Reduction of Stray Losses in Flange–Bolt Regions of Large Power Transformer Tanks

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***Abstract*—In large power transformers, the presence of stray currents in the structural elements near the high current bushings can be considerable, and this leads to hot spots. This work presents a practical analysis of overheating in the bolts that join the tank and the cover, which are near the high current bushings of the transformer. Overheating results are analyzed and discussed for the case of a 420-MVA transformer. The hot spots in the flange–bolt regions are discovered by thermal maps that are obtained during power transformer operation as a part of a preventive maintenance program. In this paper, we use copper links to ensure the connection of both the cover and tank body, significantly reducing the overheating of the flange–bolt region. The copper link solution has been validated by measurements. We have used calibrated measurement instruments in all the experiments. Moreover, a 3-D finite-element analysis of the geometry of interest has been used to verify the copper link solution.**

***Index Terms*—Flange–bolt regions, hot spots, low-voltage (LV) bushings, overheating, power transformer, stray currents, tank cover, thermography, transformer failures.**

NOMENCLATURE

LV	Low voltage (in kV).
HV	High voltage (in kV).
h	Convective heat transfer coefficient [in $\mathrm{W/(m^2{}^\circ C)}$].
H_{lim}	Magnetic field strength limit (in A/cm).
I_{stray}	Measured stray current (in A).
J_{stray}	Calculated current density in copper links (in A/mm^2).
S	Transformer rating (in MVA).

I. INTRODUCTION

TRANSFORMER engineering is a very interesting and always timely subject of research [1]–[11]. Power and distribution transformers are expensive and vital components in electric power transmission and distribution systems [12]. Globally, the statistics of failures in power transformers are as follows [13]: 41% of faults are related to the tap changer, 19% with the windings, 3% with the core, 12% with the terminals, 13% with the tank and fluids, and 12% with the accessories. In Mexico, the statistics showed that 53% of failures are related to problems in the winding insulation, 19% to bushings, 11% to the tap changer, 2% to the core, 13% to other causes, and 2% to fire explosion [14]. Hot spot failures in the tank are included in the 13% of other causes. Consequently, it is important to analyze the causes and consequences of tank hot spots as well as to present solutions to the problem of bolt heating.

According to the authors' experience, overheating of distribution-transformer flange–bolt regions is not important. However, in the case of large power transformers (100 MVA and above), the overheating of flange–bolt regions can lead to transformer failure.

The main contribution of this paper is the presentation of a comprehensive and practical analysis of temperature in the flange–bolt region of large power transformer tanks. The authors show that, utilizing copper links in the bolts, stray losses and temperature in the flange–bolt region due to bad electric contact of the bolts with the tank can be effectively reduced. Three-dimensional finite element (FE) simulations were employed to further understand the experimentally obtained results.

This paper is organized as follows. Section II describes work related to stray losses and hot spots in transformer tanks. Section III presents the copper link method to reduce hot spots on the bolts of transformer tanks. Section IV presents the technical characteristics of the transformer used to verify the copper link method. In addition, the copper link solution of Section III is simulated using the finite-element method (FEM) in Section V, whose results are validated by measurements in Section VI. Section VII concludes this paper.

II. STRAY LOSS AND HOT SPOTS IN TRANSFORMER TANK

More than 20% of the total load loss is the stray loss in power transformer structural components [15]. The biggest part of stray loss takes place in the transformer tank. As the transformer ratings increase, the stray loss problem becomes increasingly significant. During the last few decades, the ratings of power transformers have been steadily growing. Stray losses can be very high, which can result in higher temperatures and local hot spots that reduce the transformer life. To become more

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competitive, transformer manufacturers have to optimize material cost, which usually leads to reduction in overall transformer size due to the reduction of electrical and magnetic clearances [15]. This further increases stray loss if appropriate shielding is not implemented.

Analytical and numerical methods have been applied for the evaluation of stray loss. The analytical techniques have certain limitations and cannot be applied to complex geometries. On the other hand, numerical methods can provide more accurate results than analytical and semianalytical methods; however, higher computational efforts are needed. In order to reduce the computational burden, numerical methods can be combined with analytical techniques.

A 3-D methodology linking an electromagnetic analytical formulation with thermal FEM is used to assess heating hazards on transformer covers [16]–[18], resulting in a practical tool to design magnetic insert arrangements [18]. Stray losses in transformer covers depend on the distribution of leakage flux produced by strong induced fields; loss estimation methods due to electromagnetic leakage flux are already available [19]. A 3-D FEM is applied for the computation of the eddy current losses in the transformer tank, clamping frame, and electromagnetic shielding [20]. A detailed review of methods for the evaluation of stray loss in power transformers can be found in [15].

Hot spots generated in the flange–bolt region of large power transformer tanks are produced by the induced stray currents, which are forced to circulate through the flange–bolt region. This region is overheated due to a bad contact between the tank and cover. This electromagnetic phenomenon can jeopardize the properties of the mineral insulating oil and impair the sealing system, the painting of the tank, and the insulation of the high current conductors. All these can cause major faults in large power transformers.

After reviewing the existing literature, the authors note that there are many papers that deal with the problem of stray losses in the tank due to high currents flowing through LV conductors [15]–[24], but research related with hot spots on bolts placed on the tank cover of the transformer is very scarce [15], [21], [25]–[27]. Kulkarni and Khaparde [15] and Karsai *et al.* [26] consider the heating of bolts as a possible hazard and recommend the use of copper links; however, in [15] and [26], theory, experimentation, or numerical simulations are not presented or discussed. In 1985, Turowski [21] carried out a meritorious work simulating the overheating in a flanged bolt joint using a hybrid FEM and reluctance network method when computing resources were very limited. In [25], the authors employed the boundary element method and FEM to calculate the circulating stray current in the loop of two bolts of the flange–bolt region.

III. COPPER LINK METHOD TO REDUCE HOT SPOTS IN FLANGE–BOLT REGIONS OF TRANSFORMER TANKS

In transformer manufacturing, three methods have been employed to reduce and avoid the heating of transformer tanks:

1) use of magnetic shunts [15], [25];
2) use of electromagnetic shields [22], [25];
3) varying the distance of the LV leads to the tank wall [22].

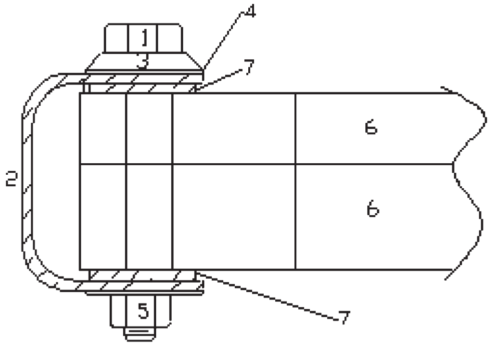

Fig. 1. Geometry of the proposed solution. 1. Stainless steel bolt A-316. 2. Copper link. 3. Belleville washers, nonmagnetic material. 4. Flat washers, nonmagnetic material. 5. Stainless steel nut, nonmagnetic material. 6. Flange for connection of tank and cover. 7. Toothed washer, nonmagnetic material.

The solution implemented in this paper consists of installing bridges of copper links in the 49 bolts distributed at the junction of the cover and tank (flange–bolt region). The configuration adopted is shown in Fig. 1. The use of copper was selected because of its high conductivity. The nuts and bolts were made of nonmagnetic stainless steel to reduce corrosion, ensuring good contact with the walls of the tank, thus avoiding the overheating due to bad contact. The link provides a low impedance path for stray currents and keeps both parts at the same electrical potential.

Turowski [21] shows that, when bolts have a good contact, the reluctance of the flange–bolt set is more than twice that of a solid wall (one piece). Furthermore, the magnetic field strength H on the surface of the bolt is 1.4 times higher than the H in the solid parts of the flange. Turowski [21] also shows the effect of having inappropriate contact between the flange and bolts, caused by painting, the magnetic field saturation, the separation of the flange, and so on. Renyuan *et al.* [23] show that values higher than $H = 40$ A/cm produce heating in the flange–bolt region. Consequently, copper links connected to the cover bolts to reduce overheating (see Fig. 1) are a viable option in the case where the cover is not welded to the tank.

In order to avoid the loosening process that occurs over time in the force that holds tightly the bolt, the connection scheme presented in [28] was used. More specifically, Belleville washers are used since they have the property of expanding to maintain a strong connection. The recommended torque for ensuring the good contact of the flange–bolt is 190 Nm. The reduction of the friction coefficient between the bolt and the flange increases the bolt tension for a given torque. For this reason, antiseize paste is used as lubricant on the surface of the flange that contacts the washer.

Federal Commission of Electricity (CFE) and Mexican Petroleum (PEMEX) [29], [30] specifications of 2006 mention that tank covers and tanks of transformers must be designed to be able to be welded. This is applicable for the following: 1) transformer ratings from 6250 to 40 000 kVA in case of CFE and 2) transformer ratings of 500 kVA and above in case of the PEMEX specification. This paper serves as a reference to the problem of hot spots in the flange–bolt region when the connection is made with bolts. According to the IEEE standard C57.12.10-2010 [31], the tank cover must be welded to the tank.

TABLE I
GSU TRANSFORMER TECHNICAL CHARACTERISTICS

Transformer rating (S)	135/375/420 MVA
Connections	HV: Wye, LV: Delta
Core	Shell type
Impedance	12 % at 420 MVA
Phases	3
Nominal low voltage (LV) current	12,124 A
Nominal high voltage (HV) current	1054 A
HV bushing	oil-gas SF_6
Cooling	OA/FOA
Serial number	24-7194
Year of manufacturing	1997
Primary and secondary voltage	20/230 kV

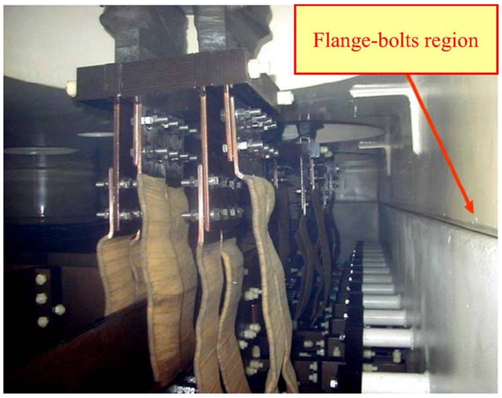

Fig. 2. Arrow shows the connection of flange–bolts inside the transformer.

However, in case that a transformer user requests it, a bolted cover can be used.

IV. TECHNICAL CHARACTERISTICS OF THE TRANSFORMER SELECTED TO VERIFY THE COPPER LINK METHOD

The generator step-up (GSU) transformer under study is located at the 2.8-GW generation power plant of Petacalco, located 12 km from the industrial port of Lazaro Cardenas, Michoacan, Mexico. The geographic location is $102^\circ\ 06'\ 22''$ west longitude and $17^\circ\ 59'\ 04''$ north latitude. The technical characteristics of the GSU transformer are shown in Table I. The transformer under study is a two-winding GSU transformer, so there is no tertiary winding.

The transformer tank was designed with a bolted cover due to transportation dimensional limitations. The connections of flange–bolts inside the transformer and the LV leads are shown in Fig. 2. The LV side is connected by an isolated phase bus of the GSU transformer, which is a conductor manufactured with aluminum.

This power transformer was installed in 1998 and operated without problems for approximately nine years with periodic maintenance. However, after this period of time, some hot spots appeared at the cover–tank connection, near the LV side. A dissolved gas analysis was performed, but no gas in transformer oil content was detected, meaning that high temperatures only existed at the outside surfaces of the tank that are not in direct contact with the transformer oil or the solid insulation. The authors do not actually know what gave rise to the problem of having loose bolts. However, owing to maintenance records, the authors do know that the transformer operated without problems during the first years. The authors speculate that transformer vibration and normal transformer temperatures during its early operation led to loosen bolts, with those located on the zones of high concentration of stray flux (near the LV bushings) being the more affected. Painting collapse and thermography images disclosed the heating problem of this transformer. As a result, an investigation was carried out by the authors in order to analyze and solve this heating problem.

The copper link method proposed in Section III solved the hot spot problems of this transformer, as shown in Sections V and VI, where the copper link solution was validated by FE simulations and measurements.

V. FE SIMULATIONS OF THE COPPER LINK SOLUTION

To understand the heating problem in the flange–bolt region, 3-D numerical simulations can be performed using FE commercial software such as those in [32] and [33]. First, a linear harmonic analysis at 60 Hz was performed with impedance boundaries in the transformer tank in order to calculate the stray losses [32], [34]. The model was enclosed within an air rectangular prism. In the exterior faces of the prism, a Dirichlet boundary was set. Second, the authors carried out a 3-D steady-state thermal analysis to calculate the temperature distribution in the flange–bolt region [32]. Stray losses calculated in the electromagnetic software package were transferred to the FE thermal package [32] like heat sources. A uniform convection boundary was placed on the external faces of the bolt, washes, nuts, and flange–bolt region to simulate a laminar free convection in the flange–bolt region. This boundary requires convective heat transfer coefficients h. The values of h were selected by the authors using a methodology that has been fully described in [16] and [17]. Hence, the calculated values of h have been determined using a method of adjustment as in [16] and [17], where the value of h was parameterized in the 3-D FE simulations. This way, h is treated as a variable and properly adjusted to obtain the best match between the measured and simulated temperatures on the transformer. The values of h were taken from a range between 0 and 25 $\mathrm{W/(m^{2\circ}C)}$, where FE simulations were performed using steps of 0.001 $\mathrm{W/(m^{2\circ}C)}$. A FE simulation is considered acceptable if the absolute error (difference between the measured and the calculated temperature) ≤ 0.7.

For 3-D problems, the electromagnetic and thermal software packages provide support for tetrahedron elements with ten nodes, which were employed to create the FE meshes. For each tetrahedron, the software solves the problem at each element vertex and at each midpoint of the element sides. A total of 42 383 FEs were used to construct the electromagnetic model. For the thermal analysis, a mesh of 275 221 FEs and 436 269 nodes was created. In the three simulations performed (described below as cases A, B, and C), the following properties and characteristics were employed.

1) Properties and characteristics of the tank and cover:
    a) The tank walls are made of low carbon steel, which has a conductivity of 5×10^6 S/m and a relative permeability of 500 [34].

   b) Low carbon steel has a thermal conductivity of $45\ \mathrm{W/(m \cdot ^\circ C)}$, a density of $7872\ \mathrm{kg/m^3}$, and a specific heat of $481\ \mathrm{J/(kg^\circ C)}$. These properties were taken from the material library of [32].
   c) The tank cover has a thickness of 3.18 cm, a height of 55.88 cm, and a width of 254 cm.
   d) The region where the nitrile gasket is placed has a width of 3.18 cm, a height of 1.27 cm, and a depth of 254 cm.
2) Properties and characteristics of the LV leads:
   a) The four LV leads of the transformer were modeled using a conductivity of 5.8×10^7 S/m and a relative permeability of 1 [34].
   b) Each copper lead has a thickness of 9.53 mm and a width of 50.8 mm.
   c) There is a separation distance of 44.77 cm between the leads and the transformer tank.
   d) The group of leads is centered with respect to the bolt.
   e) A current of 3030 A at 60 Hz was applied to each copper lead.
3) Characteristics and properties of the bolt, washers, and nuts:
   a) The bolt, nuts, and washers are made of nonmagnetic stainless steel, which has a conductivity of 1.1×10^6 S/m and a relative permeability of 1 [34].
   b) Nonmagnetic stainless steel has a thermal conductivity of $13.8\ \mathrm{W/(m^\circ C)}$, a density of $8055\ \mathrm{kg/m^3}$, and a specific heat of $480\ \mathrm{J/(kg^\circ C)}$. These properties were taken from the material library of [32].
   c) The external diameters of the washers, the washer holes, and the washer height are 5.08, 2.06, and 0.3 cm, respectively.
   d) All the washers were simulated using a polygon of 12 sides.
   e) The bolt has a length of 12 cm and a diameter of 1.905 cm. The bolt was simulated using a polygon of 12 sides. The bolt head was simulated using a polygon of six sides. This head has a height of 1.91 cm and a diameter of 5.08 cm.
   f) The external diameter of the nut is 5.08 cm, and the hole diameter of the nut is 1.91 cm. The height of the nut is 1.91 cm.
   g) The height and diameter of the bolt are 11.43 and 1.91 cm, respectively.

A. Case A

Case A corresponds to the situation where there is good contact between the bolts and the surface of the tank, i.e., when the separation between the tank and tank cover is zero. In this situation, the nitrile gasket is fully compressed (see Fig. 3).

The magnetic field strength limit, above which there is a severe heating problem in the transformer tank, is given by $H_{\mathrm{lim}} = 40$ A/cm. A maximum value of the magnetic field strength of $H = 20$ A/cm was found in the surfaces of the bolt elements: washer and nut (see Fig. 4). These field intensities are lower than H_{lim}. Therefore, there is not a severe heating problem in the transformer tank for this case.

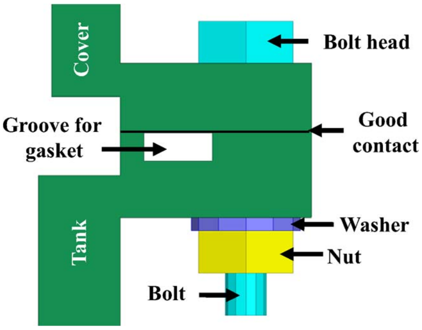

Fig. 3. Geometry for Case A.

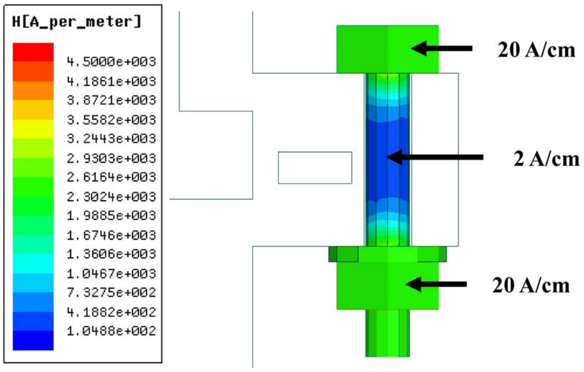

Fig. 4. Distribution of magnetic field strength (A/m) in the flange–bolt region for Case A.

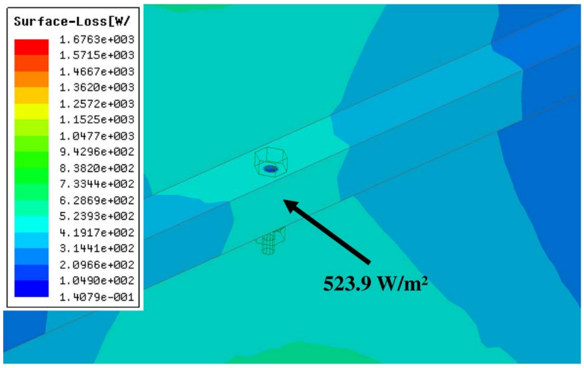

Fig. 5. Loss density distribution $(\mathrm{W/m^2})$ for Case A.

A loss density value of $523.9\ \mathrm{W/m^2}$ was found in the flange near the bolt (see Fig. 5). In this case, stray currents circulate through the entire tank. These currents produce low stray losses in the tank. In this case, the tank and cover are at the same electrical potential.

For the thermal model, authors allocated a convection boundary on the external faces of the tank and bolt elements. An ambient temperature of 30 °C and a convective heat transfer coefficient $h = 13\ \mathrm{W/(m^{2\circ}C)}$ were established. A maximum temperature of 84.476 °C was calculated in the flange–bolt region through the FEM simulations (see Fig. 6). In this case, there is no heating problem in the cover–tank region.

B. Case B

Case B simulates the situation of a loose bolt. It corresponds to the situation where there is bad contact between the bolt and the tank surface: the nitrile gasket has a height of 2 mm

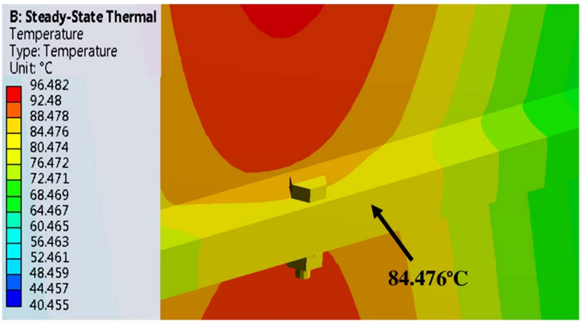

Fig. 6. Temperature distribution (°C) for Case A in flange–bolt region.

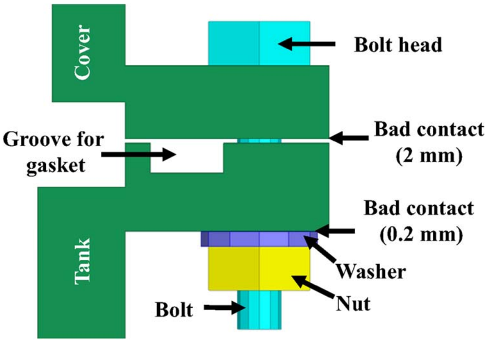

Fig. 7. Geometry for Case B.

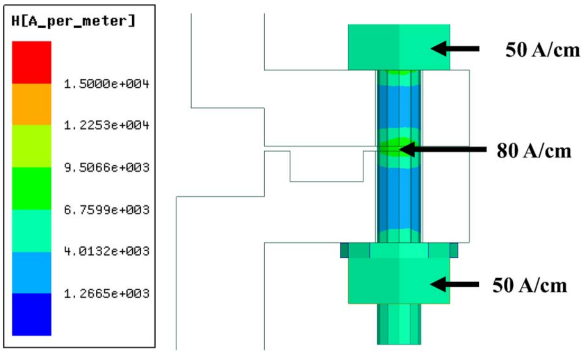

Fig. 8. Distribution of magnetic field strength (A/m) in the flange–bolt region for Case B.

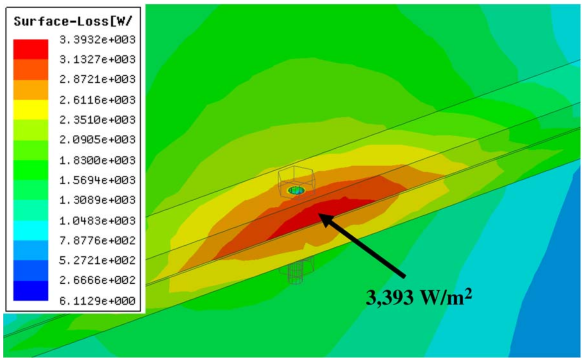

Fig. 9. Loss density distribution ($\mathrm{W/m^2}$) for Case B.

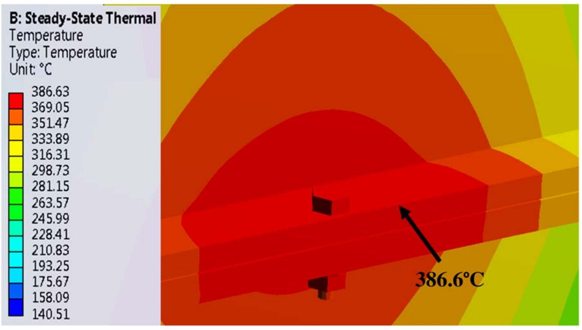

Fig. 10. Temperature distribution (°C) for Case B in the flange–bolt region.

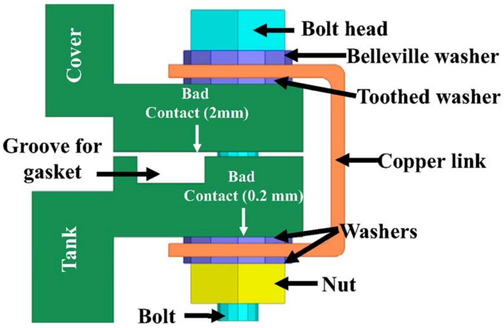

Fig. 11. Geometry for Case C. The copper link has a thickness of 0.635 cm, a width of 5.08 cm, and a length of 8.125 cm.

in excess, simulating an inadequate tightening (see Fig. 7). A magnetic field strength $H = 50$ A/cm was found in the surfaces of the bolt elements, and a maximum magnetic field strength $H = 80$ A/cm was found at the bolt surface exposed to the gap (see Fig. 8). These values are above H_{lim}. Therefore, there is a severe heating problem in the transformer tank in Case B.

A high loss density value of 3393 $\mathrm{W/m^2}$ was found in the tank–cover region near the bolt (see Fig. 9). High stray currents are induced in the tank and circulate through the flange separately. These stray currents produce high stray losses and overheating in the flange–bolt region. In this case, the tank and cover are not at the same electrical potential.

An ambient temperature of 35 °C and a coefficient $h = 3.875\ \mathrm{W/(m^{2}{}^{\circ}C)}$ were employed for the convection boundary. A maximum temperature of 386.6 °C was obtained in the flange–bolt region with the FEM simulations (see Fig. 10). In this case, there is an important overheating problem in the tank–cover region. The high temperatures shown in Fig. 10 can damage some elements of the power transformer: the paint, the seal system, and the transformer oil.

C. Case C

Case C simulates the situation where there is no good contact between the bolt and tank surface. The bolt top side was connected to the bolt bottom side by means of a copper link to ensure good electrical contact between the tank and its cover. The inadequate contact between the tank and the cover is taken into consideration by using an excess of 2-mm height in the nitrile gasket. A copper link is put in the bolt as shown in Fig. 11 to avoid heating problems.

A maximum value of magnetic field strength $H = 24$ A/cm was determined from the FE simulations in the surfaces of the bolt head, washers, nut, and copper link. This value is lower than H_{lim}, which means that, in this case, there are no heating problems in the transformer tank.

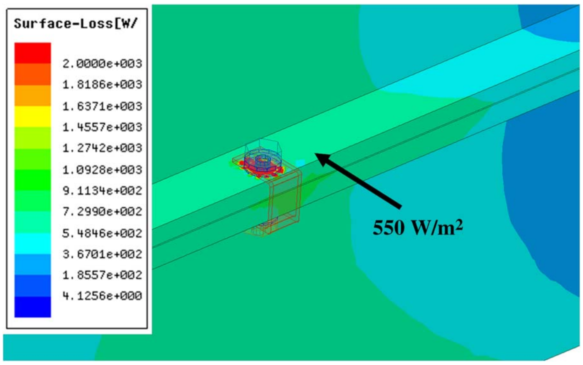

Fig. 12. Loss density distribution (W/m^2) for Case C.

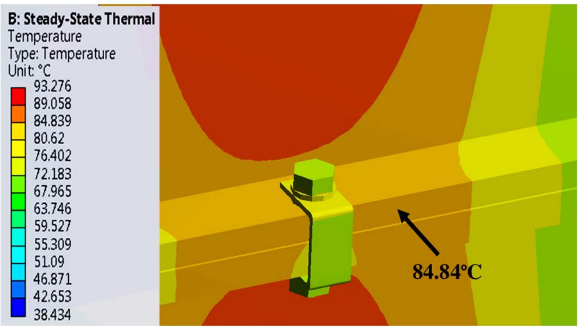

Fig. 13. Temperature distribution (°C) for Case C in flange–bolt region.

A loss density value of 550 W/m^2 was found in the flange near the bolt (see Fig. 12). High stray currents are induced in the tank wall and circulate through the flanges separately. The copper link eases the circulation of the stray currents between the tank cover and its tank. Thus, the copper links provides a path of low impedance for the stray currents. The stray current in the copper link was calculated from the FE simulation, giving a value of 34.15 A. The copper links ensure that the tank and cover are at the same electrical potential. As a result, we conclude that copper links truly help to solve the heating problem in transformer tanks.

An ambient temperature of 30 °C and a convective heat transfer coefficient $h = 13\ \mathrm{W}/(\mathrm{m}^{2\circ}\mathrm{C})$ were employed for the convection boundary. A maximum temperature of 84.84 °C was calculated in the flange–bolt region (see Fig. 13). Therefore, there is no heating problem in the tank–cover region.

Note that the values of h employed in this paper are in the range from 2 to 25 $\mathrm{W}/(\mathrm{m}^{2\circ}\mathrm{C})$. The values of h in this range are very common in 3-D FE simulations that consider laminar free convection of air in hot structural elements of transformers [16], [17].

VI. VALIDATION OF THE COPPER LINK SOLUTION BY MEASUREMENTS

Experimental tests were not conducted in an HV laboratory. They were performed within the substation itself, so we are reporting field measurements. Basically, we made two measurements: 1) temperature measurements using an infrared camera and 2) current measurements using a hook-on ammeter. These measurements were performed with calibrated instruments (a calibrated instrument is a measuring equipment that is compared against a standard instrument of higher accuracy to adjust and rectify the accuracy of the instrument).

TABLE II
CALCULATED CURRENT DENSITY IN COPPER LINKS OF POINTS 1 TO 16 OF FIG. 14, EXCLUDING POINTS 2 AND 7

Points of Fig.14	I_{stray}(Measured stray current in A)	J_{stray}(Calculated current density in copper links in A/mm^2)
1	39.9	0.12
3	84.4	0.26
4	35.2	0.11
5	27.4	0.08
6	84.8	0.26
8	5.4	0.02
9	16.3	0.05
10	2.8	0.01
11	1.7	0.01
12	0.6	0.00
13	1.7	0.01
14	8.2	0.03
15	3.4	0.01
16	7.1	0.02

An infrared thermography technique is a nondestructive inspection method used in preventive maintenance for carrying out quick and accurate measurements. Thus, defective parts can be detected through the simple observation of infrared images, and there is no need to disconnect the transformer. The authors employed this technique to measure the temperature in the flange–bolt region of the transformer. We were careful enough to take infrared images properly. When thermal images are captured inappropriately, the image color can appear to be too bright or too dark. The main characteristics of our infrared camera are as follows: thermal sensitivity of < 0.05 °C, accuracy of ±2%, resolution of 307 200 pixels, and range from -20 °C to 650 °C.

Hook-on ammeters provide convenient means for measuring alternating currents without the need to interrupt the transformer operation. Because the conventional ammeter is connected in series, the test circuit must be broken to remove the ammeter, and the circuit must be reconnected at the conclusion of the current measurement. However, the breaking and reconnection in our case is inconvenient since the transformer is actually operating. The main characteristics of our hook-on ammeter are as follows: operating temperature from -10 °C to 50 °C, operating altitude of 2500 m, accuracy of 2% ± 5 counts (10–100 Hz), diameter of measurable conductor of 30.5 mm maximum, and range from 0 to 999.9 A. The stray current measurements were used for the calculation of the maximum current density, which is, in turn, employed to select the dimensions of the copper links in this paper. Table II shows that the calculated maximum value of current density is $J_{\mathrm{stray}} = 0.26\ \mathrm{A/mm}^2$, which takes place at point 3 of Fig. 14. We found the following: 1) high stray currents in the bolts located near the LV bushings and 2) low stray currents in the bolts located near the HV bushings. We also measured high stray currents on the region near the loose bolts. In this case, critical loose bolts are indeed located near the LV bushings, where high magnetic fields are produced. These magnetic fields

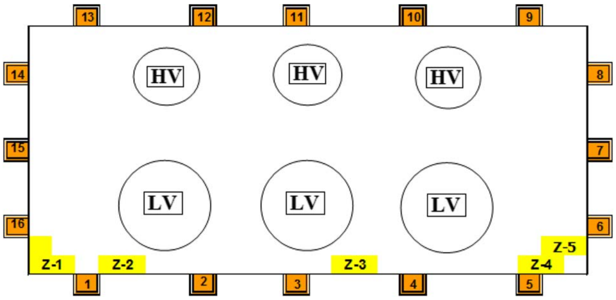

Fig. 14. View of transformer cover. Zones Z-1 to Z-5 presented hot spots.

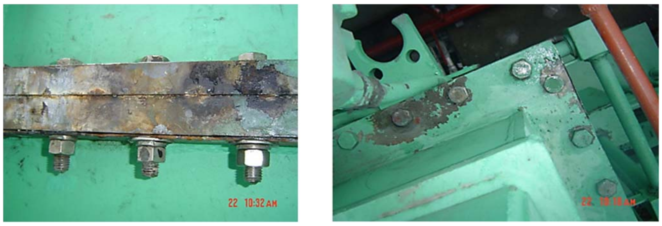

Fig. 15. (a) Paint loss due to overheating (zone 2: 386.9 °C) in the connection of flange–bolts (left). (b) Paint loss due to overheating (zone 1: 140.8 °C) in the connection of flange–bolts (right).

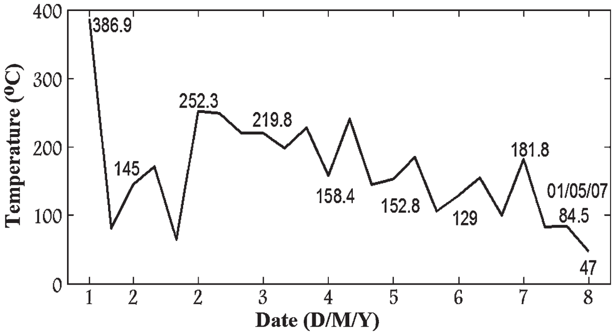

Fig. 16. Thermal behavior of zone 2. Date 1: 3/09/05. Date 2: 5/09/05. Date 3: 12/09/05. Date 4: 14/09/05. Date 5: 16/09/05. Date 6: 20/04/06. Date 7: 30/04/07. Date 8: 21/02/08.

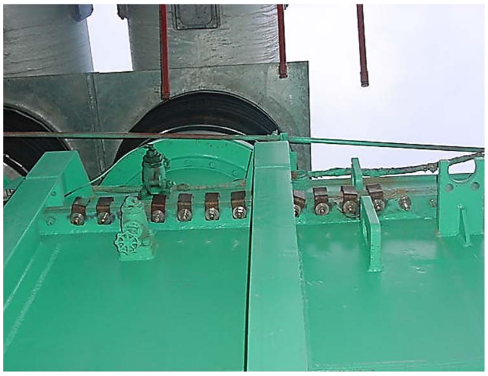

Fig. 17. Several copper links were used as a conductor bridge between the tank and the cover.

TABLE III
TEMPERATURE MEASUREMENTS IN 1997, 2005, 2007, AND 2008. THE USE OF COPPER LINKS IN MAY 2007 REDUCED THE TEMPERATURE IN ZONE 2 TO 84.5 °C

DATE (D/M/Y)	LOAD (MW)	TEMPERATURE (ºC)		
		Ambient	Zone 1 or 4	Zone 2
1997	350	30	Zone 1: 60	85
03/Sept/2005	350	35	Zone 1: 140.8	386.9
01/May/2007	350	30	Zone 4: 59	84.5
21/Feb/2008	175	29	Zone 1:45	46.8

aggravate the problem of induction of high stray currents in the tank and cover. On the other hand, the magnetic fields produced by transformer windings have a poor impact on the induced stray currents in the tank and cover because the entire tank is shielded by magnetic shunts located in the tank walls.

Fig. 15 shows the cover of the failed transformer, indicating that there was overheating (presence of hot spots) in zones Z-1 to Z-5. This maximum current density $(J_{\text{stray}} = 0.26\ \text{A/mm}^2)$ represents a very safe value that allows the use of copper links of 322.58 mm^2 of cross-sectional area. Hence, copper links are selected using a current density criterion.

The authors found the evidence of areas with high temperatures (paint loss), which are shown in Fig. 15. Temperature measurements were therefore carried out using infrared thermography. Fig. 16 shows the thermal behavior of zone 2 at the junction of the tank cover with the transformer tank. It can be observed that temperatures above the limit of 135 °C occurred at several points. According to McShane [35], it is not advisable to let the temperature of the transformer metal parts (where there is poor contact with the transformer oil) to reach values greater than 140 °C because, above this temperature, gas formation can take place within the transformer oil.

The manufacturer staff carried out the following changes in the studied transformer:

1) changed the existing bolts and nuts by new ones made of nonmagnetic material (stainless steel A316);
2) installed Belleville washers of nonmagnetic material (stainless steel A316);
3) installed toothed washers of nonmagnetic material (stainless steel A316);
4) installed bridges using copper link in 49 bolts.

Fig. 17 shows ten copper links between the tank cover and the tank. Table III shows the most relevant measurements of temperature that were collected from September 3, 2005 to February 21, 2008. In May 2007, a total of 14 copper links were placed on the transformer cover, while all old nuts and bolts were replaced by new bolts and nuts made of nonmagnetic material (stainless steel A316). It can be seen from Table III that the proposed solution reduced the temperature to 84.5 °C in zone 2 considering a load of 350 MW. We note in Table III that the minimum and maximum ambient temperatures are 29 °C and 35 °C, respectively, which correspond to a tropical climate.

It is interesting to notice that a 14.5% difference was found between the stray current measured in the copper link (see Table II for the link at point 1 of Fig. 14, where $I_{\text{stray}} = 39.9$ A) and the stray current calculated in the copper link by the FE simulation (34.15 A). A difference of 0.61% was found between the measured (zone 2: 85 °C; see Table III) and calculated temperatures (FE simulation: 84.476 °C; see Fig. 6).

Fig. 18 shows the infrared thermography in zone 2, before and after placing the copper link. In September 2005, before

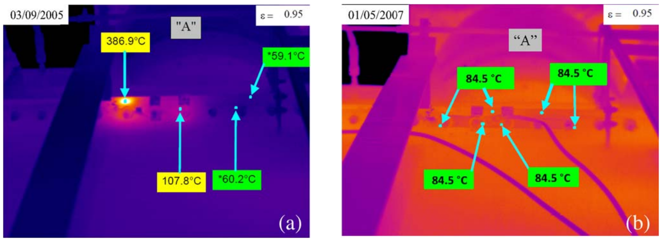

Fig. 18. Temperature measurement of zone 2. (a) Before placing the copper links. (b) After placing the copper links.

placing the copper link, the maximum temperature reached 386.9 °C as Fig. 18(a) shows. A difference of 0.1% was found between the temperature measured (zone 2: 386.9 °C; see Table III) and the temperature calculated by the FE simulation (386.6 °C).

After placing the copper link in the cover bolt of zone 2 (May 2007), the temperature was reduced to 84.5 °C as Fig. 18(b) shows. A difference of 0.4% was found between the temperature measured (zone 2: 84.5 °C; see Table III) and the temperature calculated by the FE simulation (84.84 °C).

Similarly, in zone 4, the maximum temperature was 86 °C before placing the copper links, while the maximum temperature was reduced to 59 °C when copper links were placed. Thus, the use of copper links has been very effective to reduce the overheating problem. The temperature in the flange–bolt regions was decreased, and the problem of the loose bolt was solved. We stress out that, after the application of the copper links, the power transformer operated without heating problems.

VII. CONCLUSION

This paper has shown the detrimental effect of bad physical contact between the cover and walls of power transformer tanks. The results indicate that an applied torque of less than 190 $\mathrm{N \cdot m}$ (loose bolts) increases the thickness of the sealing system. This, in turn, causes an increase in stray currents as the bolts serve as current paths. This leads to the overheating of the flange, which could result in extreme fire explosion. To avoid the occurrence of such hot spots, it is important that the bolts are kept tight at all times, by an arrangement like the one used in this work (Belleville washers, antiseize paste, and proper torque provided by the transformer manufacturer). Furthermore, when copper links are installed between bolts, which connect the cover and the transformer tank, they help to avoid potential differences that produce the stray currents, providing, in addition, a greater surface for heat dissipation. Experimental and numerical work has been used to substantiate our claims, proving that they are very effective in reducing the overheating problem in the transformer tank. The design of the copper links was carried out using a criterion of current density. From our measurements and simulations, we have found that hot spots are located in zones Z-1 to Z-5. Our recommendation would be to place copper links only in these zones. However, since the cost of each copper link is extremely low ($0.5) compared to the very high cost of the transformer ($2 000 000), our practical recommendation is to place copper links in all bolts.

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