Article

“In Situ” Evaluation of Mechanical Wear of Mobile Contacts of Electricity Voltage Regulator

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Abstract: This in situ study presents an analysis of the wear of mobile contacts of switching in an automatic line voltage regulator, regarding the surface wear of the contacts. It is interesting to analyze the contacts of this equipment due to the friction and wear generated during the contact change, in order to predict and contain mechanical operation failures. The contacts were evaluated for mass loss, profilometry, and analysis in a scanning electron microscope, after remaining in operation in the regulator for about one year and switching the contacts almost 2500 times. This study aims to evaluate the performance of the contacts, in terms of surface wear, correlating the number of switching and the effects generated on the contacts in terms of loss of mass and surface damage. With the results obtained, it is possible to conclude that with each switching maneuver the mobile contact loses about 0.002895% of its initial mass. In addition, there was a change in the topography of the sample, associated with its wear, suggesting that the wear is different along the surface of the regulator contacts studied.

Keywords: mechanical wear; voltage regulator; mobile contacts; fixed contacts; on load contact-changer

1. Introduction

The constant connection and disconnection of equipment from the electrical network causes the electrical load of the distribution network to oscillate constantly, resulting in the oscillation of the electrical voltage supplied by the distributor. A series of problems can occur when the voltage values are very far from the rated operating voltage of the grid, from the failure of operation to the burning of electrical devices [1].

Voltage regulators are electromechanical devices capable of keeping the voltage supplied by electrical substations constant, as close as possible to the nominal voltage of the network. The on-load tap changer changes the contacts of its power transformer to keep the output voltage at a pre-defined level, even if there is a change in load and voltage at the equipment input. This regulation of the output signal is due to the control of the turn ratio for a given load, without interrupting the supply from the electrical current. However, the high number of switches causes deterioration or wear of the mechanical contacts, causing operational failures. The reliability of the electricity distribution system

requires the proper functioning of voltage regulators to guarantee the operability of the system [2–4]. Thereafter, the voltage regulator requires the adoption of more efficient preventive maintenance measures to ensure better system performance and reliability and equipment life [5–7]. A voltage regulator is basically composed of: tap changer, transformer, insulating oil, control module, housing, and support hardware. The most frequent failures of a regulator occur due to low insulation or defects in the positioning system of the contact-changer. The switch is the most vulnerable part of failures, as it is an electromechanical switching mechanism, it undergoes mechanical and electrical stresses [8]. Generally, defects in the contacts or switch positioning mechanism are the most frequent causes of failures [9]. During the switching of a new contact position, an electric arc occurs and this discharge causes the burning of insulating oil, causing the formation of carbon in the middle of the oil. Discharges cause physical wear on the contacts and release particles of conductive material in the insulating oil. With each new contact switching maneuver, there is an increase in the concentration of carbon and the accumulation of conductive particles. The oil loses its insulating capacity and thus allows the formation of arcs of longer duration and intensity [10,11]. Therefore, it is also verified that the wear of the contacts contributes to the degradation of the fundamental characteristics of the insulating oil.

Voltage regulator switching contacts are among the most vulnerable components to failure, as they are the only moving parts of the equipment. Regulators are currently maintained through regular inspections or in the event of failures, however this repair procedure is time consuming, leaving the equipment out of service for a long time [12]. Preventive techniques for maintaining this equipment have been developed over the years to allow the early interpretation of an incipient failure and to define correct diagnoses, thus avoiding an unnecessary stop in the production process to carry out unscheduled maintenance [13–15]. Among the techniques currently used in fault detection we have: oil and insulation analysis, analysis of contact-changer contacts, and mechanical analysis [16].

This paper presents the preliminary investigation of the mechanical wear of the switching contacts of a single-phase 414 kVA/13.8 kV automatic voltage regulator. Said regulator was monitored in loco in operation in the electric network during the period of a complete year, and subsequently tests were carried out in its main components seeking to evaluate and understand the wear mechanisms of the contacts to correlate with the wear conditions according to the number of switching maneuvers. The object of the present study, therefore, is the search for subsidies to predict the wear of these components by reading the number of equipment maneuvers for predictive diagnostics. Predicting the levels of wear and the quality of operation of voltage regulator contacts is something sought by electrification companies, in an attempt to reduce costs with early withdrawals from regulatory banks of the network for maintenance, in addition to avoiding catastrophic failures and interruptions in the electrical system, caused by defective equipment and lack of maintenance. The analysis of the results of the tests and of the wear data obtained in this evaluation on a real scale of application show that it is possible to correlate the wear evolution with the number of maneuvers, predicting a more assertive intervention indicator. The results obtained present an excellent contribution to the distributor, which from the study can optimize the maintenance of the regulator studied considering the evolution of the wear compared to the average of maneuvers characteristic of the study region and can also extrapolate the study to the other regulators in its network. The researchers also understand that even with the positive results obtained, it is necessary to evaluate a larger sample to consolidate the results, and for this reason this article also brings an important scientific contribution to new investigative studies aimed at defining methodologies or even equations for predicting maintenance of voltage regulators.

2. Materials and Methods

The central idea of this work is focused on the monitoring in situ of the mechanical wear of the contacts of a voltage regulator, in an investigative way, during the period of a whole year in real operation in the electric network. In this way, it sought to identify the initial operating conditions of the regulator's contacts, by means of mass testing, optical profilometry, and scanning electron microscope

of the contacts before the equipment goes into the field. After one year in operation, the same tests are performed again on the contacts, now mechanically worn by the maneuvers in the studied voltage regulator in order to compare the initial and final test results and to better understand the behavior of the mechanical wear of the contacts and its direct relationship with switching maneuvers.

2.1. Voltage Regulator

The reference equipment used in this study was the TOSHIBA Type B Single-Phase Voltage Regulator, owned by the company COOPERA (Cooperativa Pioneira de Eletrificação) in the patrimony of n°1697, as presented in Figure 1.

Figure 1. Toshiba Single-Phase Voltage Regulator operating in COOPERA's network.

Some technical characteristics of the reference voltage regulator, which were used for the study, are presented in Table 1 with data taken from the equipment identification plate.

Table 1. Toshiba Voltage Regulator Datasheet.

Single-Phase Voltage Regulator Toshiba—Type B	
Rated Power	414 kVA
Rated Voltage	13.8 kKV
Rated Current	300 A
Frequency	60 Hz
Serial Number	E03001
Insulating Oil	Mineral Naphthenic
Volume of Oil	710 L
Mass of Oil	639 Kg
Mass of the Active Part (with cap)	995 Kg
Total Mass	2130 Kg
Mass of Tank and Accessories	496 Kg
Switch Type	CR-3
Electronic Control	TB-R800
Manufacturing	mar/03
Equity Number (COOPERA)	1697

In order to allow a more precise analysis of the results and in an attempt to simulate the regulator in the conditions of a new one, the studied equipment underwent preventive maintenance at Fluxo Transformadores, before being installed in the field. During preventive maintenance, the regulator was disassembled and some worn components were replaced with new ones. The tap changer in use was replaced by a completely new tap changer, and accompanied by new mobile and fixed contacts. Figure 2 introduces the Toshiba bypass switch, model CTR-3, before installation in the regulator.

Figure 2. New on-load contact-changer CTR-3 Toshiba.

The Figures 3 and 4 present the mobile and fixed contacts that make up the on-load tap changer before installation in the studied voltage regulator.

Figure 3. Position of mobile and fixed contacts on the tap changer.

Figure 4. Mobile contacts studied.

The regulator went through the procedure of replacing the used components with new ones and then the procedure for drying the internal part in an oven and reassembling the equipment was carried out. Finally, it was replenished with a new load of insulating mineral oil LUBRAX AV 70 IN—LI and some test procedures were carried out to check the good operating conditions before sending the equipment to the field.

The voltage regulator was installed in the COOPERA company network on 4 June 2019. Through Figure 5 it is possible to see the equipment being replaced in the network.

Figure 5. Voltage regulator being installed in the COOPERA company network, after removal for maintenance.

The equipment remained in the field until the date of 29 June 2020, when it was then taken out of service again and taken to the workshop for disassembly of the on-load tap changer and analysis of the moving contacts after the period in operation.

2.2. Chemical Analysis of Contacts

The chemical analysis of the contacts was performed at the SATC Technological Center using Dispersive Energy X-Ray Fluorescence Spectrometry equipment, model EDX7000, from the manufacturer Shimadzu.

Figure 6 shows the mobile contact and the fixed contact used in this test and in the analysis in a scanning electron microscope. It is possible to see in Figure 6 the regions removed from the contacts for use in the aforementioned tests.

Figure 6. Mobile contact (a) and fixed contact (b) after sample removal from each contact to perform the tests.

It was necessary to perform the cut of each contact due to adapting the sample size to the equipment used in the tests. The mobile contact was cut in only one region, as can be seen in Figure 6a. However, the fixed contact in Figure 6b was cut in the “Cut X” and “Cut Y” positions, due to the fact that the fixed contacts have two different materials in their structure, as shown in Figure 6: it is possible to visually perceive that the material of the contact ends is different from the material that makes up the rest of the contact.

2.3. Mass Test

This section presents the methodology used for testing the mass of the main contacts of the voltage regulator. Initially, while the regulator was previously checked in the workshop before going to the field, the mobile and fixed contacts were tested for their mass.

Subsequently, with the removal of the field voltage regulator, the contacts were weighed again on the scale, in order to identify the current mass of the contacts and calculate the loss of mass that occurred during the period in operation.

For weighing the mobile contacts, the precision scale of the Sartorius model Practum224-10BR was used; this scale has up to four decimal places of precision. When weighing the fixed contacts, it was necessary to use another scale, since the previous scale weighed bodies of up to 220 g of mass only. In this way, the precision scale of the manufacturer Marte model AD500 was used, with up to three decimal places of precision when weighing the fixed contacts.

2.4. Profilometry Test

The purpose of this test was to determine the roughness values and obtain topographic images of the surface of the moving contacts on a micrometric scale. This test sought to determine the characteristics of the moving contacts in terms of surface roughness and topography on a micrometric scale, carrying out the test before the regulator studied went into the field and again after the period of operation of the equipment had ended. In this way, we sought to analyze and correlate the results obtained on the behavior of mobile contacts before and after about a year in operation in the regulator.

This test was carried out by LAPEC (Corrosion Research Laboratory) at the Federal University of Rio Grande do Sul. Figure 7 shows the images of the samples tested before the contacts were installed in the voltage regulator. The measurements were made in triplicate on the surface of the samples, previously cleaned with alcohol, in the regions shown in Figure 7.

Figure 7. Sample 1: (a) whole body, (b) measured region; Sample 2: (c) whole body, (d) measurement region.

Figure 8 shows the images of the samples tested after removing the mobile contacts from the voltage regulator. It is possible to identify wear marks in the analyzed samples. Again, measurements were made in triplicate (and at three points in three areas) on the surface of the samples, previously cleaned with alcohol, in the regions shown in Figure 8.

Figure 8. Sample 1: (a) whole body, (b) measurement region; Sample 2: (c) whole body, (d) measurement region.

For the measurements to be made in the same places in both samples, a Cartesian coordinate system was used, with the origin centered in the lower left corner of the samples. The coordinates of the points are shown in Table 2 and the schematic representations in Figure 9.

Table 2. Coordinates of the sample measurement points.

Region	Ordered Pair (mm)
Point 1	(9.5; 8.1)
Point 2	(11.5; 19.7)
Point 3	(9.1; 27.4)

Figure 9. Schematic representation of the measurement points: (a) coordinate axis and (b) location.

The micrometric roughness of the samples was measured using a GT-K optical interferometer (Bruker, Billerica, MA, USA), using the green laser, obtaining the values of S_a (μm) and S_z (μm). According to the information provided by the manufacturer of the optical interferometer, S_a is defined as the average roughness assessed on the surface, while the S_z is based on the average difference between the five highest peaks and the five lowest valleys on the surface [17].

The analyses of linear roughness of the samples were made using the Surface Roughness Tester SJ-400, Mitutoyo brand, using the ISO 4287 standard [18]. R_a is considered the arithmetic mean of the absolute values of the ordinates of spacing of the roughness profile points in relation to the midline. R_z was adopted as the arithmetic mean of the five partial roughness values, considering the points of greatest distance, above and below the midline [17].

2.5. Scanning Electron Microscope

The analysis by scanning electron microscopy was performed at the SATC Technological Center, the equipment used was the scanning electron microscope model MA10, EVO series from the manufacturer Carl Zeiss with dispersive energy spectroscopy Quantax Bruker.

The purpose of the scanning electron microscope images was to analyze the surface of the mobile contact and the fixed contact in Figure 6, after being removed from the regulator's operation. In this way, it is possible to identify and quantify the presence of certain chemical elements on the surface of the contacts. The dispersive energy spectroscopy resource was used to obtain spectrographs of the elements present on the surface of the contacts.

3. Results and Discussion

3.1. Voltage Regulator

The regulator tap change maneuver counter was reset during the maintenance of the equipment at Fluxo Transformadores and then the equipment was put into operation on the power grid. During the period of operation of the field voltage regulator, approximately one year and one month, the contact-changer switched the moving contacts 2496 times. This number of operations varies from regulator to regulator: it is an intrinsic factor of the location where the equipment was installed along with the load characteristics of the installation point in the electrical network.

3.2. Chemical Analysis

The results obtained through the chemical analysis of the mobile contacts are shown in Table 3.

Table 3. Chemical composition by weight (wt %) of the mobile contacts according to the chemical analysis test.

Cu (%)	W (%)	Al (%)	Cl (%)	Ge (%)	K (%)	S (%)	Ca (%)	P (%)	Mn (%)	Ti (%)	V (%)
49.507	45.909	1.59	0.75	0.722	0.421	0.335	0.265	0.246	0.120	0.095	0.040

It is possible to verify through Table 3 that copper and tungsten are the components most present in mobile contacts. The other chemical components detected were aluminum, chlorine, and germanium.

In addition to these, there are traces of the elements potassium, sulfur, calcium, phosphorus, manganese, titanium, and vanadium.

The chemical analysis of the fixed contacts is shown in Table 4 for the analysis performed at the “Cut X” point of Figure 6b and Table 5 presents the analysis performed at the “Cut Y” point of Figure 6b.

Table 4. Chemical composition by weight (wt %) of the fixed contact at the “Cut X” point of Figure 6b according to the chemical analysis test.

W (%)	Cu (%)	Ge (%)	P (%)	Se (%)	Ca (%)	S (%)	K (%)	Ba (%)	V (%)
61.436	36.139	0.804	0.444	0.359	0.243	0.235	0.164	0.127	0.048

Table 5. Chemical composition by weight (wt %) of the fixed contact at the “Cut Y” point of Figure 6b according to the chemical analysis test.

Cu (%)	Zn (%)	Ca (%)	Si (%)	Cl (%)	S (%)	Mn (%)	Tm (%)
67.018	31.870	0.545	0.327	0.114	0.063	0.036	0.027

Table 4 shows that tungsten and copper are the components most present in fixed contacts. The rest of the chemical components detected were germanium, phosphorus, selenium, calcium, and sulfur. Traces of potassium, barium, and vanadium were also detected.

It can be seen through Table 5 that copper and zinc are the components most present in this region of the analyzed fixed contact. The rest of the chemical components detected were calcium, silicon, and chlorine. Sulfur, manganese, and thulium elements were detected in very small quantities.

3.3. Mass Test

3.3.1. Mass Test of Moving Contacts

Table 6 presents the results of the mass tests of the mobile contacts, before the installation of the mobile contacts in the voltage regulator and after the period of operation in the field, and compares the resulting mass loss in each contact.

Table 6. Comparison of the masses of the voltage regulator’s mobile contacts.

Mobile Contacts	Start of Operation 4 June 2019	Finish of Operation 29 June 2020	Weight Loss (g)
Mass contact 1 (g)	84.1798	78.0961	6.0837
Mass contact 2 (g)	83.3829	77.2943	6.0886

Through Table 6, it is possible to verify that the mobile contacts lost mass during the period in operation. From 4 June 2019 to 29 June 2020, the mobile contacts (a) and (b) lost 6.0837 g and 6.0886 g of mass, respectively. This percentage is equivalent to about 7.22% and 7.30% of the initial mass, respectively.

During the period in operation, the voltage regulator switch switched the taps 2496 times. Table 7 shows the average rate of mass loss for each maneuver performed.

Table 7. Average loss of mass of the moving contacts by tap maneuver.

Mobile Contacts	Average Mass Loss per Tap Maneuver (mg/maneuver)	Average Mass Loss per Tap Maneuver (%/maneuver)
Mass contact (1)	2.4374	0.002895
Mass contact (2)	2.4393	0.002925

It is understood that the results of the wear obtained are closely related to the operational conditions of this specific case, so that in order to obtain more assertive parameters that allow a mathematical equation for wear, it would be necessary to analyze a much larger sample of regulators.

Due to the impossibility of carrying out studies in a larger sample at this time, the present study considers that the wear data presented in Table 7 are linear throughout its useful life. It is possible to validate the assertion of the linearity of wear of the regulator contacts during its useful life since the load curve does not change significantly in the vast majority of cases.

From the consideration of the linearity of the wears obtained in this regulator during the 12 months sampling, it is possible to project the future wear in relation to the number of switching, and consequently to point out with greater precision the ideal moment for removal of the regulator's operation, optimizing operational resources and humans.

It is also necessary to consider that the manufacturer indicates the replacement of the contact with 150,000 switching without differentiating the load and overload conditions to which the regulator is subjected. Generally, the manufacturer's nominal specifications are for ideal operating conditions, which are not consistently found in real applications. In this case, there is a risk that in severe operating conditions, even before reaching the nominal number of operations, the regulator reaches the wear limit, generating catastrophic failures taking the regulator out of operation and in several cases, it generates damage to consumers due to electrical outbreaks.

3.3.2. Mass Test of Fixed Contacts

Table 8 presents the results of the mass test of the fixed contacts, before and after the removal of the operating voltage regulator, and also compares the evolution in the mass indices of each contact.

Table 8. Comparison of the masses of the voltage regulator fixed contacts.

Fixed Contacts	Start of Operation 4 June 2019	Finish of Operation 29 June 2020	Weight Loss (g)
Fixed contact 00	272.681	272.795	+0.114
Fixed contact 01	220.146	220.390	+0.244
Fixed contact 02	217.276	217.422	+0.146
Fixed contact 03	218.142	218.321	+0.179
Fixed contact 04	225.504	225.609	+0.105
Fixed contact 05	222.031	222.133	+0.102
Fixed contact 06	219.960	220.044	+0.084
Fixed contact 07	226.159	226.224	+0.065
Fixed contact 08	225.298	225.460	+0.162

Unlike mobile contacts, which lost mass index, fixed contacts had a slight increase in mass value, as shown in Table 8. Naturally, fixed contacts have less wear and tear than mobile contacts [19].

Therefore, better performance was already expected from these contacts in terms of wear resistance. However, the fixed contacts gained mass instead of losing it. Through visual analysis, it is possible to notice that there is a light layer of "dirt" impregnated on the surface of the fixed contacts and that perhaps this may be able to interfere with the mass levels. It is suggested that this "dirt" may be a residue of particulate matter from mobile contacts, acquired during the friction generated in tap switching maneuvers.

Figure 10 shows the fixed contacts of the voltage regulator after removing the equipment from operation.

Visually it is possible to observe a greater wear on some contacts, such as: fixed contact 04, 05, 06 and 07. It is believed that the greatest wear on contacts 06 and 07, mainly, may be linked to the operating conditions of the regulator on site where they were installed. Everything suggests that the equipment has maneuvered more often on the most visually worn contacts, by performing tap change switching more frequently in these positions [20]. In addition, the most accentuated wear on these contacts can also be observed through the mass loss data in Table 8. It appears that contacts 04, 05, 06

and 07 also had an increase in their mass levels, however, they absorbed significantly less mass than the other contacts.

Figure 10. Fixed contacts after removal of the voltage regulator from operation.

3.4. Profilometry Test

Through Table 9 for comparison purposes, the roughness values obtained for these same samples in those same regions, in June 2019 are shown. Table 10 presents the roughness values obtained for the samples measured in July 2020.

Table 9. Micrometric roughness values obtained by linear roughness meter in June 2019.

Regions	Sample 1		Sample 2	
	Ra (μm)	Rz (μm)	Ra (μm)	Rz (μm)
Point 1	0.87	6.7	0.60	4.9
Point 2	1.04	7.4	0.77	5.1
Point 3	0.86	5.7	0.54	4.1

Table 10. Micrometric roughness values obtained by a linear roughness meter in July 2020.

Regions	Sample 1		Sample 2	
	Ra (μm)	Rz (μm)	Ra (μm)	Rz (μm)
Point 1	0.7	6.0	0.6	5.2
Point 2	1.1	8.4	0.8	6.0
Point 3	1.0	7.7	0.8	5.9

In general, samples 1 and 2, compared to the measurements made in June 2019, had an increase in the Rz roughness values, that is, they are related to the peaks and valleys. This shows a change in the topography of the sample, which may be associated with wear.

Comparing the Rz values in Point 3 of the Table 9 with that of Table 10, data from June 2019 and July 2020, respectively, it is noticeable that there is a considerable increase in the Rz value for both Sample 1 and Sample 2. It is suggested that this more pronounced morphological change in Rz at Point 3 occurs because the wear at that point is greater than at the other two points analyzed, thus increasing the roughness in the region of Point 3. Most likely, this wear is greater at Point 3 as a result of the fixed contact having a larger dimension in the region where Point 3 operates. Figure 11 allows to visually check the fixed contact 07 and the region that offers physical contact at Point 3 with the mobile contact during the tap switching maneuver.

Figure 11. Fixed contact 07 of the voltage regulator.

Through Figure 11 it is possible to visually check the wear marks resulting from the friction generated during the movement of the mobile contact over the fixed contact, when switching the regulator taps. It is possible to notice that the region of the fixed contact through which Point 3 of the analyzed mobile contact travels is slightly larger than the other points analyzed in the profilometry test. Thus, it is suggested that the wear at Point 3 of the moving contacts and the roughness R_z are accentuated because the fixed contact is greater at that point.

In addition, during the period in which the voltage regulator was in operation in the field, the operating conditions of the insulating oil were checked every three months, by performing physical-chemical and chromatographic tests of the insulating oil. In the last oil analysis performed on the equipment, before the regulator was removed from operation, solid particles immersed in the oil were found. Thus, it is also suggested that these particles can influence the increase in wear of the contacts, through their interaction during the switching of taps, acting on the abrasive wear of three bodies.

In view of these considerations, it would be interesting to continue research that guides the monitoring of roughness levels of the contacts and the analysis of particles immersed in insulating oil during scheduled maintenance, since it was possible to verify that the roughness of the contacts changes disproportionately over the entire surface and that the presence of solid particles in the oil can also influence the premature wear of the contacts. This increase in the heterogeneity of the contact surface, due to the increase in roughness with each new switching of taps, preponderantly accelerates the wear of the regulator contacts, since the increase in the roughness levels decreases the “perfect contact” between bodies and accelerates wear. In this way, the development of studies or even the creation of a mathematical model or a new maintenance protocol that allows the wear and aging of voltage regulator contacts to be monitored more closely could prevent serious damage to equipment by preventing the occurrence of early failures of these components.

3.5. Scanning Electron Microscope Analysis

It is possible to visually check through Figure 12, wear marks on the moving contacts used in the voltage regulator during the period in operation. Tap change switching creates wear marks on the contact surface and results in loss of mass [1].

Figure 12. Worn mobile contacts after period in operation on the regulator—(a) (Contact a) and (b) (Contact b).

Figure 13 shows the points analyzed in a scanning electron microscope on the surface of the mobile contact in Figure 12a.

Figure 13. Points analyzed in scanning electron microscope in the mobile contact of Figure 12a.

The spectroscopy spectra by dispersive energy and the quantification of the chemical elements found in the analyzed points of Figure 13 can be seen in Figure 14 and Table 11.

Figure 14. Dispersive energy spectroscopy spectra analyzed in the points of Figure 13.

Table 11. Mass of chemical elements at the points analyzed in Figure 13.

Point 1296		Point 1297	
Element	%	Element	%
Cu	83.18	Cu	66.45
O	5.67	C	11.64
C	4.79	O	10.08
Zn	2.72	Al	4.17
Al	2.36	W	3.68
W	1.17	Zn	2.88
Se	0.10	N	0.54
		Ta	0.46
		S	0.09
		Se	0.02

Table 11 shows the presence of a large amount of the copper element and a good amount of the tungsten element, as expected. After all, the chemical analysis of the mobile contact presented these as its main components [21]. The presence of a large amount of the carbon element on the surface of the mobile contact was also detected. This indicates that the carbon found is related to the presence of insulating oil from the voltage regulator as a contaminant on the surface of the moving contact. During the switching of a new tap position, an electric arc occurs. This electrical discharge causes the burning of the insulating oil and, with this, the formation of carbon. Consequently, this carbon can be easily absorbed by the contacts [22]. In addition, carbon formation may also be associated with another aging mechanism, the so-called long-term effect on the tap switch. This effect starts with the formation of polymerized oil on the contacts. This organic film can impair the efficiency of operation of the contacts by virtue of forming a less conductive layer on the surface of the contacts [23].

It was also possible to detect the presence of the chemical element zinc in good quantity. The zinc element was not detected in the chemical analysis of the mobile contact, but in the fixed contact.

Thus, it can be suggested that during the period in operation and the nearly 2500 switching of the regulator, there may have been adhesion of material from the fixed contact to the mobile contact.

Figure 15 shows the points analyzed in the surface of the fixed contact of Figure 6b, regarding the “Cut X” part of the contact.

Figure 15. Points analyzed in the fixed contact of Figure 6b, in the “Cut X” zone.

The spectra and quantification of the chemical elements found in the points analyzed in Figure 15 can be seen in Figure 16 and Table 12.

Figure 16. Spectra analyzed in the points of Figure 15.

Table 12. Mass of chemical elements at the points analyzed in Figure 15.

Point 1286		Point 1287		Point 1288	
Element	%	Element	%	Element	%
C	46.53	W	71.29	C	48.59
O	25.94	Cu	19.74	Cu	18.03
Cu	8.75	C	5.65	O	17.22
Si	3.98	O	1.11	N	10.27
Ti	3.68	Zn	0.79	Zn	2.13
Ba	3.28	Se	0.54	Cl	1.84
N	2.48	Ni	0.41	K	0.54
S	1.54	Al	0.19	S	0.49
Zn	1.31	Ti	0.15	Na	0.48
Al	0.98	Fe	0.07	Si	0.14
W	0.93	Ca	0.06	Sn	0.13
Fe	0.35	P	0.00	Al	0.08
Ti	0.25			Se	0.08
Ni	0.00				

Through Table 12, it is possible to identify the presence of the elements tungsten and copper in great quantity, thus affirming the results presented during the chemical analysis, confirming these two elements as its main chemical elements. In addition, the presence of a large amount of the carbon element was detected. As in the mobile contact assay, carbon was detected again, but it does not have enough of the initial chemical composition of both contacts. Once again it is suggested that the appearance of carbon is yet another indication that the insulating oil is capable of contaminating the surface of the contacts. It is also suggested that the appreciable increase in the mass of the fixed contacts, detected in the mass test, may be a direct factor in the accumulation of insulating oil impregnated on their surface.

Figure 17 shows the points analyzed in scanning electron microscope on the surface of the fixed contact of Figure 6b, regarding the “Cut Y” part of the contact.

Figure 17. Points analyzed in the fixed contact of Figure 6b, in the “Cut Y” zone.

The spectra and quantification of the chemical elements found in the points analyzed in Figure 17 can be seen in Figure 18 and Table 13.

Figure 18. Spectra analyzed in the points of Figure 17.

Table 13. Mass of chemical elements at the points analyzed in Figure 17.

Point 1277		Point 1278	
Element	%	Element	%
C	36.03	Cu	51.17
Zn	33.06	Zn	17.29
O	24.86	C	13.17
Cu	6.05	O	11.32
		Na	0.54
		W	0.51

Table 13 again presents a large amount of copper and zinc elements, confirming them again as main elements, as well as in the results presented in the chemical analysis of this part of the fixed contact. The presence of a large amount of carbon was also detected, supposedly from insulating oil. In small quantities, the tungsten element was also found on the surface of the fixed contact,

thus creating the possibility of adhesion of particulate material from the mobile contact to the fixed contact, arising from the friction generated during switching maneuvers [22].

4. Conclusions

The present work is a preliminary investigation that presents the main conditions of mechanical wear of the contacts of a voltage regulator used as an object of study. After the in situ monitoring of this equipment in real operation in the electrical network for 12 consecutive months, it was possible to conceive a set of conclusions that allow the future development of methodologies and mathematical equations to optimize the preventive maintenance of this equipment.

The chemical analysis of the contacts of the regulator under study allowed the identification of the main characteristics of these elements, allowing the clarification of doubts caused by the lack of bibliographic information, precisely indicating their chemical composition, which is important data for a better understanding of the abrasive wear process among contacts.

The roughness results and the observation of the physical conditions of the worn contacts suggest that the mechanical wear occurs disproportionately along the surface of the contacts. The roughness test detected an increase in the R_z value at a given point on the surface of the mobile contact, which shows a change in the topography of the contact, which is probably associated with its wear. In view of this, it is suggested to continue research that follows the roughness levels of the contact surfaces, since the detection of the increased contact roughness evidenced in this work serves as a warning, as the uncontrolled increase in the heterogeneity of the surface of these components can accelerate wear on contacts.

The data of loss of mass of the contacts correlated to the data of the number of tap switching maneuvers was of extreme importance to allow the identification of the conditions of wear of the contacts through the percentage analysis of lost mass in the analyzed period and the possibility of projecting their future wear. From these data, it is possible to predict the ideal time to replace worn components with new ones, optimizing human and operational resources.

New voltage regulators leave the factory under ideal assembly conditions so that all components are assembled following strict standards and procedures. On the other hand, when the regulators after some time of use are subjected to invasive maintenance actions and their contacts are replaced, the conditions no longer follow the same assembly standards. The difference between these two conditions generates different wears, and after the first replacement of the regulator contacts, the wear is necessarily greater, and therefore, the manufacturer's suggestion for maintenance according to the maximum number of switching no longer reflects what may appear in practice. Therefore, the present work makes an important contribution towards obtaining a better understanding of the wear mechanisms depending on the operational life of the equipment.

The test in the scanning electron microscope raised the possibility of interaction between the contacts through the identification of particles of mobile contact in fixed contact and vice versa. In addition, it was possible to identify the presence of contaminating particles, as well as the presence of a large amount of carbon, suggesting contamination of the contacts and a possible decrease in their electrical conductivity through the contamination of mineral insulating oil from the voltage regulator on the contacts. Such results obtained in the scanning electron microscope allow a better understanding of the microstructural issue of the microscopic structure of the analyzed contacts after their exposure during the period in real operation in the voltage regulator.

The results obtained in this study elucidate several questions that clarify important issues for a more assertive assessment of the need to maintain the regulator according to the number of maneuvers. However, it is understood that it is necessary to expand the study to a larger sample of regulators in situ, under different conditions, to more accurately validate the evolution of wear mechanisms.

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the infrastructure and methodology for validation, participated in the writing of the paper; P.R.S.M., research on the mechanical wear of voltage regulator switching contacts; O.H.A.J., research on the use of voltage regulators and the most recurrent problems of this equipment, participated in the writing of the paper; C.L.I., application of data validation and treatment methodology; J.D.S., participation in project design and technical feasibility; L.D.B., research on the mechanical wear of voltage regulator switching contacts. All authors have read and agreed to the published version of the manuscript.

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