25th IMEKO TC4 International Symposium
23rd International Workshop on ADC and DAC Modelling and Testing
IMEKO TC-4 2020
Brescia, Italy / September 12-14, 2022

Temperature Rise in MV Switchgears: the Role of Loose Busbar Joints

Susanna Spinsante[1], Grazia Iadarola[1], Gianmarco Mazzocchi[2], Claudio Romagnoli[2]

[1] *Department of Information Engineering, Polytechnic University of Marche, Ancona, Italy, {s.spinsante,g.iadarola}@staff.univpm.it*
[2] *IMESA SpA, Jesi, Italy, {gianmarco.mazzocchi,claudio.romagnoli}@imesaspa.com*

***Abstract* – The identification of the different causes of a Medium Voltage (MV) switchgear failure is a complex task. Among the conditions contributing to failure, thermal cycling due to loose joints and electrical components may act as a trigger for fault. This paper presents an experimental analysis of temperature variation taking place in 27 different points of a MV switchgear and originating from loose mechanical and electrical joints in the busbars, compared to the normal operating condition. The loose joints - due to improper installation, vibrations, or ageing of components - are obtained by applying a controlled clamping below the recommended operational value of 45 Nm torque, to six busbar joint screws (two for each phase). Results show that when the applied clamping goes below 10% of the recommended value, temperature does not rise significantly in points other than the loose ones, while the main circuits exhibit a detectable variation of their electrical resistance.**

I. INTRODUCTION

Faulty joints are counted among the major causes of switchgear failure, that not only disrupts power production, transmission, distribution, or conversion, but may also lead to dangerous accidents. A faulty or loose connection, in fact, can increase electrical resistance and, as a consequence, heat-dissipated power. Temperature rise due to increase in heat may escalate until the joint or nearby insulation completely fails, thus resulting in a fault. Estimates supported by experience of well-established industrial operators report that around 25% of Medium Voltage (MV) switchgear faults are determined by loose joints or hot spots in the switchgear [1]. Thermal monitoring, together with Circuite Breaker (CB) drive and partial discharge monitoring, is one of the main tasks nowadays addressed by predictive maintenance solutions designed for switchgears [2, 3]. In fact, in order to reduce costs, more and more electrical equipment operators are changing their traditional approach to maintenance, moving from reactive and preventive maintenance, towards embedded monitoring systems, typically based on Internet of Things (IoT) systems, joint with Artificial Intelligence (AI) and Machine Learning (ML) approaches, able to interpret sensor-measured data inside the switchgear, and provide a prediction of incoming fault. Unfortunately, continuous temperature measurements that could be very helpful in training predictive maintenance algorithms, are extremely rare or even not existing at all for the switchgear, over its long lifetime [4, 5].

In current practice, infrared inspections of the switchgear are performed regularly through ad-hoc viewing ports in the enclosure, using handheld thermal cameras [6]. In order to implement predictive maintenance systems exploiting real-time measurements, proper temperature sensors should be installed inside switchgears, where several electrical connections are established by mechanically screwing together with metal conductors, such as busbars. As Joule's first law states, $P \propto I^2 R$, so both current and resistance contribute to generated heat from current circulating in a conductor. Loose joints, corrosion, and deterioration increase the resistance of electrical contacts; as a consequence, the detection of hot spots allows to identify the possible points from which a fault could originate.

Loose joints may be due to improper action by the operator, such as a wrong torque applied to screws after a maintenance operation; or they may be due to ageing of components, or mechanical stress, such as vibrations, determined by the operational environment where the switchgear is located. A real-time thermal monitoring system should be equipped with enough temperature sensors to monitor all possible faulty joints inside the switchgear, but this could rapidly increase the number of sensing units needed, thus increasing also cost and complexity. As a consequence, this study focuses on the effective role of loose joints in causing temperature rise inside the switchgear. To this aim, loose joints are established on purpose in six busbar screws, two for each phase, and the variation of the temperature relative to the ambient temperature is measured both at the loose screws and in other 21 different points inside the switchgear, by means of type K thermocouples. The attained temperature variations are compared to those registered during normal operation of the switchgear, in the same positions. Additionally, the variation of the electrical resistance of the switchgear main circuits, before and after the simulation of the fault, is analysed. This analysis is different from the one found in [7], where the temperature rise in MV switchgears compliant to the IEC 62271-1:2011 standard was verified, based on the procedure indicated by the norm. In this study, the tested switchgear is already certified according to IEC 62271-200:2021: the analysis of the temperature variation is aimed at the possible implementation of an IoT sensor-based thermal monitoring system to support enhanced maintenance services of the switchgear.

The paper is organized as follows. Section ii. describes the measurement setup, and the switchgear chosen for tests. Experiments are presented in Section iii., while Section iv. discusses the obtained results. Finally, conclusions are drawn in Section v..

II. MEASUREMENT SETUP

Figure 1 shows a graphical representation of the single-panel, air-insulated MINIVER-C MV switchgear chosen for experiments [8]. This metal-enclosed switchgear selected for experimental tests is manufactured by IMESA SpA and responds to the characteristics fixed in accordance to IEC 62271-200:2021: 12 kV operating voltage, 630 A continuous current, 50-60 Hz frequency.

Figure 2 shows the locations of the type K thermocouples inside the switchgear enclosure. The thermocouples used (Nickel-Chromium/Nickel-Alumel, model SR30KX, manufactured by TC Srl) can operate in the temperature range from 0 °C to 1100 °C in the continuous measurement mode, and in the range from -180 °C to 1350 °C in the short time measurement mode. They are cabled as twisted pairs, in EN IEC 60332-1 compliant flame-resistant silicone rubber. About the position of the temperature sensors, thermocouples numbered from 1 to 24 (denoted by red labels, in Fig. 2) are mechanically fixed onto the switchgear point at which the temperature measurement has to be performed, while thermocouples numbered from 25 to 27 (identified by blue labels, in Fig. 2) are used to measure internal air temperature in cables compartment, busbars compartment, and LV compartment used for auxiliary equipment, respectively. The thermocouples numbered from 19 to 24 are applied onto M10 screws that join flat copper omnibus bars: they are made loose on purpose, reducing the applied torque with respect to the prescribed one, by means of a calibrated torque screwdriver (accuracy of applied torque value: ±1%). Temperature values at the different switchgear points, and ambient temperature, are measured once every 2.5 min.

A National Instruments NI Compact DAQ 9178 system has been used for the automatic measurements, equipped with an NI 9208 Current Analog Input Board (featuring 16 analog input channels, with a minimum input range of ±21.5 mA, and a conversion time per channel of 2 ms in high-speed mode) and NI 9214 16-Channel Isothermal Thermocouple Input Modules (featuring a conversion time per channel of 735 μs in high-speed mode, a voltage measurement range of ±78.125 mV, and a temperature sensitivity of 0.01 °C). Table 1 details the position of each thermocouple inside the switchgear, while pictures in Fig. 3

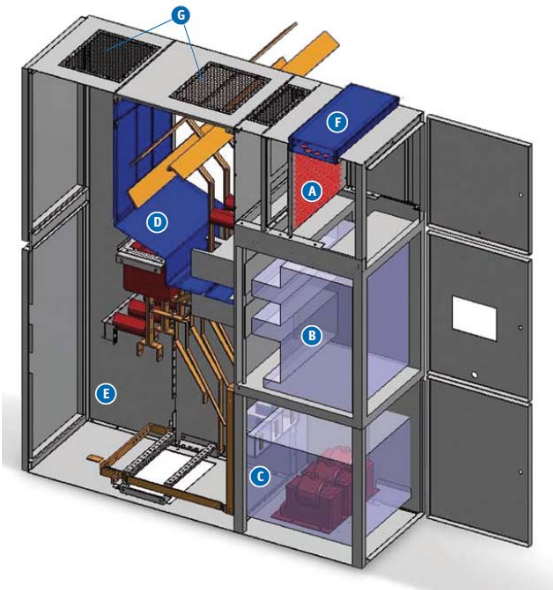

Fig. 1. The MINIVER-C MV switchgear chosen for experiments. The different compartments are: A) Low Voltage (LV) auxiliary instruments; B) circuit breaker (CB); C) voltage transformers (VT); D) busbars; E) lines; F) interconnection channel; G) gas vent slot (from [8]).

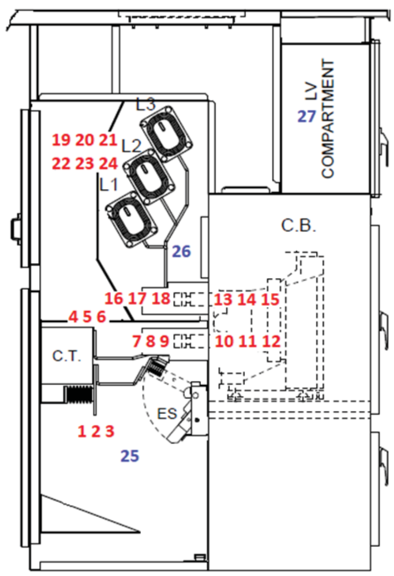

Fig. 2. Position of the 27 type K thermocouples in the MV switchgear. Each of the 3 phases (L1, L2, L3) at the indicated locations has its dedicated thermocouple.

Table 1. Position of each thermocouple inside the switchgear

Label	Position	Phase
T1,T2,T3	Outgoing cable joint	L1,L2,L3
T4,T5,T6	Top contact CT	L1,L2,L3
T7,T8,T9	Lower pole	L1,L2,L3
T10,T11,T12	Lower CB tulip	L1,L2,L3
T13,T14,T15	Upper CB tulip	L1,L2,L3
T16,T17,T18	Upper pole	L1,L2,L3
T19,T20,T21	Omnibus bar joint	L1,L2,L3
T22,T23,T24	Omnibus bar joint	L1,L2,L3
T25	Internal cables compartment	
T26	Internal busbars compartment	
T27	Internal LV compartment	

show some sample installations of the type K thermocouples, labeled according to Table 1.

III. EXPERIMENTS

A. Measurements in standard operational conditions

In standard operational conditions, omnibus bars joints are mechanically obtained with M10 screws nominally clamped at a standard torque of 45 Nm. Rated clamping of M12 screws on current transformers (CT) amounts to 60 Nm; lower and upper pole joints M16 screws are clamped at 165 Nm torque.

Based on these settings, a first experiment consists in measuring the overtemperature, with respect to the external ambient temperature, at the different points of the switchgear, when operated with a rated current of 630 A provided by a calibrated three-phase current generator. Current is maintained until a stable thermal regime is obtained, meaning that all the measured points do not exhibit a temperature variation greater than 1 °C over the last hour of the measurement interval. The overtemperature values of interest for this study are obtained as the difference between the highest temperature measured at each position and the average external ambient temperature. The last one equals 19.1 °C, measured by two additional type K thermocouples located at a 1 m distance from the closed switchgear, in oil bath to avoid perturbations, during a measurement interval of 8 hours and 7 min. As temperature values are sampled every 2.5 min, there are 194 temperature measurements collected from each of the 27 thermocouples.

Before and after the temperature measurement session in standard operational conditions, the electrical resistance of each phase main circuits (IN-OUT, column, CB and CT) is also measured. This way, it is possible to check if the resistance changed because of the thermal behavior of the switchgear.

B. Measurements with loose busbars joints

In a second experiment, the omnibus bars joints, corresponding to thermocouples numbered from 19 to 24, are made loose on purpose, by reducing their effective applied torque from 45 Nm to 4 Nm, i.e. less than 10% of the prescribed value. This condition simulates what would happen, in practice, if the operator forgets to clamp the busbars screws in the switchgear. The temperature measurement session lasts 8 hours and 2 min, so that a total amount of 192 overtemperature values are measured by each thermocouple, with respect to the average ambient temperature of 18. 0 °C. For the applied torque value at the busbar joints, the overtemperature is measured in all the positions listed in Table 1, in order to evaluate how much the loose busbars joints affect the thermal behavior of the switchgear, in the different points monitored. All the other joints are maintained at their rated clamping values, as described in subsection III.A..

Again, the electrical resistance of each phase main circuits (in-out, column, CB and CT) is measured as well, before and after the loose joints measurement session, to check if the resistance values changed or not.

IV. RESULTS AND DISCUSSION

Figure 4 shows the temperature values measured in the first experiment, when the switchgear is operated in standard conditions with the correct torque applied to all the joints. For better reading, curves are grouped based on the measured phase, namely L1 in Fig. 4a), L2 in Fig. 4b), and L3 in Fig. 4c). In all these graphs, the highest curves indicating the greatest increase in temperature, correspond to thermocouples applied onto the top contact of the CT, the lower and upper poles, the lower and the upper CB tulip. The lowest increase in temperature (curves located on the bottom part of each graph) is registered on the outgoing cable joints and on the omnibus bars joints, for all the phases. The last graph in Fig. 4d) shows the time change of the ambient temperature, both inside the switchgear enclosure (T25, T26, and T27) and outside it (T28). It is visible how the highest increase in air temperature takes place inside the busbars compartment, corresponding to thermocouple T26. Temperature measured in standard operational conditions follows the same trend already observed in [9].

The fourth column of Table 2 reports the results obtained from the first experiment: in standard operating conditions, the highest overtemperature values are measured at the phase L3 lower pole (37.9 °C), the phase L2 lower CB tulip (37.8 °C), and the phase L2 lower pole (37.7 °C), respectively. These values are well below the temperature rise limits set by IEC 62271-200:2021 common specifications, irrespective of the specific part, media, type of material, and applied surface treatment of the MV switchgear under test. Table 3 reports the values of the electrical resistance of each phase main circuits (IN-OUT, column, CB

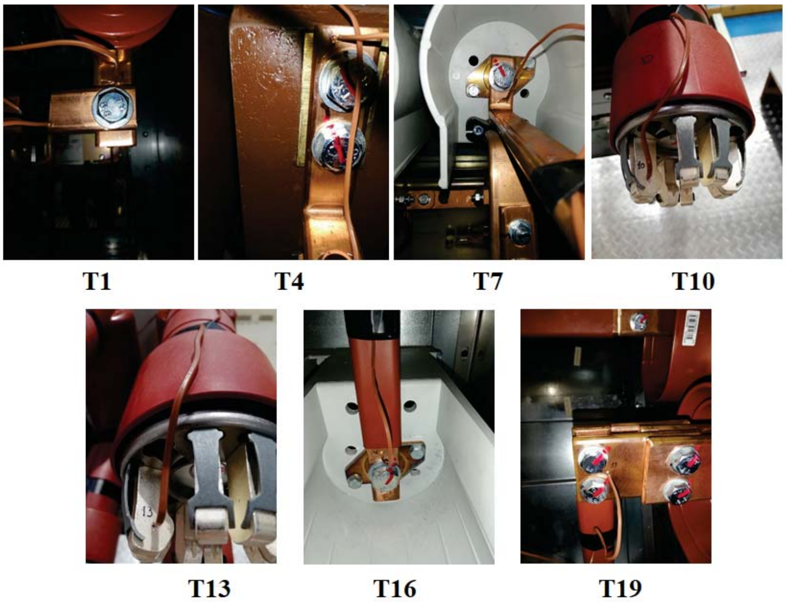

Fig. 3. Some of the type K thermocouples listed in Table 1 and installed inside the switchgear.

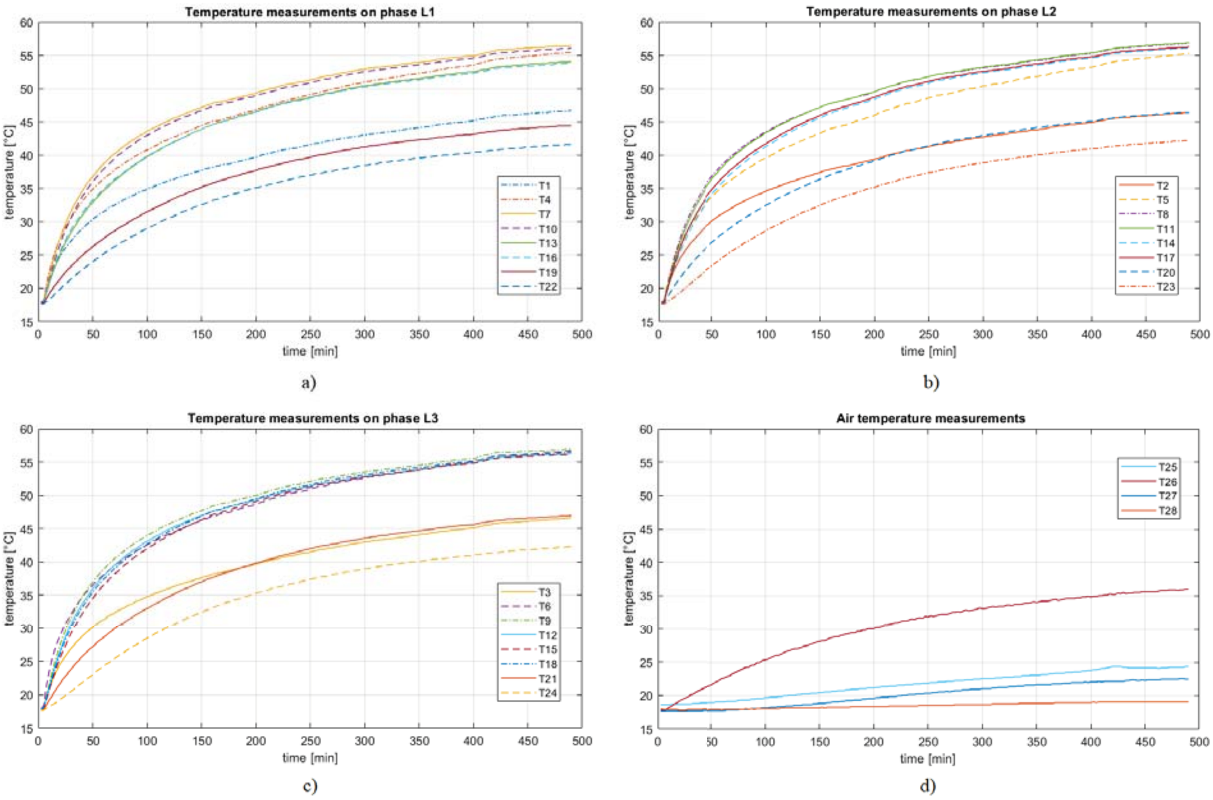

Fig. 4. Temperature measurements in standard operational conditions: a) phase L1, b) phase L2, c) phase L3, d) internal and external air.

Table 2. Measured overtemperature values in standard operational conditions of the MV switchgear, with ambient temperature = (19.1±0.4) °C, and in the loose busbars joints conditions (4 Nm applied torque), with ambient temperature = (18.0±0.4) °C

Thermocouple	Position	Phase	Overtemperature [°C] (normal conditions)	Overtemperature [°C] (loose joints)
T1	Outgoing cable joint	L1	27.6	27.5
T2	Outgoing cable joint	L2	27.3	27.2
T3	Outgoing cable joint	L3	27.5	27.3
T4	Top contact CT	L1	36.3	36.5
T5	Top contact CT	L2	36.2	34.9
T6	Top contact CT	L3	37.6	36.6
T7	Lower pole	L1	37.4	37.5
T8	Lower pole	L2	37.7	36.3
T9	Lower pole	L3	37.9	37.7
T10	Lower CB tulip	L1	37.0	37.2
T11	Lower CB tulip	L2	37.8	37.9
T12	Lower CB tulip	L3	37.2	37.1
T13	Upper CB tulip	L1	35.0	35.9
T14	Upper CB tulip	L2	37.0	37.7
T15	Upper CB tulip	L3	37.1	37.5
T16	Upper pole	L1	34.7	36.1
T17	Upper pole	L2	37.2	38.1
T18	Upper pole	L3	37.4	37.9
T19	Omnibus bar joint	L1	25.3	**29**
T20	Omnibus bar joint	L2	27.3	**30.7**
T21	Omnibus bar joint	L3	27.9	**30.5**
T22	Omnibus bar joint	L1	22.5	**25.5**
T23	Omnibus bar joint	L2	23.1	**24.9**
T24	Omnibus bar joint	L3	23.2	**25.7**
T25	Internal air, cables compartment		5.3	4
T26	Internal air, busbars compartment		16.9	17.4
T27	Internal air, LV compartment		3.4	3.5

Table 3. Electrical resistance values (in $\mu\Omega$) before and after the thermal test in standard operational conditions, for each phase (L1, L2, L3) main circuits (±1 $\mu\Omega$ uncertainty)

	IN-OUT		Column		CB		CT	
Phase	Before	After	Before	After	Before	After	Before	After
L1	185	179	156	152	56	53	36	35
L2	189	186	160	157	57	56	31	31
L3	205	202	175	172	55	54	38	36

and CT), measured before and after the execution of the standard operational conditions test. As shown, the main circuits resistance values do not show significant variations, as reasonably expected for the standard operation conditions of the certified switchgear.

The last column of Table 2 provides the overtemperature values measured in the second experiment, when the torque applied to omnibus bars joints is less than 10% of the recommended one. The most significant increase in overtemperature is measured by thermocouples located in the loose joints (from T19 to T24): on average, it amounts to 2.8 °C, with the highest increase of 3.7 °C in the omnibus bar joint of phase L1 (T19). In all the other positions, the overtemperature determined by the loose busbars joints varies less than ±1.4 °C, with respect to the one measured in standard operational conditions. On average, the variation amounts to 0.2 °C, that is irrelevant. Table 4 shows the variations of the resistance values, after and before the test. The most relevant ones are found in the IN-OUT (-4.8%) and column (-7.8%) circuits of phase L1 (versus -3.2% and -2.6%, respectively, found after the normal conditions test), and in the IN-OUT circuit of L2

Table 4. Electrical resistance values (in $\mu\Omega$) before and after the experiment with loose busbar joints, for each phase (L1, L2, L3) main circuits ($\pm$1 $\mu\Omega$ uncertainty)

	IN-OUT		Column		CB		CT	
Phase	Before	After	Before	After	Before	After	Before	After
L1	205	195	167	154	55	53	36	35
L2	204	197	162	160	57	55	31	31
L3	216	215	176	171	53	52	37	37

(-3.4%, versus -1.6% found after the normal operational conditions test). In all cases, the measured resistance decreases following the thermal conditioning due to the experiment performed, with respect to its original value.

V. CONCLUSION

Temperature rise of MV switchgear primary circuits has a relevant impact on the switchgear insulation lifetime that, in its turn, may rapidly lead to faults. A practical rule of thumb states that insulation lifetime halves for each rise of 10 °C in average temperature. While loose joints are usually deemed responsible for hot spots in MV switchgears, this paper has shown, by extensive measurements, that even when omnibus bars joints are kept at an extremely low clamping (less than 10% of the recommended one), temperature does not rise significantly in those joints (less than 4 °C), and even less in other points of the switchgear. On the contrary, even limited thermal variations may affect the main circuits resistance values. These results suggest the need to reconsider the effective role of loose joints in predictive maintenance models applied to MV switchgears.

VI. ACKNOWLEDGMENT

This research activity was supported by IMESA SpA and partially by the POR MARCHE FESR project *Marche Innovation and Research fAcilities for Connected and sustainable Living Environments (MIRACLE)* - CUP B28I19000330007.

REFERENCES

[1] M. W. Hoffmann, S. Wildermuth, R. Gitzel, A. Boyaci, J. Gebhardt, H. Kaul, I. Amihai, B. Forg, M. Suriyah, T. Leibfried, et al., "Integration of Novel Sensors and Machine Learning for Predictive Maintenance in Medium Voltage Switchgear to Enable the Energy and Mobility Revolutions", Sensors 2020, vol. 20, 2099, 10.3390/s20072099.

[2] J. I. Aizpurua, V. M. Catterson, I. F. Abdulhadi and M. S. Garcia, "A Model-Based Hybrid Approach for Circuit Breaker Prognostics Encompassing Dynamic Reliability and Uncertainty", IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 48, no. 9, pp. 1637-1648, Sept. 2018, doi: 10.1109/TSMC.2017.2685346.

[3] M. Chevalier and V. Boutin, "Heading to Models of Failure Rate Evolution, with Respect to Environmental and Usage Conditions in Time", 2019 Annual Reliability and Maintainability Symposium (RAMS), 2019, pp. 1-6, doi: 10.1109/RAMS.2019.8768942.

[4] M. S. Jadin, S. Taib, "Recent progress in diagnosing the reliability of electrical equipment by using infrared thermography", Infrared Physics & Technology, Volume 55, Issue 4, 2012, pp. 236-245, ISSN 1350-4495, doi: 10.1016/j.infrared.2012.03.002.

[5] A.S. Nazmul Huda, S. Taib, "Application of infrared thermography for predictive/preventive maintenance of thermal defect in electrical equipment", Applied Thermal Engineering, Volume 61, Issue 2, 2013, pp. 220-227, ISSN 1359-4311, doi: 10.1016/j.applthermaleng.2013.07.028.

[6] K. Gitzel, J. Gebhardt and T. Kozel, "Automatic Analysis of thermograms - challenge in thermal monitoring of switchgears using infrared cameras", CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution, 2021, pp. 395-399, doi: 10.1049/icp.2021.1581.

[7] S. Iderus and G. Peter, "Temperature Rise Test on Medium Voltage Switchgear Assembly Based on IEC Standard", 2020 8th International Conference on Orange Technology (ICOT), 2020, pp. 1-5, doi: 10.1109/ICOT51877.2020.9468746.

[8] IMESA SpA, "MINIVER/C Medium Voltage Switchgears", [online] `https://www.imesaspa.com/media/multimedia_prodotto/19/MV%20SWITCHBOARD_MINIVER%20C.pdf`, retrieved on April, 22^{nd}, 2022.

[9] K. Perdon, M. Scarpellini, S. Magoni, L. Cavalli, "Modular online monitoring system to allow condition-based maintenance for medium voltage switchgear", CIRED - Open Access Proceedings Journal, 2017, (1), p. 346-349, DOI: 10.1049/oap-cired.2017.0415.