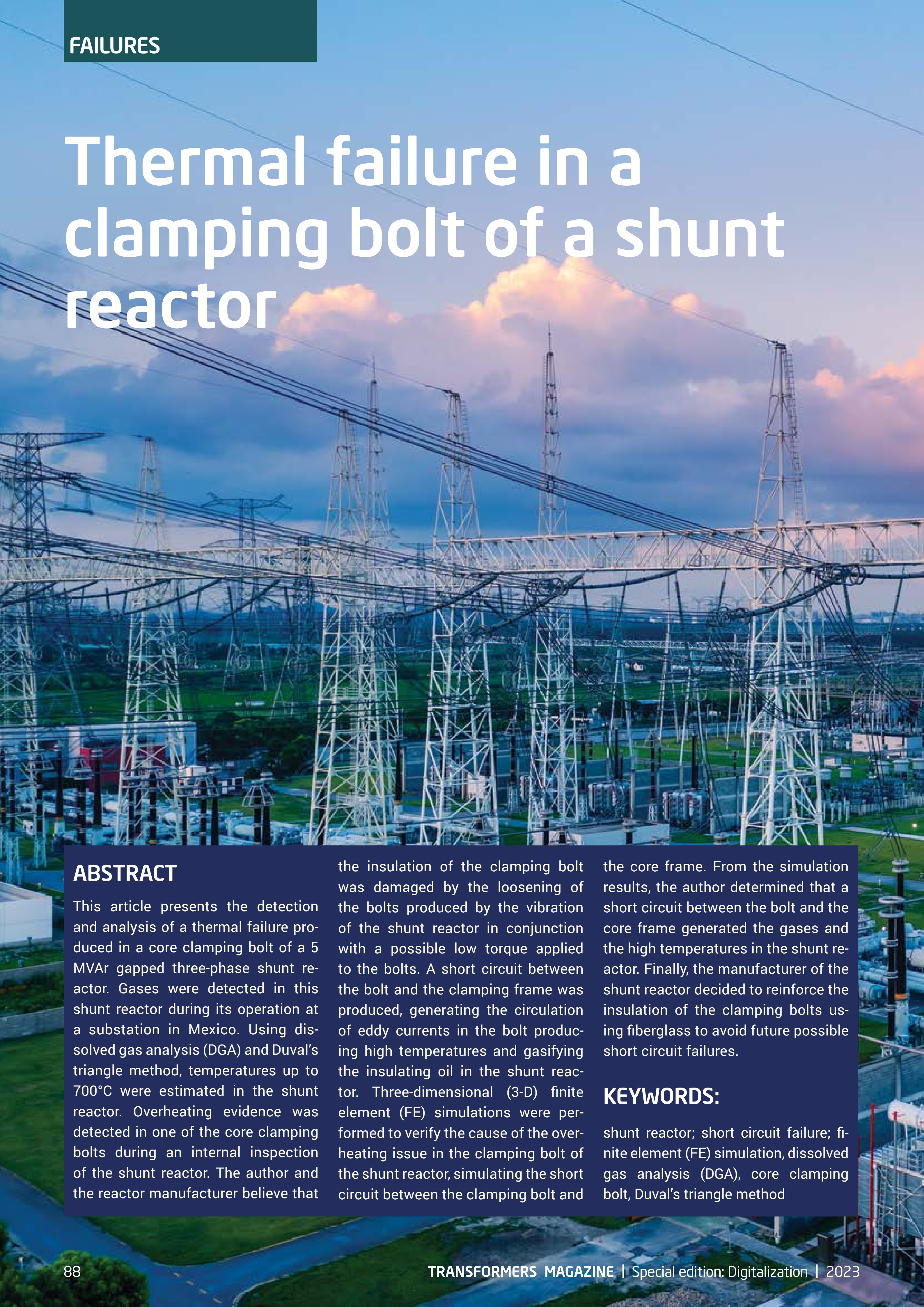
Thermal failure in a clamping bolt of a shunt reactor



ABSTRACT

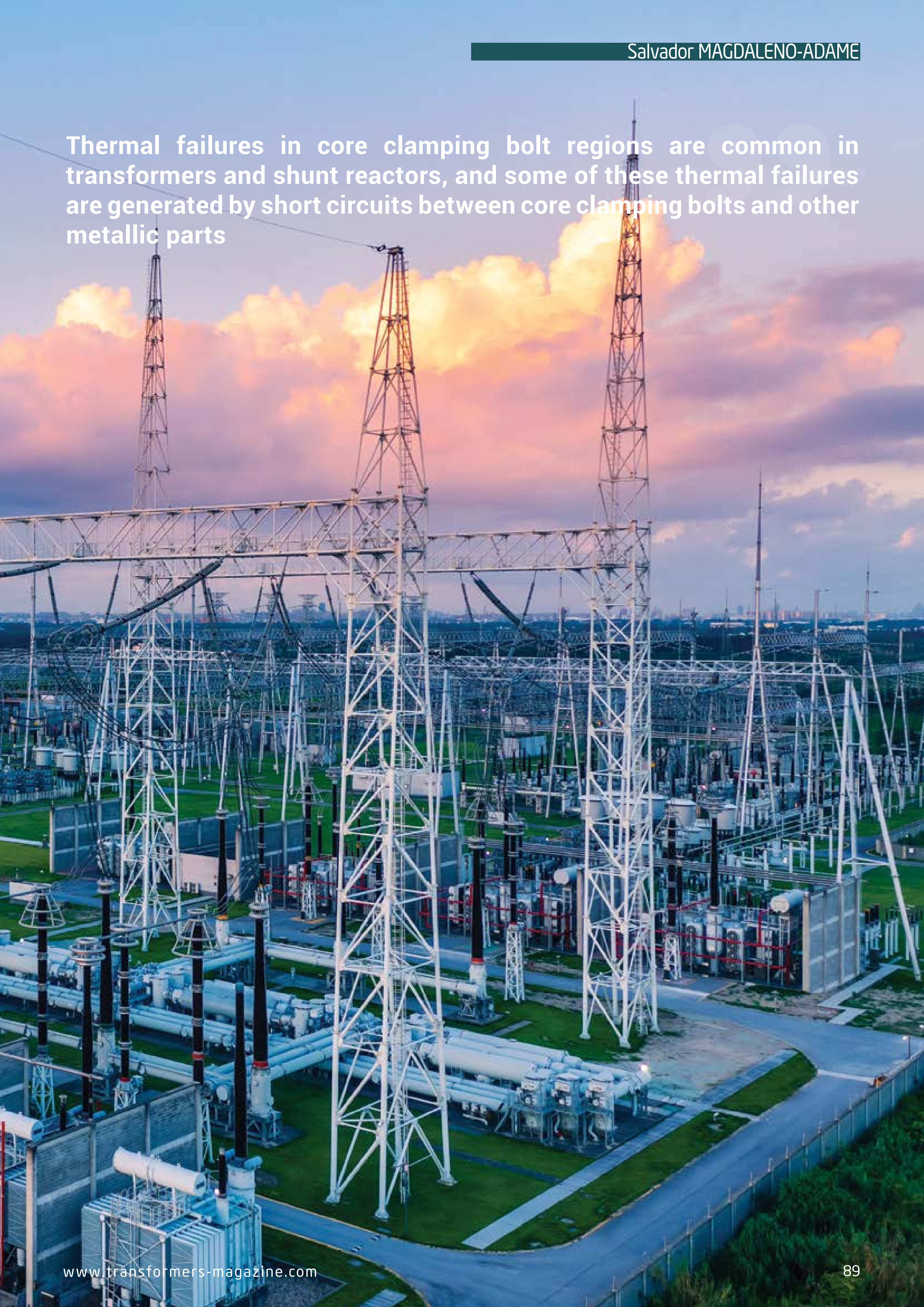
This article presents the detection and analysis of a thermal failure produced in a core clamping bolt of a 5 MVAr gapped three-phase shunt reactor. Gases were detected in this shunt reactor during its operation at a substation in Mexico. Using dissolved gas analysis (DGA) and Duval's triangle method, temperatures up to 700°C were estimated in the shunt reactor. Overheating evidence was detected in one of the core clamping bolts during an internal inspection of the shunt reactor. The author and the reactor manufacturer believe that the insulation of the clamping bolt was damaged by the loosening of the bolts produced by the vibration of the shunt reactor in conjunction with a possible low torque applied to the bolts. A short circuit between the bolt and the clamping frame was produced, generating the circulation of eddy currents in the bolt producing high temperatures and gasifying the insulating oil in the shunt reactor. Three-dimensional (3-D) finite element (FE) simulations were performed to verify the cause of the overheating issue in the clamping bolt of the shunt reactor, simulating the short circuit between the clamping bolt and the core frame. From the simulation results, the author determined that a short circuit between the bolt and the core frame generated the gases and the high temperatures in the shunt reactor. Finally, the manufacturer of the shunt reactor decided to reinforce the insulation of the clamping bolts using fiberglass to avoid future possible short circuit failures.

KEYWORDS:

shunt reactor; short circuit failure; finite element (FE) simulation, dissolved gas analysis (DGA), core clamping bolt, Duval's triangle method

Salvador MAGDALENO-ADAME

Thermal failures in core clamping bolt regions are common in transformers and shunt reactors, and some of these thermal failures are generated by short circuits between core clamping bolts and other metallic parts



The presence of gases was monitored and detected in a 5 MVAr three-phase shunt reactor during its normal operation condition

Introduction

Thermal failures in core clamping bolt regions are common in transformers and shunt reactors [1]–[3]. Some of these thermal failures are generated by short circuits between core clamping bolts and other metallic and magnetic parts, producing the circulation of high currents in these bolts [4]–[7]. These currents can develop high temperatures in the bolts and the near-clamping frame regions. In power transformers and shunt reactors that are immersed in insulating oil, these high temperatures break down the oil and generate gases, which leads to a failure of these apparatus during their operation in the electrical power systems. Different overheating issues and overheating faults produced by core clamping bolts in transformers and shunt reactors have been detected and analyzed [4]–[7]. For example, in [4] and [5], thermal failures produced in the connection bolts of core clamping structures of transformers are presented. During internal inspections, some regions with overheating evidence were detected in the connection bolts of core clamping frames. The insulation of these bolts failed, and high currents circulated in the bolts, producing high temperatures and overheating the regions of the bolts. In [6], a severe thermal fault produced by a melted core clamping bolt is presented. The stainless-steel clamping bolt was completely melted in the interior of the magnetic core of a transformer. The insulation of the bolt failed and produced a short circuit between the bolt and the steel laminations of the magnetic core, generating the circulation of high currents in the bolt. The circulation of these high currents melted an important portion of the clamping bolt. In [7], a thermal failure was detected in a core clamping bolt of a shunt reactor. The presence of gases was detected in the reactor using dissolved gas analysis (DGA). Parts of a core clamping bolt were found in one of the core clamps of the shunt reactor during an internal inspection. The bolt and some core steel laminations presented overheating signs. The clamping bolt was removed from the magnetic core, and the insulation of the bolt presented evident damage. In this case, the overheating failure was produced by the circulation of a high current in the bolt produced by a short circuit between the bolt and the laminations of the core and the steel clamping structure of the shunt reactor.

On the other hand, other interesting thermal failures produced by core clamping bolts have been detected in hydroelectric generators. For example, in [8], thermal failures in the stator core clamping bolts of a real hydroelectric generator were studied and analyzed using finite element (FE) simulations. The authors performed an internal inspection of the generator to detect and locate the thermal failures. Several stator core clamping bolts presented severe damage with visible signs of overheating and melting, while some bolts presented mechanical fractures. The insulation of the bolts was destroyed and carbonized. The main cause of the overheating failure was a short circuit between the bolts and the core bars, precisely where the insulation material was damaged and destroyed. When the insulation material between the core bars and the bolts was destroyed, a short circuit was produced between them. High currents circulated in the bolts and core bars, subjecting the bolts to high electromagnetic forces, producing mechanical vibration that eventually led to overheating and melting of the bolts of the generators.

In this article, the origin of a thermal failure in a core clamping bolt of a shunt reactor is presented, analyzed, and demonstrated using Multiphysics three-dimensional (3-D) finite element (FE) simulations. The process utilized to diagnose the thermal failure in the shunt reactor is presented. Utilizing electromagnetic and thermal finite element simulations, the author demonstrated that the thermal fault was produced by a short circuit between the bolt and one of the clamping frames producing the circulation of high current in the bolt and producing temperatures of almost 850 °C.

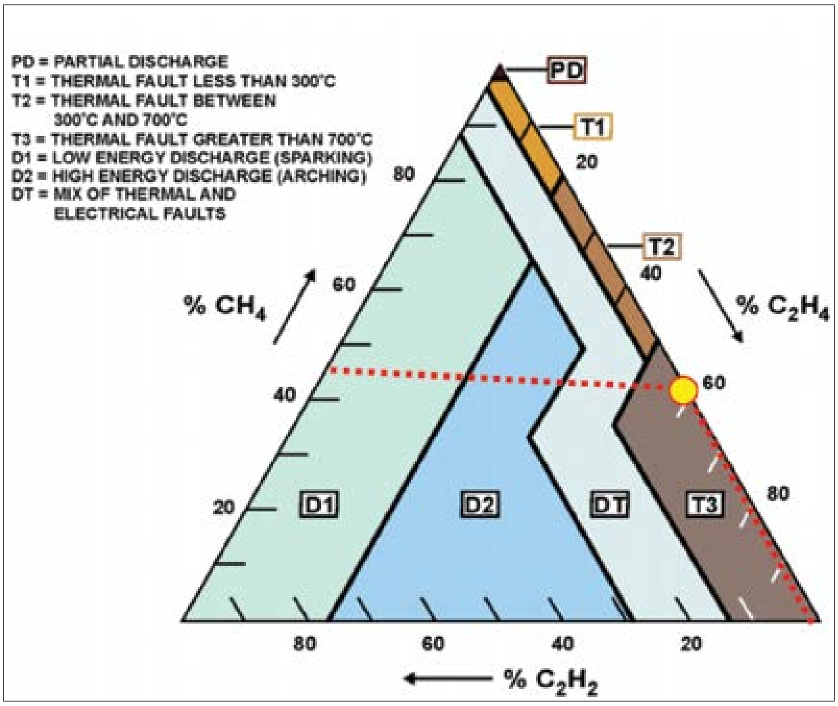


Figure 1. Identification of the thermal fault in the shunt reactor using Duval's triangle method

Overheating Failure in the Shunt Reactor

The presence of gases was monitored and detected in a 5 MVAr three-phase shunt reactor during its normal operation in a substation in Mexico [9]. Table 1 shows the characteristics of the shunt reactor [10]. Over five months, high amounts of hydrogen (H_2), ethylene (C_2H_4), acetylene (C_2H_2), and methane (CH_4) were detected in the shunt reactor, indicating the presence of a possible high-temperature fault. Table 2 shows the dissolved gas analysis (DGA) results obtained in the shunt reactor [9]. A thermal fault was confirmed using Duval's triangle method and the DGA results of Table 2. From Duval's triangle, a thermal fault type T3 was diagnosed in this shunt reactor, see Figure 1. A thermal fault type T3 indicates a failure in insulating oil and/or paper above 700 °C with evidence of carbonized oil, with metal coloration or melting. The possible causes for these thermal faults could generate overheating regions, partial discharges, and sustained electric arcs [11]-[13]. Despite the detection of gases in the shunt reactor, the Mexican electric utility company and substation operators decided to run the failure of the shunt reactor, which never fully occurred.

After detecting the thermal fault, the shunt reactor was put out of service, and the substation staff decided to send the shunt reactor for repair to the original manufacturer. An internal inspection was performed to locate the failure region in the shunt reactor. Clear signs of overheating were found in the region of one of the non-magnetic stainless steel clamping bolts in one of the top low-carbon steel clamping frames of the shunt reactor, see Figure 2 (a). The bolt presented evidence of carbonized oil and insulation residues, but it did not present cracks or evidence of melting. It indicates that the temperature of the clamping bolt reached temperatures below 1400 °C (melting point).

Visible signs of overheating were found in the region of one of the non-magnetic stainless steel clamping bolts in one of the top low-carbon steel clamping frames of the shunt reactor

The carbonized residue of insulation was found around the bolt region, with more found on the top coil region. The clamping bolt was removed from the top frame, and the manufacturer discovered that an important part of the insulation along the bolt had been damaged and destroyed, leaving the bolt bare, see Figure 2 (b). Generally, several layers of insulating paper are employed to insulate the clamping bolts from the core yokes and frames. The insulation along the bolt prevents possible contact between the bolt and the core frames and contact between the bolt and the magnetic core laminations. The author and manufacturer believe that the main cause of the damaged bolt insulation was produced by the loosening of the bolts produced by the vibration of the shunt reactor in conjunction with a low torque applied to the bolts during the tightening process [14]. The reactor vibration loosened the clamping bolt, damaging and destroying its insulation and producing a short circuit between the core frame and the bolt, generating the circulation of a high current in the bolt and generating high temperatures in the bolt-frame region. Thermal faults have been detected in high-voltage shunt reactors due to vibrations [15], [16].

To verify this assumption about the short circuit between the bolt and the frame, 3-D Multiphysics FE simulations were performed to verify the cause of overheating in the bolt of the shunt reactor. In the next sections of this paper, the results of the 3-D FE simulations will be presented, and the origin of the overheating fault will be demonstrated.

Table 1. Characteristics of the shunt reactor [9], [10]

Characteristic	Value
Number of phases	3
Nominal Power	5 MVAr
Nominal Voltage	115 kV
Nominal current	25.1 A
Frequency	60 Hz
Cooling system	ONAN
Top oil temperature	80 °C

Table 2. DGA results of the shunt reactor [9]

Gas, content	Dec 10th	Dec 12th	Dec 31st	Jan 31st	Feb 28th	Mar 31st	Apr 30th	May 31st
CO, ppm	80	90	130	160	175	195	210	215
H_2, ppm	80.5	186	760	3110	8500	10100	12700	12300
CH_4, ppm	123	317	1650	7220	19300	45500	64600	73100
C_2H_6, ppm	43.2	93.8	508	2420	5840	11000	17200	19100
C_2H_4, ppm	181	437	1800	7120	25900	51600	70500	78500
C_2H_2, ppm	1.8	2.4	2	9.4	34.2	163	153	262

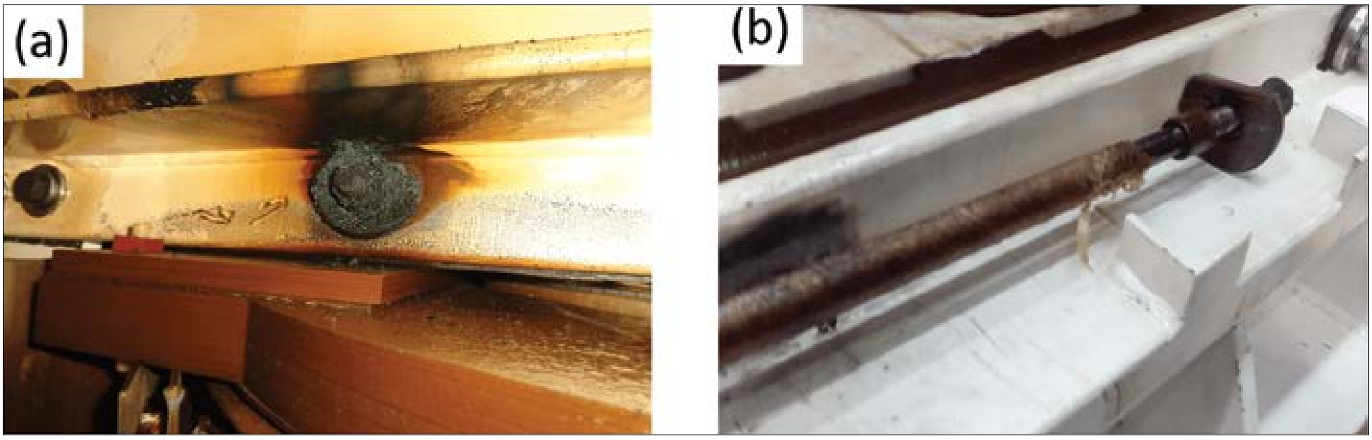


Figure 2. a) Bolt and frame with signs of overheating, b) insulation of the bolt destroyed [9]

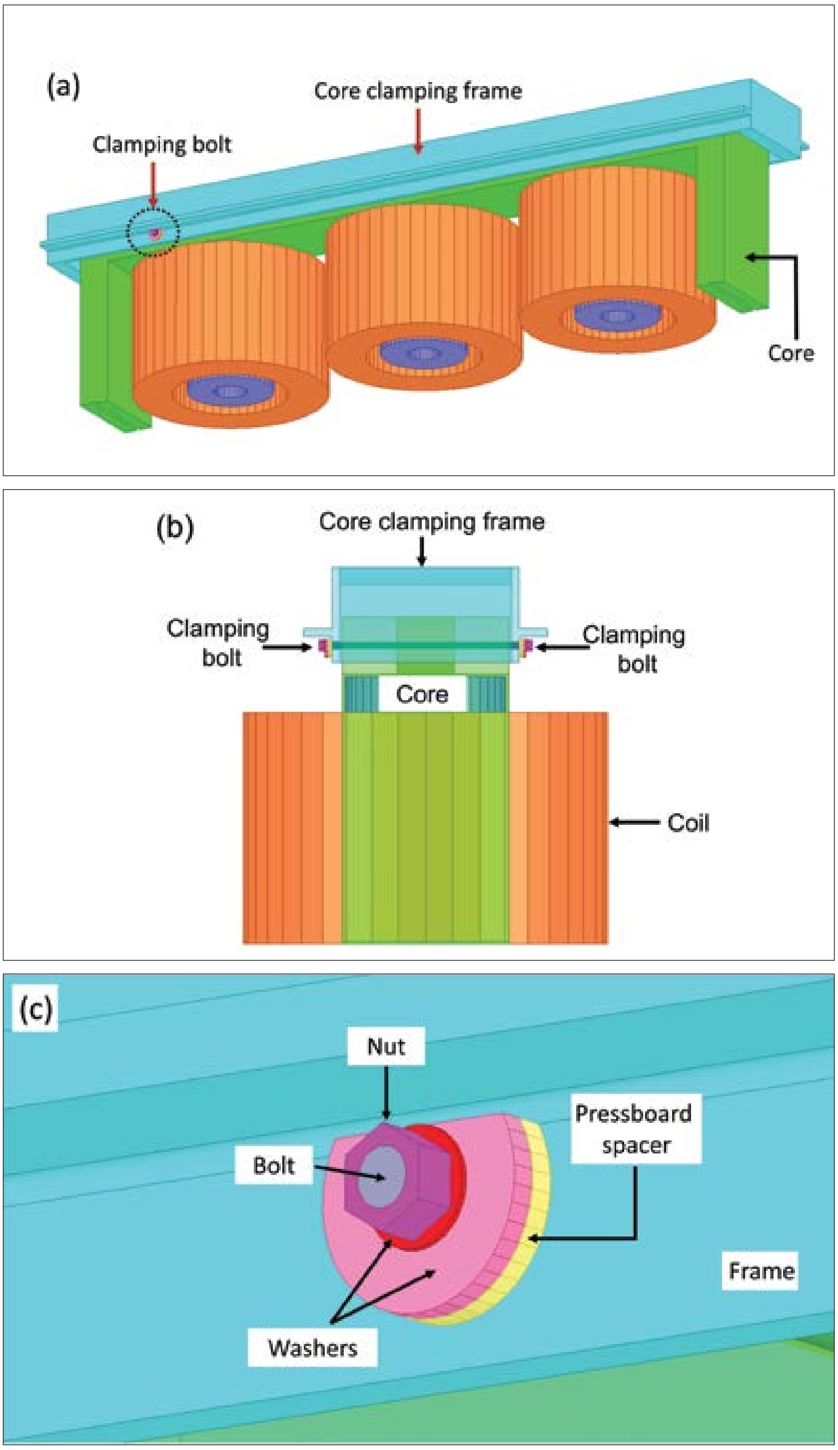


Figure 3. a) shunt reactor model, b) lateral view of the shunt reactor model, c) view of the clamping bolt region

3-D finite element electromagnetic and thermal simulations were performed to figure out the cause of overheating in the clamping bolt of the 5 MVAr shunt reactor

Multiphysics Analysis

3-D finite element (FE) simulations were performed to figure out the cause of overheating in the clamping bolt of the 5 MVAr shunt reactor. Time-harmonic FE simulations were performed to compute the power losses in the clamping system of the shunt reactor, including the power losses in the bolt. The current circulating in the bolt was computed in this analysis. Static thermal simulations were carried out to compute the temperature distribution in the clamping system and clamping bolt utilizing the power losses computed in the time-harmonic analyses. The Multiphysics FE analyses permit us to analyze the presence of hot spots or regions with high temperatures in structural parts of power transformers and shunt reactors [17], [18]. Moreover, the Multiphysics FE analyses permit us to analyze different techniques for the reduction of these hot spots or high temperatures in shunt reactors and power transformers, for example, magnetic shunts, electromagnetic shields, stainless steel inserts, etc.

The interest regions of the 3-D shunt reactor model are presented in Figure 3. The coils of the shunt reactor are made of copper conductors, and the magnetic core is made of laminations of grain-oriented electrical steel. The clamping frames are made of low-carbon steel, while the bolts, nuts, and flat washers are made of non-magnetic stainless steel.

Overheating Failure Analysis of Clamping Bolt

A single clamping bolt is modeled and put in direct contact with one of the clamping frame sides of the shunt reactor to simulate the short circuit conditions presented in the real shunt reactor. All the other clamping bolts are completely insulated from the frames, and no current is circulating through them. For this reason, these bolts are omitted in the model of Figure 3. A current density of 130 A/cm^2 and a short circuit current of 160 A were computed in the clamping bolt under short circuit conditions. This current circulates in the bolt, passing through the magnetic core holes. This current produces a small and saturated region with a magnetic flux density of 2 T around the magnetic core holes, see Figure 4.

A current density of 130 A/cm2 and a short circuit current of 160 A were computed in the clamping bolt under short circuit conditions

Figure 5 shows the loss density distribution in the clamping frame region. A maximum loss density of 3000 W/m^2 was computed in the frame region in the bolt-hole region. Figure 6 shows the current circulating in the bolt during the short circuit between the bolt and the clamping frame of the shunt reactor.

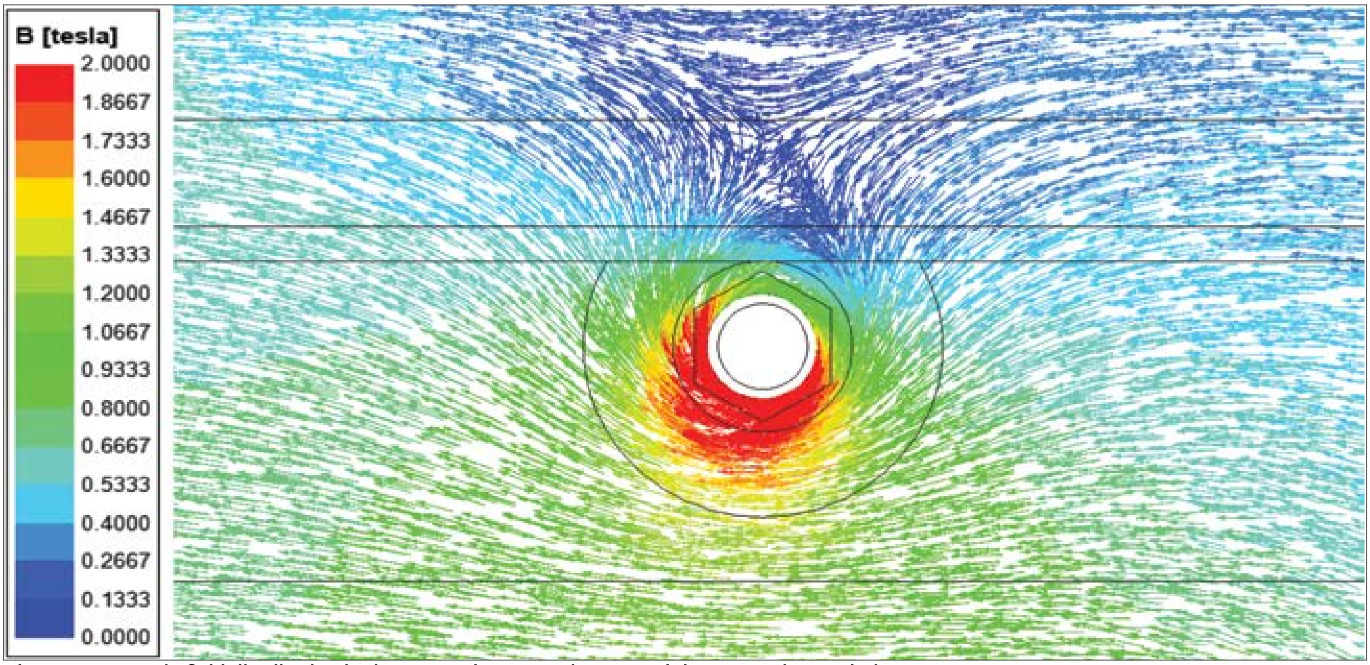


Figure 4. Magnetic field distribution in the magnetic core region around the magnetic core hole

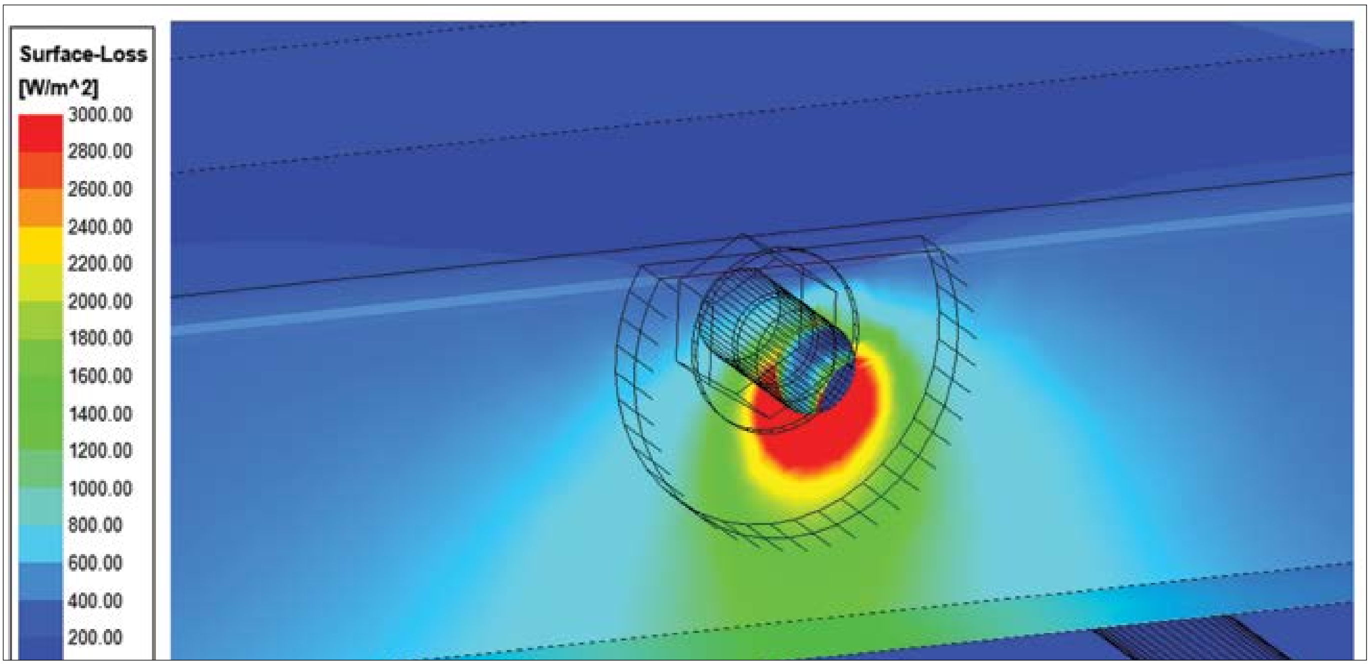


Figure 5. Loss density distribution in the bolt-frame region

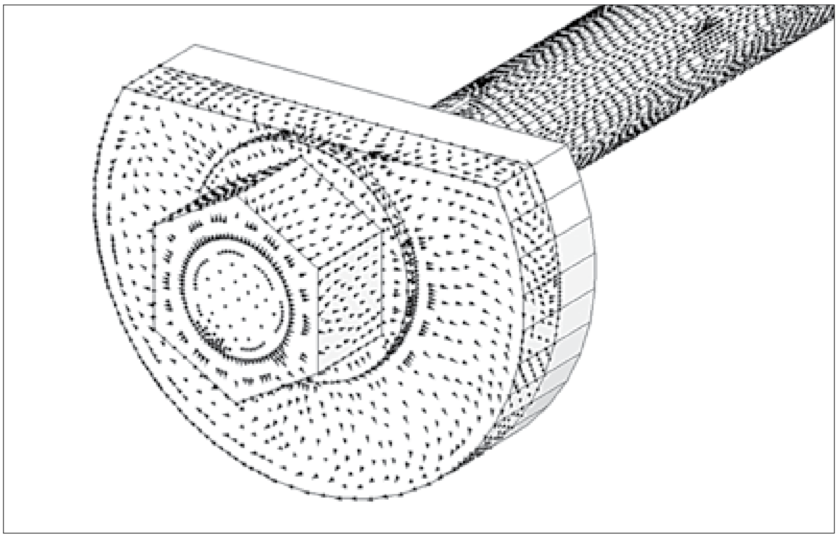


Figure 6. Short circuit currents circulating in the clamping bolt

The numerical calculations showed that the bolt reached an average temperature of 850 °C and a maximum temperature of almost 950 °C

Figure 7 shows the temperature distribution during the presence of the short circuit current in the clamping bolt. The bolt reached an average temperature of 850 °C and a maximum temperature of almost 950 °C. The poor circulation of the oil in the bolt-magnetic core region helped to increase the temperature of the bolt.

Based on the simulation results, the manufacturer decided to repair the shunt reactor, reinforcing the insulation of all the stainless-steel clamping bolts with several layers of fiberglass to prevent future short-circuit failures. In addition, the manufacturer replaced all the pressboard spacers with thick fiberglass spacers, and a bolt torque of 57 Nm was verified for all the bolts during the tightening process. Finally, the temperature of the repaired shunt reactor was monitored and tested in the high-voltage laboratory before shipping the shunt reactor to the customer.

Conclusion

In this article, the cause of the overheating failure of a clamping bolt in a high-voltage shunt reactor was presented and studied using Multiphysics finite element simulations. Because of the loosening of the clamping bolt produced by the vibration of the shunt reactor during its normal operation, the main insulation of the clamping bolt was damaged and destroyed, producing a short circuit between the bolt and the frame of the shunt reactor. A considerable short circuit current circulated in the bolt for a prolonged time, heating the bolt and the frame region where the short circuit was produced. The high temperatures in the bolt region broke down the oil and generated gases, and a thermal failure was diagnosed for the shunt reactor. Temperatures up to 800 °C were estimated in the bolt region of the shunt reactor. Finally, the reactor manufacturer decided to reinforce the insulation of the clamping bolts to prevent the risk of future short circuit failures in the clamping bolts.

Based on the simulation results, the manufacturer decided to repair the reactor, reinforcing the insulation of all the stainless-steel clamping bolts with several layers of fiberglass to prevent future short-circuit failures

Acknowledgements

The author thanks R. Ocon from Industrias IEM and E. Cortina and J.C. Olivares from UAM for the technical and design information about the shunt reactor, and the author thanks them for the invitation to be a consultant and external assessor for the analysis of this shunt reactor.

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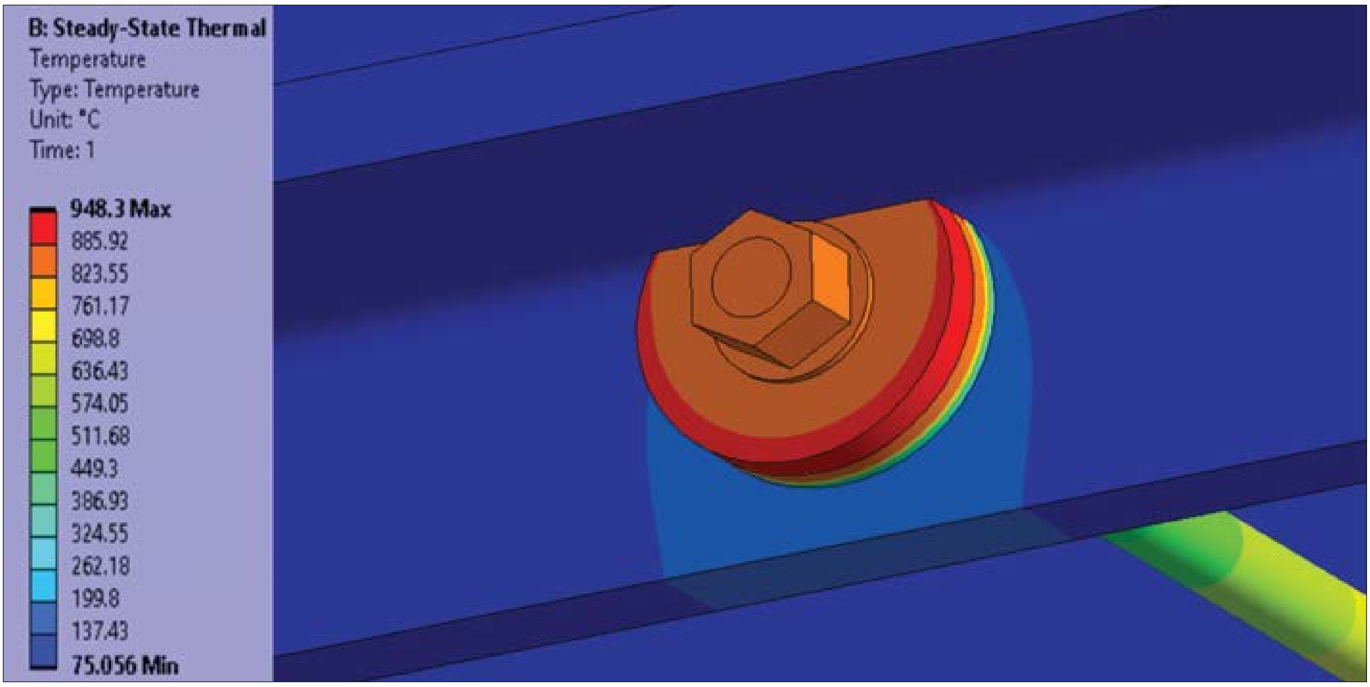

Figure 7. Temperature distribution in the clamping bolt and frame region

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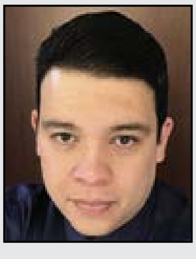

Salvador Magdaleno-Adame received a B.Sc. degree in electrical engineering from the Universidad Michoacana de San Nicolas de Hidalgo in 2008 and an M.Sc. degree in electrical engineering from the Instituto Tecnologico de Morelia in 2013. From 2008 until 2010, he worked at Industrias IEM S.A. de C.V. as an R&D engineer for power transformers, where he conducted research and design reviews on shell-type and core-type power transformers, and he also worked on the development of HV shunt reactors. He has occupied several magnetic and electromagnetic engineering positions in companies in the United States, working in diverse magnetic and electromagnetic technologies, including transformers, permanent magnet motors, actuators, loudspeakers, permanent magnet technologies, magnetic materials applications, etc. He has authored over 60 papers for journals and conferences, and he has over 20 years of experience in finite element electromagnetic analysis of electromagnetic devices. He owns a consultancy business called **"Salvador Consultant – www.salvadorconsultant.com"** to support the magnetic and electromagnetic industry in the United States.