of green vegetable oil in their transformers, then an additional cost increase would be observed. This would be related to the cost of the green oil vs. mineral oil and the design being adapted for typically lower cooling performance of the ester liquids, different dielectric performance, etc. This additional cost increase would be 9-12% in the presented cases.

The proposed solution for a small replacement transformer of reduced nameplate power rating would provide a benefit of one-to-one replacement within the existing compact substation, but also would be very economical as compared to a conventional transformer meeting Tier 2 requirements.

The cost of transformers using optimized advanced insulation system would be **the same or within just 2% extra cost** when compared to conventional units filled with mineral oil and not fitting the existing installation limits (see Table 3 and 4). If compared to Tier 2 transformers filled with vegetable oil, the compact solution would provide direct cost saving of approximately 10%, which is significant.

But if the total installation cost is compared for the replacement of a transformer in a compact substation, the replacement with our new proposed solution would also eliminate the cost of:

- **purchasing of new compact substation (with larger dimensions),**
- **cost of installing it.**

In case of replacement of 160 kVA transformer in a compact substation with the de-rated 125 kVA unit, the total saving could be as high as 60% (based on the typical cost of substation and installation works).

Total Ownership Cost (TOC)

When looking at TOC, it can be seen that transformers with ester liquids with reduced losses to comply with Tier 2 requirements are more expensive in use than transformers meeting Tier 1 requirements. The increased purchase price of a Tier 2 transformer cannot be compensated by capitalized savings on power losses - at least not in the case of transformers with such a low load as typically seen in European rural networks. When comparing conventional transformer designs (with Kraft cellulose insulation) , the TOC increase for Tier 2 vs. Tier 1 transformers would be in the range of 7-10%.

However, the use of de-rated transformers would allow for savings on TOC. The initial purchase price would be lower and core losses would be lower. This is an important factor in case of transformers with low loading factor. **As per the Tables 3 and 4, the TOC cost saving for the de-rated Tier 2 transformers could be 4-6% depending on transformer size while assuming a 25% typical loading of currently installed transformers.**

The TOC comparison would change depending on the actual load of the given transformer. Higher loading would make winding losses more significant in the TOC formula. Therefore, the TOC for a smaller rating transformer would increase more with higher loads.

Fig. 2 presents TOC calculation example for a conventional transformer of 400 kVA and its de-rated replacement unit of 315 kVA. Average loading referred to the 400 kVA rated transformer is used as a base for the calculations. The chart shows that TOC for the de-rated transformer is lower at low average loads up to 30% (i.e. up to 120 kVA load). For higher average loads, which are not common today in European rural networks, the TOC would be higher for this de-rated transformer.

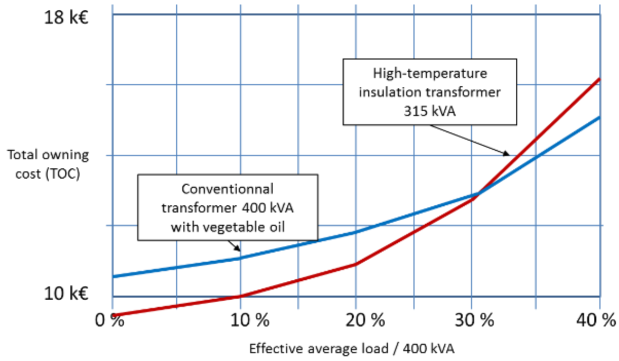

Figure 2. TOC example comparison for transformers 400 kVA and 315 kVA depending on average loading (load percentage related to 400 kVA)

TRANSFORMER DESIGN CONCEPT

Aramid enhanced cellulose paper

The design of transformers described in this article is based on new innovative insulation concept: cellulose paper enhanced with aramid. It is a unique insulating material comprised of high-quality electrical grade cellulose pulp and web-like binders made from high temperature aromatic polyamide polymer (aramid). Because the product is comprised of both cellulose and aramid ingredients, it exhibits properties that are between typical insulating papers made of cellulose and aramid based papers. [3]

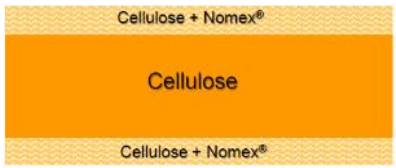

Figure 3. Schematic structure of aramid enhanced cellulose paper

Aramid papers (like DuPont™ Nomex®) have been used for years in special transformer applications resulting in transformer compactness and increased reliability by allowing long-term high temperature operation of insulation systems. **The new solution of cellulose paper enhanced by the aramid component has been developed in order to improve the thermal performance (thermal class) of cellulose paper and still offer an economical and affordable solution for the enhancement of transformer properties.** Long-term laboratory studies have proven the thermal performance of the new insulating paper to be better than common Kraft cellulose papers and thermally upgraded papers.

Fig. 4 shows life time characteristics of engineered cellulose paper Nomex® 910 (i.e. expected useful life vs. operating temperature). As seen in the chart, the tested paper could operate at 120°C in mineral oil (MO) or 140°C in representative natural ester and expected useful life would be equivalent to thermally upgraded Kraft paper

(TUK) operated at 110°C. The established thermal class is 130 in mineral oil and 140 in natural ester liquid (based on a sealed tube test as per IEEE C57.100-2011) [4, 5].

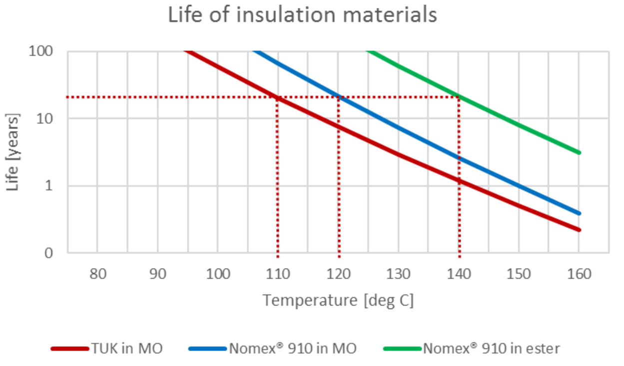

Figure 4. Life time characteristics and normal operating temperature of engineered cellulose paper Nomex® 910 in various liquids vs. thermally upgraded Kraft paper (TUK) in mineral oil

Transformer thermal design

The concept of small de-rated transformers is based on an insulation system combining aramid enhanced cellulose paper with vegetable oil (natural ester liquid). This allows for the designing of transformers at higher operational temperatures, as per IEC/EN 60076-14. However, the presented design concept assumes transformer ratings based on normal temperatures allowed for conventional designs as per IEC/EN 60076-2. Table 5 shows summary of design parameters for conventional and de-rated high temperature designs.

Table 5. Design parameters for conventional and de-rated high temperature transformers

	Conventional transformer	**High-temperature insulation transformer**	
	At rated power	**At rated power**	**At 1.25 p.u. rated power**
Liquid	Mineral or vegetable oil	Vegetable oil	
Solid insulation	Cellulose	Cellulose + Nomex® 910	
Industry standard	EN 60076-2	EN 60076-14	
Top oil rise	60 K	60 K	90 K
Winding average rise	65 K	65 K	95 K
Hot spot rise	78 K	78 K	110 K
Reference temperature (for load loss calc.)	75°C	75°C	115°C

The high temperature allowance of the insulation system is only intended for significant improvement of overloading capability of transformers. With this, the de-rated smaller units are still capable of handling loads equivalent to the original larger units while having longer theoretical insulation life as well.

Transformer aging evaluation

Fig. 5 shows the comparison of the relative aging rate for insulation materials used in the design of a conventional 400 kVA transformer (Kraft cellulose paper) and a high temperature 315 kVA transformer (aramid enhanced cellulose paper).

The relative aging rate was calculated based on hot spot temperatures within transformer windings at various loads. Then, these temperatures were used to calculate the relative aging rates for each material using the IEC Loading Guide equation format. Operating temperatures for normal insulation life were assumed to be:

- 98°C for Kraft cellulose paper, as per IEC 60076-7,
- 140°C for aramid enhanced cellulose paper in natural ester, based on long-term studies performed on the material and resulting life time characteristic.

The relative aging formulas are shown below:

$$V_K = 2^{\frac{T-98}{6}} \qquad V_{AECP} = 2^{\frac{T-140}{7}}$$

Where:

V_K – relative aging rate for Kraft cellulose paper,
V_{AECP} - relative aging rate for aramid enhanced cellulose paper in natural ester,
T – hot spot temperature in °C.

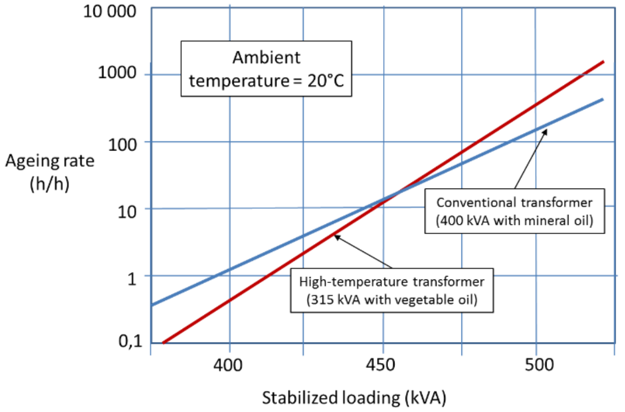

Figure 5. Relative aging rate of insulation materials used in 400 kVA unit (Kraft cellulose) and 315 kVA unit (aramid enhanced cellulose paper) in function of transformer load

The insulation aging calculations show that the transformer design based on an insulation material with higher thermal class has lower aging during normal operation and overloads. Although the transformer has been de-rated for reducing its dimensions, it could safely operate at 400 kVA without excessive aging.

Calculations show that the life of the de-rated transformer could be even longer than that of the conventional transformer (lower relative aging rate). It would require a load of above 450 kVA for the temperatures of the de-rated 315 kVA transformer to cause an aging rate of insulation higher than in the conventional design. This is expected to be a very rare case, which allows for the assumption that the expected life of a de-rated transformer with an improved insulation system would be longer than a transformer with a conventional insulation system.

Fig. 6 shows an example simulation of insulation aging for an imaginary 24 h load profile on the substation. Insulation aging is calculated based on calculated winding hot spot temperatures and the aging formulas corresponding to insulation materials used in each transformer.
It can be observed that insulation system of the 315 kVA transformer, although operating at higher temperatures (solid green line), shows lower aging (solid red line) as compared to the conventional insulation system of 400 kVA transformer (dotted green and red line accordingly). As a result, after the 24 h loading cycle the 315 kVA unit only shows aging equivalent to less than 4 h, while the 400 kVA unit shows aging equivalent to more than 10 h.
This confirms the expected lower sensitivity of de-rated 315 kVA transformer to occasional overloads or exposures to higher ambient temperatures. For example, these could be hot summer days with high sun radiation on the substation cabinet or situations where the kiosk substation’s ventilation would be clogged or not fully efficient.

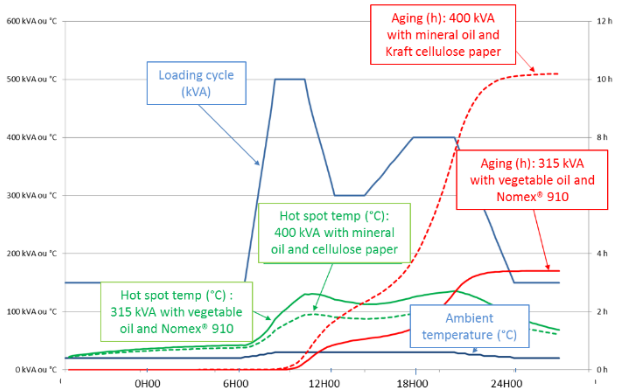

Figure 6. Example simulation of insulation aging for imaginary 24 h transformer loading profile

CONCLUSIONS

The solution presented in this article can be an attractive way of avoiding the lock-in effect in case the transformer installed in a compact substation has to be replaced after 2021 and has to meet the requirements of Tier 2 of EC Regulation 548/2014. **The solution is based on an alternative and innovative insulation material. It not only meets the key requirement, i.e. matching size limitations based on original transformer and installation location. It also provides additional benefits that should be attractive for the users:**

- Reduced footprint and weight of a new transformer
- Lower Total Ownership Cost (increased energy efficiency), when considering the typical, relatively low loading patterns in typical rural distribution networks
- Extended life expectancy
- Improved overload capability
- Reduced sensitivity to high ambient temperatures or malfunctioning ventilation or cooling systems in substations
- Reduced environmental impact by reduced consumption of raw materials
- Reduced impact on environment by use of vegetable and biodegradable oil
- Improved fire safety if class K ester is used

The choice of an environmentally friendly high temperature class transformer will be especially beneficial when:

- Average load is relatively low and periodic peak loads are high (e.g. in rural distribution networks)
- Ambient temperatures are higher than normal (e.g. in case of insufficient ventilation, hot climate)
- Reduced dimensions are required to fit-in existing infrastructures

At the time this publication is made prototype transformers are installed and being evaluated in one of the European countries. Other distribution utilities are considering evaluation and implementation of the concept as well.
Although the development of the solution was specifically triggered by the possible needs in the compact rural substations, it could be valid for other cases that power distribution utilities may experience in the future. The authors believe the work could inspire innovative thinking of the actual power rating defined for distribution transformers and encourage using new available designs and material solutions.

Acknowledgments

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