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Comparative advantage of using GRP in compact substations

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Abstract: This study presents the comparative advantage of using glass fibre reinforced polyester (GRP) as material for compact secondary substations (CSS). The analysis is done based on calculations of the expected lifetime of the CSS by processing the measurable top oil temperature of the transformer. The benefits are compared for the equipment in terms of loss of lifetime for three different enclosure materials: GRP, steel and concrete.

1 Introduction

The term smart secondary substation [1] provides a strategic position to the secondary substation in distribution networks because service quality improvement is achieved thanks to the option of flow monitoring, distributed energy resources management, and network automation and control.

The competitive environment that utilities are facing nowadays is forcing them to rethink their equipment investment and maintenance strategies. Economic perspective points out the need for extended lifetime and reduced maintenance costs for compact substations and the equipment enclosed within them to reduce lifecycle costs. From the point of view of reliability, utilities are demanding substations that offer benefits in terms of service conditions with extended lifetime.

The lifetime of compact secondary substations (CSS) is mainly dependent on the lifetime of the equipment installed within them. However, the enclosure housing this equipment also plays an important role as it is the key element in providing protection to the equipment.

Service conditions of CSS are normally determined by environmental data and based on statistics and/or predictions. This offers the utilities preliminary information in choosing electrical ratings and technical characteristics. However, utilities do not know in detail what the actual service conditions will be and how these will affect the equipment and its lifetime. Therefore, condition-based maintenance driven by the technical condition of the equipment is needed. This also reduces maintenance costs because it is based on real needs and not on predictions or time.

Combining both aspects of condition-based maintenance and the extended lifetime of CSS, this paper presents the comparative advantage of using glass fibre reinforced polyester (GRP) as material for the enclosure. The advantage is analysed in terms of the loss of lifetime of the equipment inside the substation for three different materials; GRP, concrete and steel.

The paper is divided into the following sections: the first section presents the most relevant characteristics of the GRP CSS in terms of material and properties; the next section deals with the estimated theoretical loss of lifetime in the CSS, followed by a section on the comparative advantage of using GRP for CSS and followed by conclusions.

2 GRP compact substation

GRP is a composite material made of polyester with a high glass content. GRP is a well-known material used for lightweight, strong, non-corrosive and easily shapeable constructions all around the world. GRP is proven in several industries that make high-level demands on performance and strength – including wind turbine blades and cable distribution cabinets as examples in the electrical industry. GRP is used wherever high strength-to-weight ratios and rigidity are required. GRP is a material with excellent properties for outdoor enclosures, making it an ideal solution for CSS housing.

For the GRP CSS, the key element for walls, doors and roof is a double-layer design. This concept of a double layer provides different benefits in terms of increased strength and better thermal behaviour, thus protecting the equipment from the environment.

The comparison carried out through the following sections considers a typical wall element in steel and concrete. In the case of a steel CSS, the thickness of the steel has been set at 1.5 mm, which is the most common thickness in this kind of substation, while the concrete has been considered as reinforced with a wall thickness of 90 mm, in order to cover most of the concrete CSS on the market.

GRP has the lowest level of thermal conductance when compared with steel and concrete. This fact, in addition to the double-layer design with air insulation in between, provides the benefit of a heat exchange blocker, which prevents the CSS from being influenced by fast changes in the outer environment, such as sun radiation, as in the case of steel CSS. This heat exchange blocker can be seen in terms of *U*-value in Table 1.

In terms of specific heat, or in other words, the capacity of the material to keep the energy, a GRP substation would be close to a steel substation and much lower than a concrete CSS (Table 2).

The benefits of low-level specific heat are demonstrated by the case of a CSS operating at night, during which the temperature is of course lower than during the day, with a lower load on the distribution network and thus less losses in the CSS. With a concrete CSS, it is more difficult to evacuate the heat inside the walls, thus the transformer needs to be cooled down over a longer period.

3 Transformer lifetime estimation

Lifetime estimation for transformer and medium-voltage gas-insulated switchgear is addressed in different ways in the literature [2–4]. For this paper, data only concerning the transformer are shown in terms of top oil temperature, as this is the key element in a medium-voltage/low-voltage compact substation.

One appropriate way to establish a criterion for the end-of-life of a transformer is to focus on the ageing process and status of the transformer insulation. The relative ageing rate is referred to the

Table 1 *U*-value in W/(m^2 K)

steel	33,333
concrete	12.22
GRP	7.2

Table 2 Specific heat in kJ/K for a 1 m length wall element

steel	12
concrete	396
GRP	40

winding hot-spot temperature, which is defined according to (1) for non-thermally upgraded paper and to (2) for thermally upgraded paper:

$$V = 2^{((\theta_h - 98)/6)} \quad (1)$$

$$V = e^{((15000/110+273)-(15000/\theta_h+273))} \quad (2)$$

where θ_h is the hot-spot temperature in °C.

The loss of life L over a certain period of time is represented in (1)

$$L \simeq \sum_{n=1}^{N} V_n \times t_n \quad (3)$$

where V_n is the relative ageing rate during interval n, according to (1) or (2); t_n the nth time interval; n the number of each time interval; N the total number of intervals during the period considered.

Practically, the hot-spot temperature cannot be measured for a substation in the field. Therefore, the calculation may be made based on the difference equations approach found in Clause C.4 of Annex C of the IEC 60076-7, the loading guide for oil-immersed transformers. In this method, the top oil temperature is the main input for calculating the hot-spot temperature.

A prerequisite for the method explained above is having a small time step. The way of achieving this is to install real-time monitoring of the top oil temperature and to process the data in real time. For a compartmented CSS, different sensors can be installed on the outside, in MV and transformer rooms to collect data regarding temperature, humidity and other gases, which might influence the condition of the equipment.

For this paper, a theoretical approach was considered due to the lack of exactly the same conditions for each of the three substation with different materials. This approach is based on calculating the top oil temperature through the thermal modelling of the transformer inside the substation. This calculation requires the losses of the transformer and ambient temperature as input.

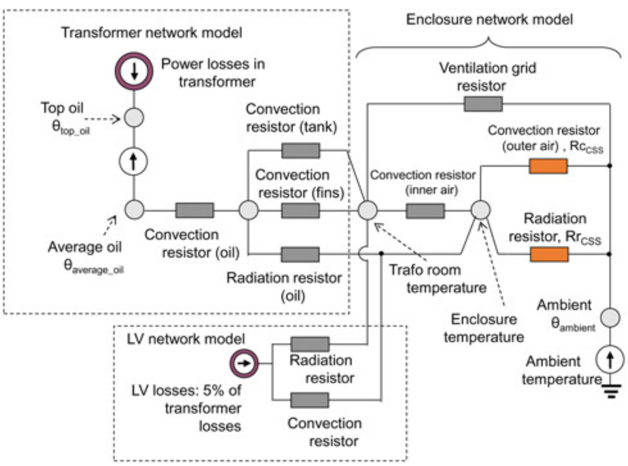

Fig. 1 *CSS simplified thermal model*

Transformer losses depend mainly on the load and can be calculated with simple mathematics.

A simplified thermal model of the CSS was applied (Fig. 1). This model considers both the transformer, the low-voltage distribution board and the substation thermal networks.

It must be stated that in the thermal model in Fig. 1, the convection resistor to the outer air, Rc_{CSS}, and the radiation resistor to the ambient air, Rr_{CSS}, depend on the enclosure material type. These parameters will therefore be different depending on whether the CSS is made of GRP, steel or concrete.

4 Comparative advantage

The results shown in this section are based on the calculation of the hot-spot temperature based on the top oil temperature obtained by applying the thermal model of Fig. 1 to the same transformer installed in substations made of GRP, concrete and steel. Once the hot spot has been calculated, the loss of lifetime can be estimated.

The following boundary conditions were considered to evaluate all three solutions under the same parameters and measure the performance of the equipment with regard to the enclosure material used for the substations:

- Same load profile for a given day (Fig. 2*a*);
- Same transformer constants such as oil exponent, winding exponent, ratio copper loss/iron loss, hot-spot gradient and thermal network;
- Same ambient temperature profile (Fig. 2*a*);
- Same thermal resistors of Fig. 1 except Rc_{CSS} and Rr_{CSS}, which change depending on the enclosure material.
- Time step for the calculations set to 3 min.

Fig. 2 shows a comparison in terms of the calculated top oil temperature and the calculated hot-spot temperature based on the difference equations as per IEC 60076-7. The load considered is a typical domestic load, in which there is a valley in the middle of the day and two peaks; one in the morning and a high one in the evening. The graphs are divided into three sections for ease of analysis: Period 1 comprises a night operation with low temperatures; Period 2 comprises a day operation with a flat load and high temperatures; Period 3 comprises an evening operation with a high load and temperature dropping from the maximum.

In terms of top oil temperature as seen in Fig. 2*b*, when the temperature goes down at night and at the same time the load goes down, the transformer installed in a concrete substation shows a higher temperature than the one installed in a GRP or steel substation. This is due to the fact that the walls of the concrete substation keep the heat inside, because the radiation prevents the cooling of the transformer in a short time. The opposite effect takes place for a steel substation, in which the enclosure material follows the outdoor environment and there is therefore no radiation to the equipment as no heat is stored in the material itself. The behaviour of a GRP substation during nighttime with a low load is close to that of a steel one, as observed in Fig. 2*a*.

For the time of the day when the temperature increases and the load remains mostly flat, Period 2 in Fig. 2*b*, a steel substation is influenced by the temperature increase, thus resulting in higher temperature in the top oil as the transformer room is influenced by higher temperature. During this period, the GRP substation shows the best performance due to the insulation provided by the double-layer design and the air insulation in between.

With a high load during the evening (see Period 3 in Fig. 2*b*) when the temperature has started to drop, the behaviour of the GRP and steel substation are quite similar, while the concrete shows a small delay in reaching the maximum oil temperature. This is based on the specific heat of the concrete material.

In the analysis of the three periods of the day, the behaviour of the transformer top oil in a GRP substation can be considered optimal as it has the best behaviour compared with a steel or concrete substation.

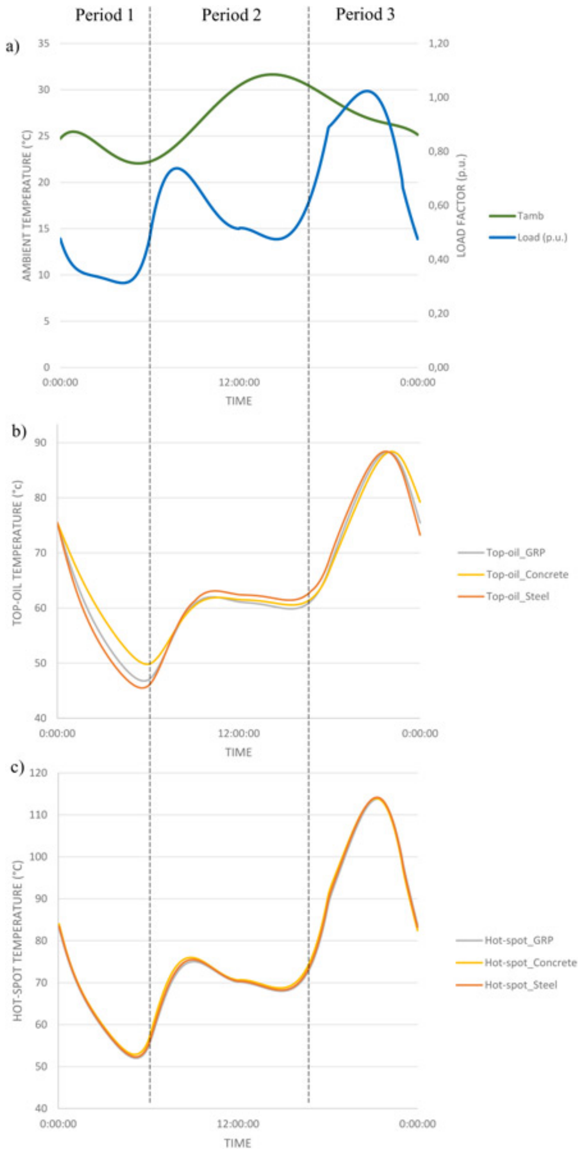

Fig. 2 *Comparison of the temperatures*

(a) Ambient temperature outside the substation and substation load factor for a given day, ***(b)*** Top oil temperature for GRP, concrete and steel substations, ***(c)*** Hot-spot temperature for GRP, concrete and steel substations

In analysing the hot-spot temperature of the transformer, it can be observed in Fig. 2*c* that this is quite similar in all three substations. However, there are some differences, mostly during the night (Period 1) and at noon (Period 2). These differences will affect the lifetime of the transformer. The total loss of lifetime for a given day can be calculated by applying (3). Results of this calculation are presented in Fig. 3.

As depicted in Fig. 3, the loss of lifetime of a GRP substation is the lowest compared with concrete (medium) or steel (highest one). In terms of benefit based on loss of lifetime, the GRP enclosure provides a benefit of 3.2% compared with concrete and 4.4% compared with steel.

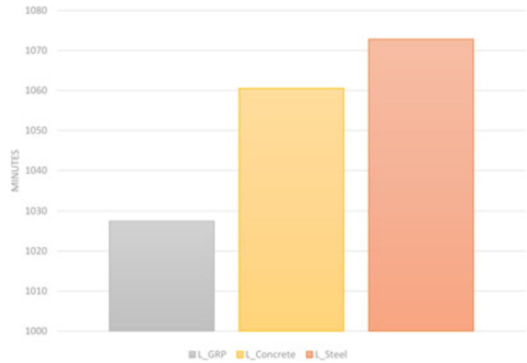

Fig. 3 *Loss of lifetime for a given day in GRP, concrete and steel substations*

5 Conclusions

A comparative advantage of using GRP as material for CSS was presented in terms of loss of lifetime for the power transformer. The comparison was made for three different enclosure materials: GRP, steel and concrete. The estimation of the loss of lifetime was made based on numerical calculations of the top oil and hot-spot temperatures of the power transformer. A simplified thermal model of the substation was also presented in order to obtain the top oil temperature considering all thermal resistances present in a substation, such as those in the power transformer, the low-voltage distribution board and those specific to the enclosure, which depend pretty much on the material used.

The comparative analysis of the lifetime of the transformer has shown that when using GRP as material for the enclosure of the CSS, the lifetime of the power transformer is higher than for steel or concrete enclosures.

GRP substations provide longer equipment lifetime due to the capabilities of the material and the original design of the CSS, which make the substation more independent of environmental conditions.

Additionally, a measuring system can be used to obtain the top oil temperature in real time, which can be used to calculate the daily loss of lifetime of the power transformer and thus set up condition-based maintenance for the equipment. At the same time, this kind of monitoring allows the detection of anomalies in the performance of the substation.

As the loss of lifetime of the transformer is lower for a GRP substation compared with steel or concrete, maintenance costs can be reduced, making this material ideal for secondary substations.

6 References

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