ABSTRACT

This article is the continuation of the paper: "Detection and reduction of high temperature in high current turrets of generator step-up (GSU) transformers – Part I" published in the April 2022 issue of "Transformers Magazine", where the author demonstrated that the heating issue in the low voltage (LV) turrets of a 90 MVA GSU transformer is produced by the low carbon steel employed in the LV turret structure and by the presence of short non-magnetic stainless steel (SS) inserts located in the turrets which were manufactured by the original transformer manufacturer. This new article presents the magnetic solution for the heating issue found in the LV low carbon steel turrets of this 90 MVA GSU transformer. Utilizing Multiphysics finite element simulations and parametric analyses, the author demonstrates that modifying and varying the geometry of the original short SS inserts is possible to reduce the temperature in the low carbon steel turrets of the GSU transformer. This article demonstrates that by elongating and increasing the width of the original short SS inserts it is possible to reduce the temperature in the low carbon steel turrets of the GSU transformer. The magnetic solution presented in this article could be implemented on-site without the need to send the transformer to repair and avoid taking out of service the transformer for a long time.

KEYWORDS:

Generator step-up (GSU) transformer, low voltage (LV) turret, finite element (FE), stray loss, thermography, stainless steel insert, electromagnetic shield, hot spot, current transformer (CT)

One of the leading causes of failure in generator step-up transformers is related to overheating and the presence of high temperatures in bushing regions and tanks

Detection and reduction of high temperature in high current turrets of generator step-up (GSU) transformers – Part II

1. Introduction

One of the leading causes of failure in generator step-up (GSU) transformers is related to overheating and the presence of high temperatures in bushing regions and tanks [1]. Power transformer standards specify that temperatures between 95 and 105 °C are permissible in low voltage (LV) bushings turrets where rated continuous currents exceed 5 kA [2], [3]. The LV turret temperature should be kept in this temperature range to avoid possible damage to the gasket seals and the presence of transformer oil leaks in the bushing-tank regions [4]. Different interesting techniques to reduce high temperatures in LV turret regions of GSU transformers have been studied and published. For example, in [5] hot spots were found in the LV turrets of a three-phase GSU transformer utilizing thermography and three-dimensional (3-D) finite element (FE) simulations. Hot spots were found in the low carbon steel structural supports for the current transformers (CTs), which are in the interior of the LV turrets and closed to the LV bushing conductors. Low carbon steel CT supports and the turret regions presented temperatures above 140 °C. The low carbon steel CT supports were replaced by non-magnetic stainless steel (SS) supports to eliminate the presence of hot spots in the turret regions of the GSU transformer. The heating issue in the GSU transformer was fixed on-site utilizing non-invasive techniques. With the SS CT supports, the GSU transformer presented temperatures around 100 °C in the turrets. In [6] a methodology to reduce the eddy currents induced by stray fields in the low carbon steel LV turrets of a three-phase GSU transformer is presented. Utilizing 3-D FE simulations, the authors analysed a set of electrical jumpers which work as electrical paths for the eddy currents induced in the turrets. The authors demonstrated that the efficiency of the electrical jumpers depends on their position in the turret region. Temperature measurements or thermal simulations of the electrical jumpers in the turrets were not presented in this research [6]. On the other hand, a SS shorting-plate technique combined with the use of non-magnetic SS inserts in low carbon steel LV turrets of a three-phase GSU transformer is

> **Incorrect use of magnetic steels in the turrets and incorrect application of techniques to reduce stray losses in turrets could produce high temperatures or hot spots in GSU transformers**

presented in [7]. Hot spots in the LV turrets of a three-phase GSU transformer were detected utilizing thermography. To reduce the temperature in the turrets, SS inserts and SS shorting plates are employed on-site. A set of SS inserts are made in the turrets, and some SS shorting plates are welded to the surface of the SS inserts. The SS shorting plates are welded between them to produce a closed path for the eddy currents induced in the turrets. The eddy currents circulate from one turret to another turret using the SS shorting-plates, reducing the stray losses and temperature. The temperature in the turrets was reduced using the SS inserts and the SS shorting plates. In [8] a numerical study about the reduction of stray losses and temperature in the LV turrets of a single-phase GSU transformer utilizing electromagnetic shields is presented. The LV turrets of this analysed GSU transformer are made of different steels. One of the turrets is made of low carbon steel, and the other turret is made of SS. A copper electromagnetic shield is attached to the inner wall region of the low carbon steel turret to reduce stray losses and temperature. The stray losses and temperature in both turrets for different levels of current in the bushing conductors were computed. For the case of 12.5 kA, temperatures above 280 °C were calculated in the low carbon steel turret equipped with the electromagnetic shield. The SS turret presented temperatures below 100 °C for the same case of 12.5 kA. The copper shield presented high stray losses compared with the stray losses in the low carbon steel turret. The authors concluded that the low carbon steel turret with the shield only can handle currents of 5 kA compared with the SS turret, which can handle currents above 10 kA, keeping turret temperatures below 100 °C. The use of electromagnetic shields in the interior of LV turrets is useful for low currents in the bushing conductors. In addition, the use of electromagnetic shields in LV turrets reduces the dielectric distances between the turret and the bushings, and high stray losses are produced in the shields, which are exposed to high stray fields (produced by high currents in the bushing conductors) producing hot spots on them generating other thermal issues in the GSU transformer. Finally, in [9] the electromagnetic and thermal effects of the use of low carbon steel turrets and non-magnetic SS turrets in three-phase GSU power transformers are presented. For currents of 5 kA, temperatures between 200 and 300 °C were computed in the low carbon steel turrets, and temperatures between 70 and 90 °C were computed in the SS turrets.

It is clear from references [1], and from [5] to [9] that the incorrect use of magnetic steels in the turrets and incorrect application of techniques to reduce stray losses in turrets could produce high temperatures or hot spots in GSU transformers which could produce catastrophic and costly failures.

In this new article, a magnetic solution is presented to reduce and to keep the temperature in the low carbon steel turrets below 105 °C, modifying and varying the geometry of the original short SS inserts of the 90 MVA GSU transformer [1]. The author demonstrates that by elongating and increasing the width of the original SS inserts, it is possible to reduce the temperature in the low carbon steel turrets. In addition, this magnetic solution could be carried out on-site, avoiding sending the transformer to repair and avoiding taking out of service the transformer for a long time [10], [11].

2. Temperature measurements in turrets of the GSU transformer

The main characteristics of the 90 MVA single-phase GSU transformer are presented in Table 1 [1].

Table 1. Characteristics of GSU Transformer [1]

Nominal transformer rating	90 MVA
Impedance	13.7 %
Phases	1
Nominal low voltage (LV) current	6.82 kA
Nominal high voltage (HV) current	678 A
Cooling system	FOW
Year of manufacturing	1991
Primary and secondary voltage	13.2/230 kV
Frequency	60 Hz

Transformer oil leaks and crystallized gasket seals were detected in the GSU transformer in the LV turret regions, indicating the presence of high temperatures in the turrets [1]. As part of preventive maintenance, the power station staff decided to monitor the temperature of this transformer using infrared thermography and temperature labels [1]. During this monitoring process, temperatures > 100 °C were measured in the LV turrets when the bushing conductors carried 95 % of the nominal current, and temperatures > 120 °C were measured in the LV turrets when the bushing conductors carried 100 % of the nominal current [1]. Fig. 1 shows photos of the measured temperature in the turrets at 95 % of the nominal current [1].

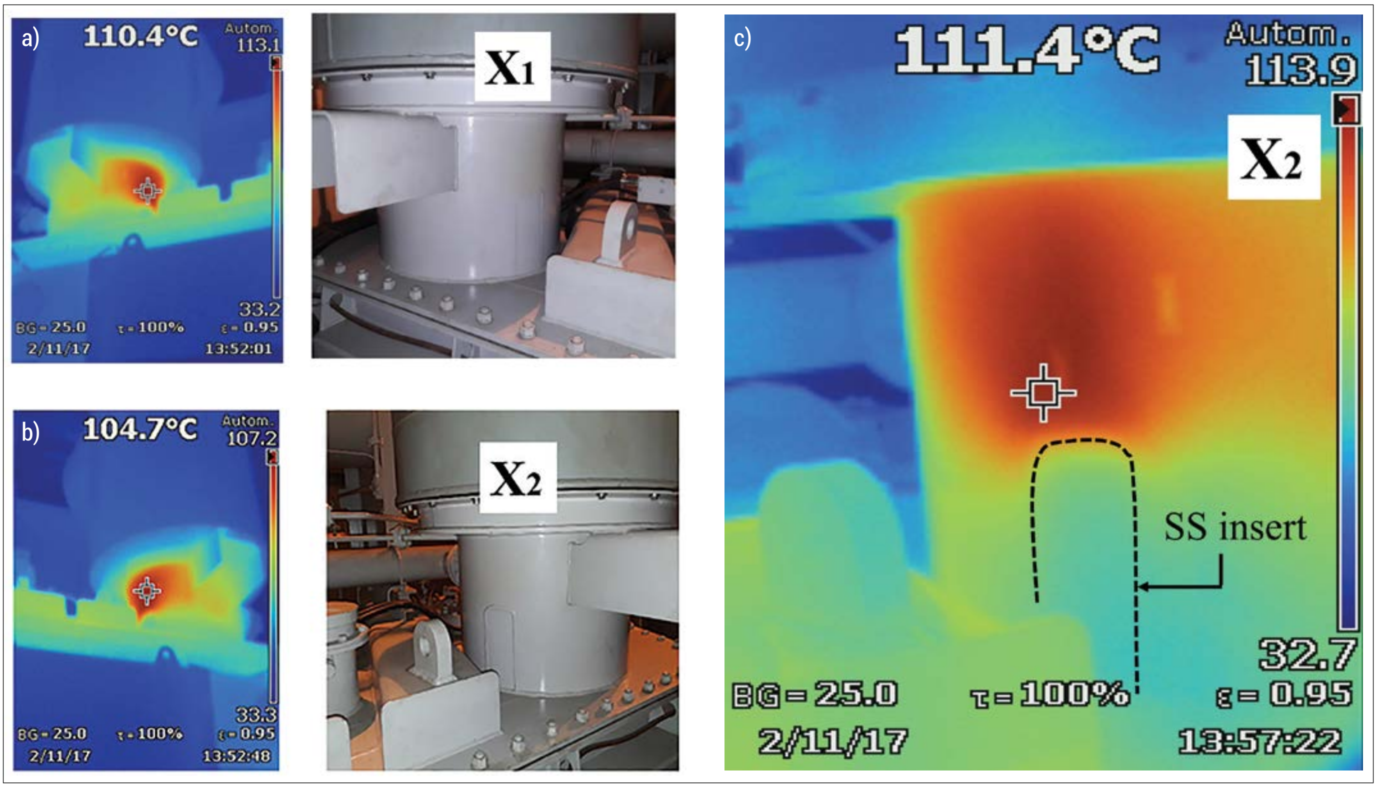

Figure 1. Temperatures measured in the LV turrets with short SS inserts at 95 % of nominal current: a) LV turret X_1, b) LV turret X_2, c) detailed temperature distribution in the LV turret X_2 [1]

With the measurements and visual inspections, it was clear that this GSU transformer presented high temperatures in LV turrets in the region above the short stainless steel inserts

A visual inspection was performed to verify the state of the LV bushing-turret regions of the GSU transformer. Some visible heating signs were detected in the internal region of the LV turrets in the region above the short SS inserts, see Fig. 2. With the measurements and visual inspections, it was clear that this GSU transformer presented high temperatures in LV turrets in the region above the short SS inserts. Several 3-D Multiphysics FE simulations were performed to determine the causes of high temperatures in LV turrets of the GSU transformer. In [1], it is demonstrated that the high temperatures in the low voltage (LV) turrets are produced using low-carbon steel in the LV turrets and by the presence of the short non-magnetic stainless-steel (SS) inserts located in the turrets. Fig. 3 shows the temperature distribution obtained in the turret of the GSU transformer under 100 % of nominal current in the bushing conductor [1]. More details about the electromagnetic-thermal FE analyses of this 90 MVA GSU transformer can be found in [1].

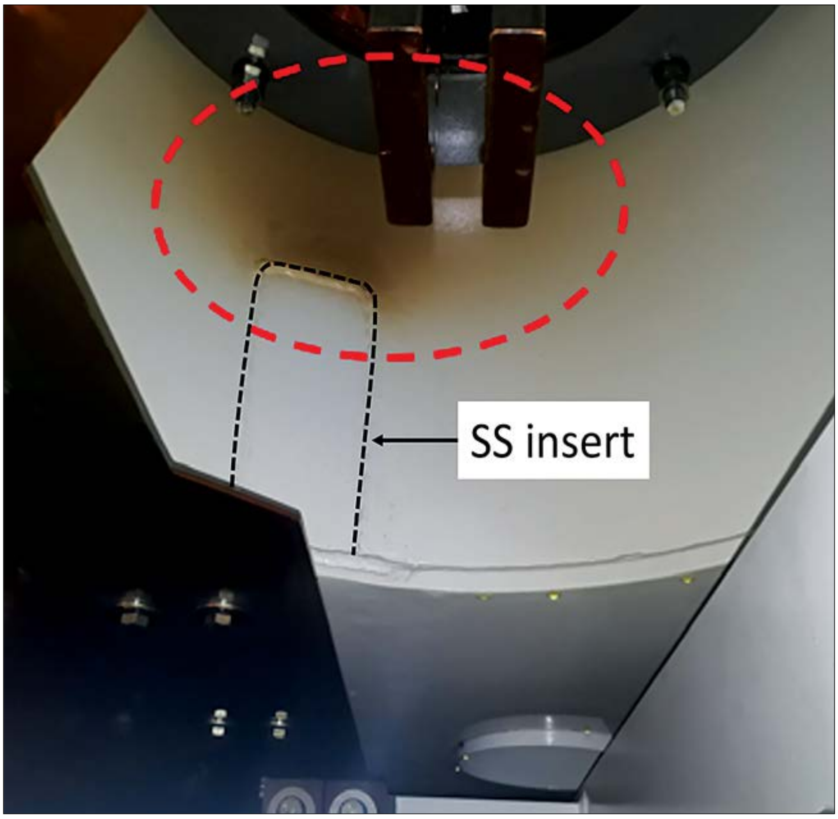

Figure 2. Photo of visible heating signs in the region above the short SS insert

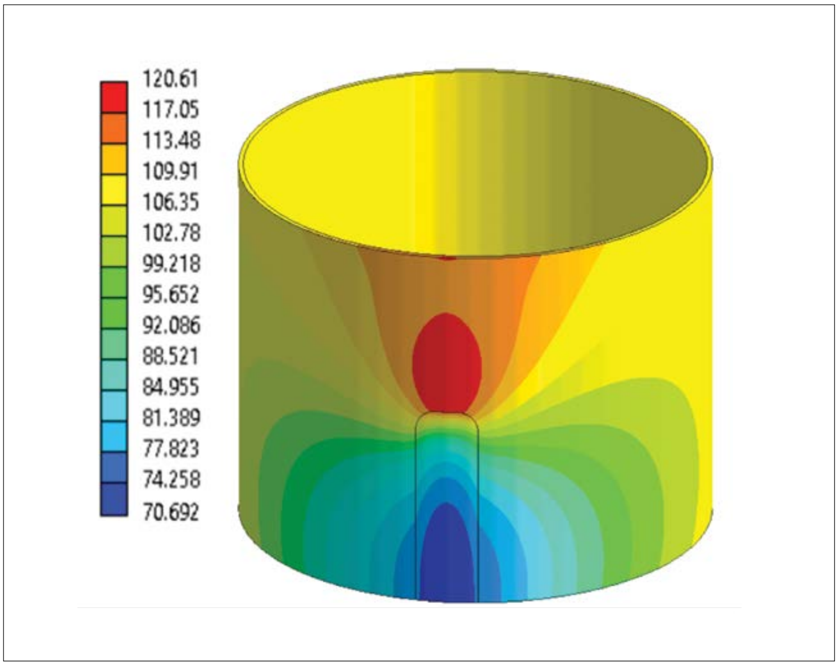

Figure 3. Temperature distribution (in °C) in the low-carbon steel turret with the short SS insert [1]

The original short stainless steel inserts were elongated up to the top of the turret in order to reduce the stray losses in the LV turrets, which will also reduce the hot-spot temperatures

3. Magnetic solution for the heating issue in turrets of the GSU transformer

According to the author's knowledge, transformer manufacturers build LV turrets out of non-magnetic stainless steel to avoid heating issues. In this case, the substitution of carbon-steel turrets with non-magnetic stainless steel turrets is not a flexible and economical option. Therefore, a different and flexible solution has been proposed to reduce the temperature in the turrets of the GSU transformer, avoiding high repair costs and preventing the GSU transformer from being put out of service for a long time [10], [11].

The author proposed to modify the original geometry of the original short SS inserts to reduce the stray losses and high temperature in the low carbon steel LV turrets of the GSU transformer. The original short SS inserts were elongated to reduce the stray losses in the LV turrets.

The original thickness of 6.35 mm and the original w_{ssi} = 80 mm have been kept constant in the SS inserts, and the h_{ssi} has been increased from 230 mm to 460 mm to cover the total height of the LV turret with the SS inserts. Fig. 4 shows the 3-D models of the LV turret with the original short SS insert and with the new elongated SS insert.

Fig. 5 shows the loss distribution in the turret with the elongated SS insert. A stray loss P_{cs} = 1.88 kW has been computed in the turret and a total stray loss P_{ss} = 45 mW has been calculated in the SS insert. The stray loss in the turret has been reduced by 16.81 % due to the presence of the elongated SS insert compared with the case of the original short SS insert (where P_{cs} = 2.26 kW) [1].

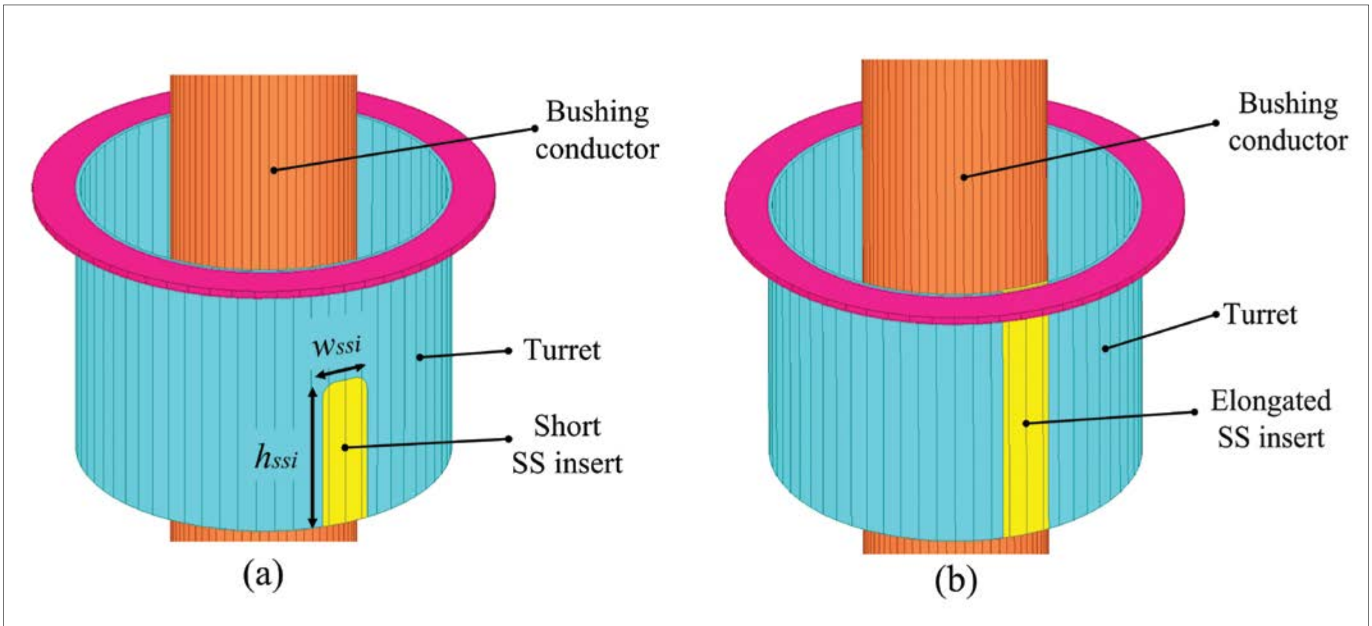

Figure 4. a) Original short SS insert with w_{ssi} = 80 mm and h_{ssi} = 230 mm [1], b) LV turret with new elongated SS insert with w_{ssi} = 80 mm and h_{ssi} = 460 mm

The stray loss in the turret has been reduced by 16.81 % due to the presence of the elongated SS insert compared with the case of the original short SS insert

Fig. 6 shows the temperature distribution in the turret with the elongated SS insert. From Fig. 6, it is evident that the temperature in the turret has been reduced compared with the temperature computed in the turret with the short SS insert, see Fig. 3. The maximum temperature in the turret is 107.87 °C, utilizing the elongated SS insert. A temperature reduction of 10.56 % in the turret has been obtained, elongating the original short SS insert, compared with the temperature computed in the turret with the short SS insert, see Fig. 3. It indicates that the elongation of the original short SS inserts works but it is not enough to reduce the temperature in the turret below 105 °C.

3-D FE parametric analyses have been performed to compute the temperature reduction when the width w_{ssi} of the elongated SS insert is varied. Fig. 7 shows the maximum temperature curve obtained in the turret for different w_{ssi} values. From the temperature curve in Fig. 7 it is clear that for the reduction of the temperature in the turret (below 105 °C), it is necessary to utilize an elongated SS insert with a w_{ssi} = 200 mm to get a maximum temperature in the turret of 104.5 °C. A temperature reduction of 13.35 % in the turret has been obtained by elongating the original short SS insert from 230 mm to 460 mm and increasing w_{ssi} from 80 mm to 200 mm, compared to the turret with a short SS insert [1]. Of course, one can increase the width of the elongated SS insert to reduce the temperature in the turret, but it will slightly increase the material cost because stainless steel is more expensive than low-carbon steel [12]. Furthermore, the curve in Fig. 7 shows that when the entire LV turret is made of 100 % non-magnetic SS, it presents a maximum temperature of 62 °C. A temperature reduction of 48.59 % has been calculated utilizing tur-

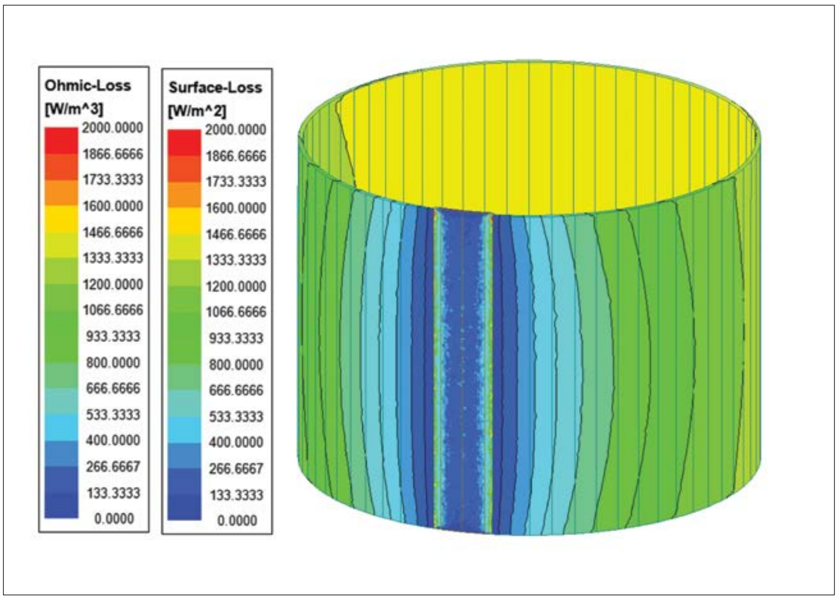

Figure 5. Loss density distribution (in W/m²) in turret and power loss distribution (in W/m³) in the elongated SS insert with w_{ssi} = 80 mm and h_{ssi} = 460 mm

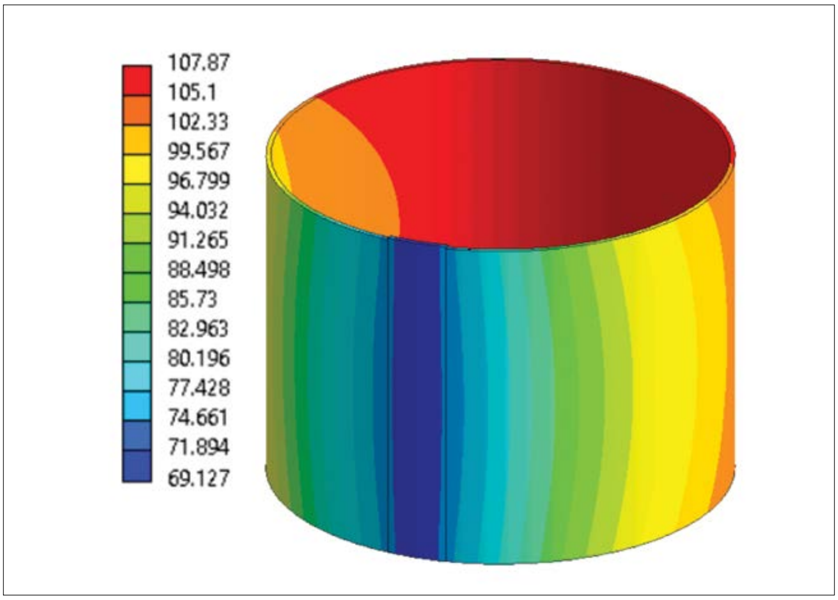

Figure 6. Temperature distribution (in °C) in the turret with the elongated SS insert with w_{ssi} = 80 mm and h_{ssi} = 460 mm

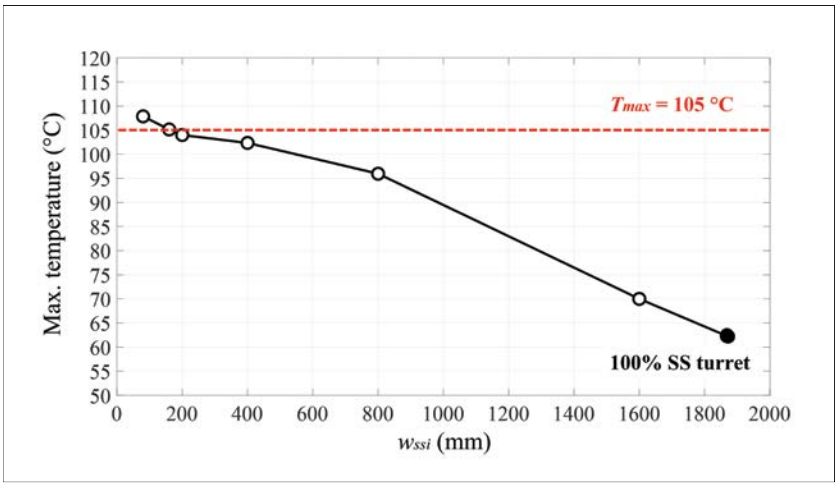

Figure 7. Temperature curve for the LV turret for different SS insert widths (w_{ssi})

3-D FE calculations show that if the entire LV turret is made of 100 % non-magnetic stainless steel, then the maximum temperature of the LV turret would be 62 °C

rets made of 100 % of non-magnetic SS, compared with the low carbon steel turret with the short SS insert.

Fig. 8 shows the temperature distribution in the turret with the elongated SS insert with w_{ssi} =200 mm and h_{ssi} = 460 mm.

The author found that the h_{ssi} of the SS inserts have a slight impact on the reduction of temperature in the LV turrets, and he found that the SS insert width w_{ssi} has an important impact on the reduction of temperature in the LV turrets.

4. Conclusion

A magnetic solution is proposed to reduce the temperature in the LV low carbon steel turrets of a 90 MVA GSU transformer. The geometry of the original short SS inserts of the GSU transformer was modified to avoid replacing the original and entire low carbon steel turrets with new turrets manufactured completely of non-magnetic stainless steel. Transformer manufacturers are building the LV turrets of non-magnetic stainless steel to avoid heating issues. In this case, the substitution of low carbon steel turrets with non-magnetic stainless steel turrets is not a flexible and economical option. Therefore, a different and flexible solution has been proposed to reduce the temperature in the turrets of the GSU transformer, avoiding high repairing costs and avoiding taking out of service GSU transformer for a long time.

The author proposed to elongate the original short SS inserts and increase the width of the SS inserts to gradually reduce the stray losses and temperature in the low carbon steel turrets. Utilizing elongated SS inserts with an equivalent width of 10.68 % of the total perimeter of the turret, the maximum temperature in the turrets is reduced below 105 °C. The temperature in the low carbon steel turrets is reduced when the width of the elongated SS inserts is increased. The LV low carbon steel turrets can be designed and manufactured with long SS inserts of width equivalent to 35 % of the total perimeter of the turret to keep the temperature below 100 °C.

The magnetic solution presented in this article will be considered for fixing the heating issue in the GSU transformer on-site.

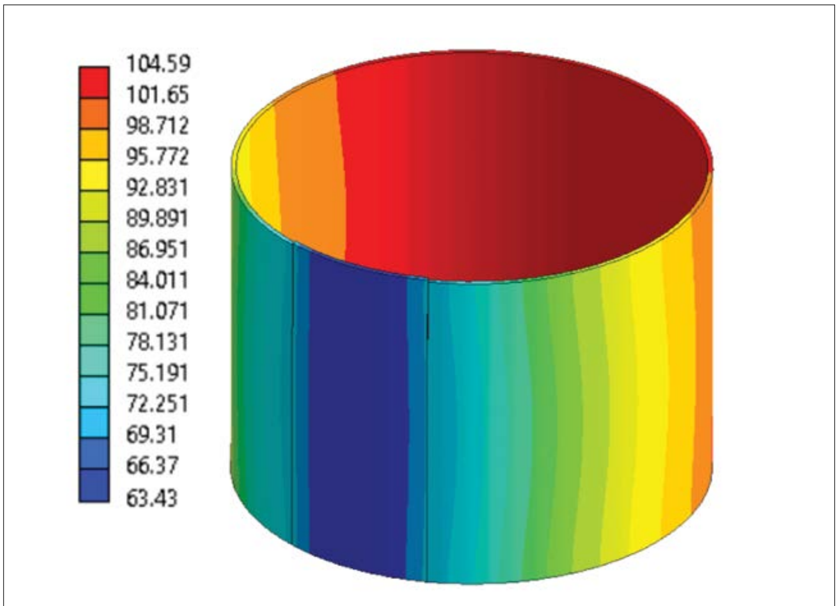

Figure 8. Temperature distribution in LV turret with the elongated SS insert with w_{ssi} = 200 mm and h_{ssi} = 460 mm

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Salvador Magdaleno-Adame was born in La Piedad de Cabadas, Michoacan, Mexico, in 1983. He received the B.Sc. degree in electrical engineering from the Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico, in 2008, and the M.Sc. degree in electrical engineering from the Instituto Tecnologico de Morelia, Morelia, in 2013. From 2008 until 2010 he worked at Industrias IEM S.A. de C.V. in Mexico as an R&D engineer in the technology department for power transformers where he conducted research on shell-type and core-type power transformers, and he also worked on the development of HV shunt reactors. He has occupied several magnetic engineering positions in companies in the USA, working in different magnetic and electromagnetic technologies, including transformers, motors, magnetic actuators, loudspeakers, permanent magnet technologies, magnetic materials, etc. He has authored over 60 papers. For many years, he has worked on a range of ideas and techniques to reduce the power losses in power transformers and distribution transformers. He owns a consultancy business called "Salvador Consultant www.salvadorconsultant.com" to support the magnetic and electromagnetic industry in the USA. His current research interests include numerical calculation of electromagnetic fields in electromagnetic devices and transformers using the finite-element method, application of different magnetic materials in electromagnetic devices, design of magnetizing fixtures utilized in the magnetization process of permanent magnets, and the development of new magnetic technologies for different applications and industries.