Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

Statistical Analysis of Electrical Component Aging in Group 6 of the Inga 2 Hydroelectric Plant Following Abrupt Shutdowns

André Mampuya Nzita[1,2,a], Léon Mwanda Mizengi[2,3], Guy Wanlogo Ndiwulu[4], Guyh Dituba Ngoma[5], Clément N'zau Umba-di-Mbudi[6], Robert Muanda Ngimbi[6], and Edmond Phuku Phuati[6]

[1] President Joseph Kasa-Vubu University, Polytechnic Faculty, Boma, Democratic Republic of the Congo

[2] Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshsasa, Democratic Republic of the Congo

[3] Direction générale de la Société Nationale d'Electricité, Kinshasa, Democratic Republic of the Congo

[4] Department of Electrical Engineering, Polytechnic Faculty, University of Kinshasa, Democratic Republic of the Congo

[5] University of Quebec in Abitibi-Temiscamingue, School of Enginneering, Rouyn-Noranda, Canada

[6] University of Kinshasa, Faculty of science and technology, Kinshasa, Democratic Republic of the Congo

[a]simmlicem57@gmail.com

Abstract. *The Inga 2 hydroelectric power plant in the Democratic Republic of the Congo plays a crucial role in national electricity production and distribution. On January 5, 2016, Unit 3 abruptly shut down, triggering a cascade of shutdowns in other units and disrupting the network frequency. This study aims to analyze the evolution of the stator and rotor winding resistances, as well as the insulation resistance of turbine-generator Unit 6, from its commissioning in 1982 until 2016. The goal is to assess the impact of sudden shutdowns on the aging of its electrical components. Measurements of stator and rotor winding resistances, as well as rotor insulation resistance, were analyzed using R software for statistical analysis. The results of this study will provide recommendations for improving predictive maintenance of Unit 6 and other units in the Inga 2 power plant. Ultimately, the study seeks to enhance understanding of the effects of abrupt stoppages on the aging process of electrical components, thereby ensuring the long-term reliability of the Inga 2 hydroelectric power plant.*

Keywords: Inga 2 hydroelectric power plant, turbine-generator group 6, stator and rotor winding resistances, predictive maintenance

Computational and Experimental Research
in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

Introduction

The Inga 2 hydroelectric power plant, located in the Kongo Central province of the Democratic Republic of the Congo, plays a major strategic role in the production and distribution of electricity on a national scale. With an installed capacity of 1,424 MW, this plant is one of the largest hydroelectric facilities in Africa [1]–[3].

Previous research has highlighted the challenges of operational management of hydroelectric plants, particularly concerning their reliability and performance in the event of technical failures [3]–[6]. A recent study also analyzed the impact of technical incidents on grid frequency, emphasizing that sudden shutdowns can lead to significant fluctuations, thus compromising the stability of the electrical grid [7].

On January 5, 2016, an accident occurred at 8:40 a.m. at group 6, following the sudden shutdown of group 3 of the Inga 2 power plant, leading to the successive shutdown of other groups in this plant as well as the Inga 1 plant. This unexpected shutdown, caused by a continuous overload of the generators, disrupted the grid frequency, dropping it to 53 Hz instead of 50 Hz. Among the notable incidents, a fire occurred in the excitation panel of group 6, located at an altitude of 98 m, likely due to contact between the busbars as a result of vibrations caused by these sudden shutdowns. This event necessitated the replacement of the digital excitation panel for this group.

In this context, this study aims to analyze the evolution of the resistances of the stator and rotor windings, as well as the insulation of turbine-generator group 6 of the Inga 2 hydroelectric power plant, from its commissioning in 1982 to 2016, a period marked by the fire in the excitation panel of group 6. The analysis will be conducted using R software for statistical purposes [8]. The objective is to statistically evaluate the differences in resistances between these two periods to better understand the impact of sudden shutdowns on the aging of the electrical components of this group. The hypothesis formulated is that the fire in the excitation panel of turbine-generator group 6 of the Inga 2 hydroelectric power plant led to an acceleration of the aging of the electrical components of this group, particularly concerning the resistances of the stator and rotor windings as well as the insulation.

Theoretical Background

This section delves into the fundamental principles of aging in electrical components, especially within hydroelectric power plants, highlighting the mechanisms that lead to the degradation of stator and rotor windings, as well as insulation materials. As electrical components age, their resistance tends to increase. This rise in resistance is influenced by various factors, including thermal stress, mechanical vibrations, and environmental conditions. Understanding how these factors interact is critical for assessing the health of aging components. The integrity of insulation materials plays a crucial role in preventing current leakage, which can lead to catastrophic failures. As insulation degrades, the risk of failure escalates, making regular testing of insulation resistance essential for safe operations. Moreover, abrupt shutdowns can introduce thermal and mechanical shocks that accelerate the aging process [2], [9]–[12]. These sudden events may result in increased resistance and compromised insulation, further jeopardizing the reliability of the system.

To effectively analyze these changes, statistical methods such as t-tests are employed. These techniques facilitate a comprehensive comparison of resistance measurements over time,

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

allowing for the identification of significant shifts in component condition [3], [8]. Finally, understanding the mechanisms of aging enables the development of predictive maintenance strategies. Such strategies aim to identify and address potential issues before they escalate into failures, thereby enhancing the overall reliability of hydroelectric plants. This theoretical framework establishes a basis for examining the specific effects of the 2016 incident at the Inga 2 hydroelectric power plant on the electrical components of Unit 6.

Materials and Methods

To carry out our experiment, we first gathered several essential materials. We used a 12 V and 90 Ah FORGO battery, which served as the main power source. In order to control the electrical flow, three 4.7 Ω resistors of the EMF-100 K type were integrated into the circuit. To ensure safety, a 10 A (K) circuit breaker was installed, thus preventing any potential risk of short circuit. To perform accurate measurements, we employed two Flux brand digital multimeters, model 1114 TRUE, which allowed us to monitor the voltages and currents in the circuit. In addition, a MIT 520/2 megohmmeter, operating at 50/60 Hz, was used to test the insulation and resistance. A VICHY VC 97 digital probe was also included for additional measurements, thus ensuring a complete and accurate evaluation of our experimental setup.

Current-voltage characteristic measurement is based on the analysis of the relationship between the current flowing in a circuit and the voltage at its terminals. This relationship is often represented graphically by a current-voltage curve, allowing to identify the behavior of the alternator under different loads [2], [11], [13]. The measurements are carried out using appropriate measuring devices, such as multimeters, which provide precise data on the operation of the alternator.

Current-voltage measurements are essential to evaluate the performance of the alternator, as they allow to detect anomalies such as overloads or imbalances in the circuit. A thorough analysis of the current-voltage curves can also reveal problems related to internal resistance or insulation defects [10], [11], [13].

Insulation measurements are carried out to evaluate the integrity of the insulating materials in electrical systems. The use of a megohmmeter allows to measure the insulation resistance of the rotor and windings, which is crucial to prevent current leakage. Insufficient insulation resistance can lead to catastrophic failures, endangering not only the equipment but also the safety of the operators [10], [11], [14].

Additional losses in the alternator are notably due to the deformation of the magnetic flux under load [2], [10], [11]. Defects in the massive parts of the poles can be caused by these losses and the resulting heat, which can lead to cracks in the components [10], [11], [15]. It is therefore essential to monitor these parameters, as they directly impact the efficiency and longevity of the alternator.

In this study, we started by measuring the resistances of the stator and rotor windings of the group 6 alternator. This step was crucial to assess the condition of the windings and determine their efficiency in the operation of the alternator. After obtaining these measurements, we then proceeded to evaluate the insulation resistances of the alternator rotor. This verification was aimed at ensuring that the insulation was adequate, which is essential to prevent any risk of short-

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

circuits and ensure the safety of the entire system. These two steps allowed us to collect fundamental data to analyze the performance of the alternator.

The measurements were carried out on site at the Inga II hydroelectric power plant over a period of two days. For each type of circuit (windings and rotor insulation), we performed five measurements on the windings and ten measurements on the insulation. This rigorous approach ensures that the data collected are statistically significant and reflect the real operating conditions of the alternator.

We used the Proficad software to create the resistance measurement scheme for the rotor and stator windings, visible in **Figures 1** and **Figures 2**. To measure the resistance of the windings, we followed a detailed procedure, illustrated by the diagrams shown in the figures. We started by making the assembly by placing the additional resistors R1, R2, and R3 in series, according to the diagrams. Once the assembly was complete, we closed switch K and recorded the current intensity as well as the short-circuit voltage. After that, we opened switch K and removed resistor R3 by shorting it with a flexible wire between terminals D and E, then closed K. At this point, we measured the current and voltage in the short circuit again. This process was repeated for resistor R2, which we shorted between terminals C and D, before taking the corresponding measurements. To cancel the voltage stored by the short circuit inductance, we opened K and shorted terminals F and G with a flexible wire, then removed this wire. Next, we made a parallel connection between R1 and R2, leaving resistor R3 aside. After closing K, we took the current and voltage measurements in the short circuit. We then added R3 in parallel with R2 and R1, then closed K to get a new set of measurements. After disconnecting the circuit, we measured the ambient temperature in the collector ring chamber.

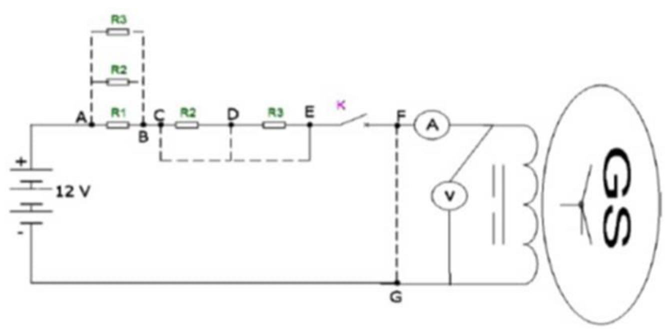


Figure 1. Rotor winding resistance measurement diagram

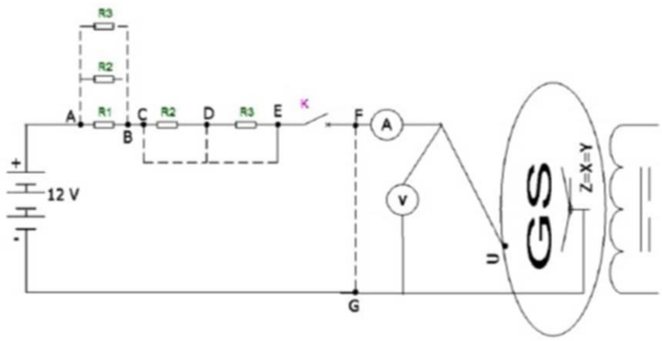
For the stator, as shown in **Figure 2**, we added an extra step. Before moving from phase UX to phase VX and then to phase WZ, we opened K again and shorted terminals F and G to cancel the voltage stored by the shorted inductor, and then removed this wire. Finally, we made sure to measure the ambient temperature in the stator enclosure, which is essential to ensuring the accuracy of our results.

We have made five types of resistor assemblies, shown in **Figure 1** and **Figure 2**. The first assembly, labeled No. 1, consists of three resistors connected in series. This arrangement is crucial to understanding the behavior of the circuit when all resistors are active. The second assembly, No. 2, presents a configuration where resistor R3 is eliminated from the circuit. This modification allows us to observe the impact of removing one resistor on the overall

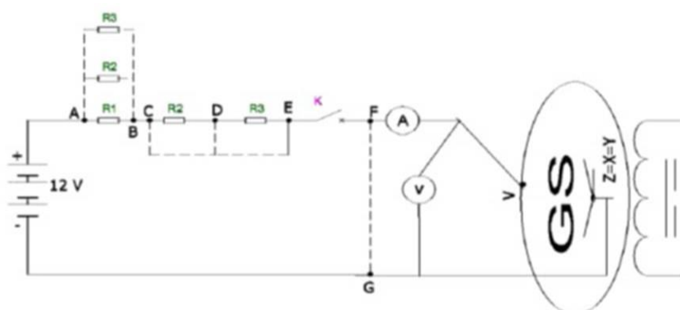
Computational and Experimental Research
in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

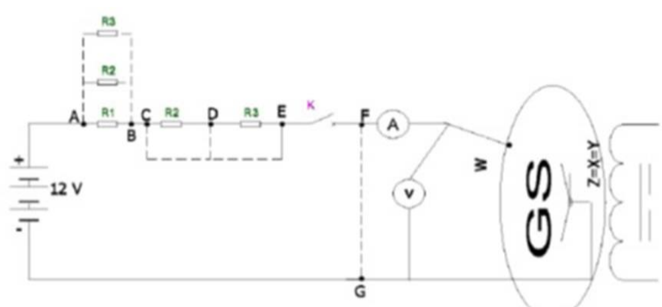
characteristics of the circuit. For the third assembly, No. 3, we eliminated resistor R2. This step helps us analyze how the remaining resistance influences the electrical behavior of the system. The fourth assembly, No. 4, parallels two resistors, which changes the dynamics of the circuit by reducing the total resistance. This configuration is essential to examine the effects of parallel connections. Finally, in assembly No. 5, all three resistors are connected in parallel. This arrangement allows us to measure the performance of the circuit when all the resistors act together, thus providing a complete overview of their impact on the operation of the system.



(a)



(b)



(c)

Figure 2. (a) Stator winding resistance measurement diagram with UX phase; (b) Stator winding resistance measurement diagram with VY phase; (c) Stator winding resistance measurement diagram with WZ phase

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

For the collection of insulation resistance data at 500 V, we made the assembly planned for the rotor, as shown in **Figure 3.** This figure shows the configuration set up to perform the insulation resistance measurements, which is essential to assess the safety and integrity of the rotor. We started by locking the machine to ensure the safety of the operation, taking care to note that the electricity injection would be carried out by an autonomous source. It was crucial that the temperature of the windings remained below 30 °C to avoid any variation that could influence the results during the tests. Next, we selected a test voltage, making sure that it was lower than the nominal voltage of the machine. Once the appropriate voltage was determined, we proceeded to inject it into the positive excitation terminal.

We then observed the value indicated by the megohmmeter needle after one minute of injection without interrupting the process [16]. This first measurement was followed by a second value taken after ten minutes, allowing us to assess the stability of the insulation resistance over time.

After recording these measurements, we cut off the voltage injection and disconnected the injection device. These steps were essential to ensure the accuracy of the results and the safety of the operation, as shown in **Figure 3**.

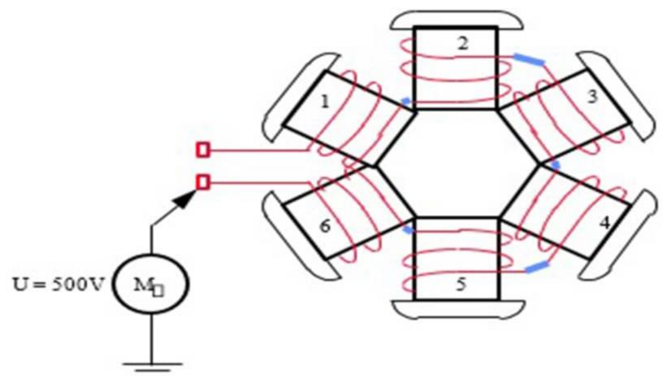


Figure 3. Rotor insulation resistance measurement diagram

Using the statistical software R, a conformity analysis was performed to compare the resistance measurements of the rotor and stator windings, as well as the rotor insulation, before and after the incident that occurred in 2016 on the excitation panel of the turbine-generator group 6 of the Inga 2 hydroelectric power plant. The methodology used relies on specific statistical tests, such as the conformity test, in order to assess whether the values measured after the accident in 2016 are consistent with the reference values obtained before the commissioning of the generator in 1982. The use of rigorous statistical tools, such as those implemented in the software R, therefore made it possible to quantitatively assess the impact of this incident on the condition of the generator and to draw clear conclusions regarding the consequences for the future operation of this turbine-generator group [2], [3], [8], [10]–[14], [16].

The resistances of the alternator windings measured at ambient temperature at this location are given by the expression [17]:

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

$$R_{t°} = \frac{V_{cc}}{I_{cc}} \tag{1}$$

Where V_{cc} is the voltage measured in a short circuit and I_{cc} is the current measured in a short circuit.

To enable comparison of measurements made before commissioning and those after the accident, the resistances of the measured windings are brought back to 75 °C by the formula:

$$R_{75°C} = R_{t°} \frac{309,5}{234,5 + t°} \tag{2}$$

Where: $t°$ is the ambient temperature at the location of the measurement test. The calculated resistance values of the rotor and stator windings brought back to 75 °C after the 2016 accident are compared to those of commissioning in 1982.

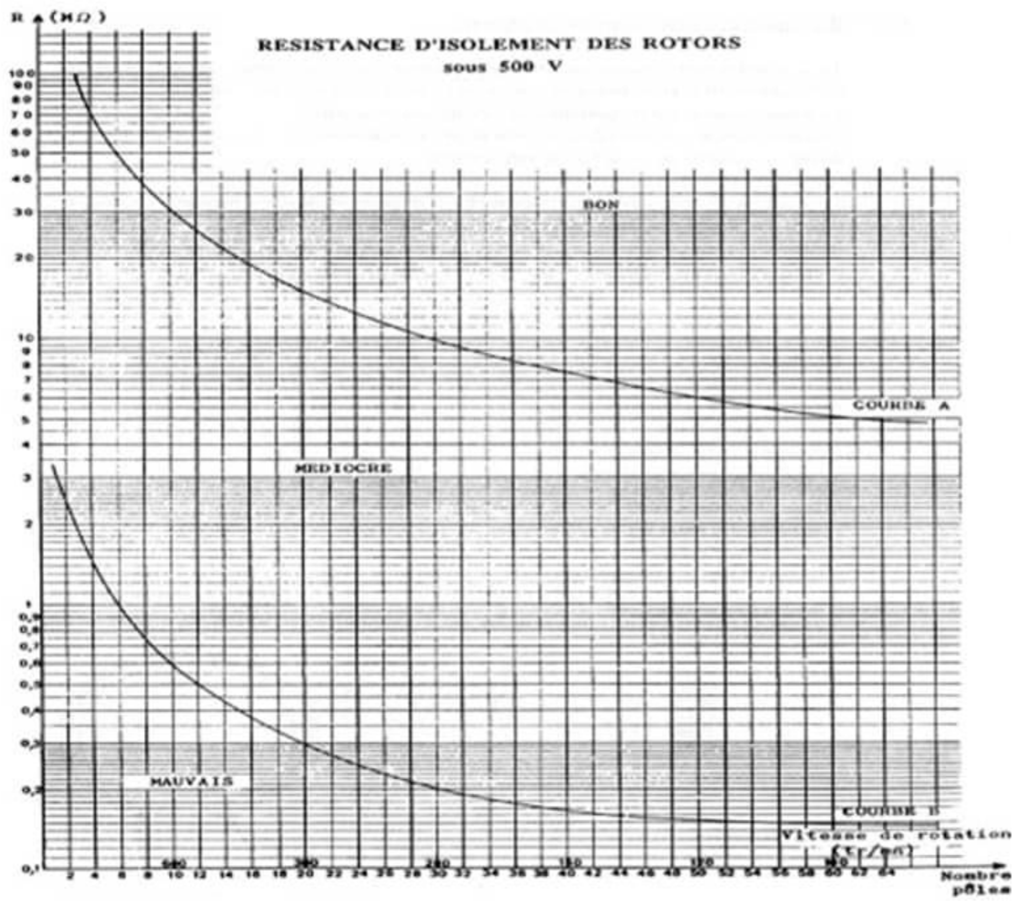


Figure 4. Insulation resistance graph of rotors under 500V [2]

Computational and Experimental Research
in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

The interpretation of the results can be done using the graph in **Figure 4** by first making the necessary corrections to the rotor insulation resistances at 20 °C using the relationship:

$$R_{20°C} = R \times 2^{\frac{(t-20)}{10}} \tag{3}$$

Where *R* is the rotor insulation resistance per minute and *t* is the ambient temperature at the measurement test location.

We analyzed the rotor insulation resistances at 500 volts, as shown in Figure 4. This graph shows three distinct zones that reflect the condition of the rotor insulation. The first zone, called "good," corresponds to insulation resistance values greater than 10 MΩ. This indicates that the rotor insulation is in good condition, providing adequate protection against current leakage. The second zone is called "average" and encompasses resistance values between 2 and 10 MΩ. When the insulation resistance falls within this range, it means that the condition of the rotor insulation is acceptable, but careful monitoring is required to prevent future degradation. Finally, the last zone, called "poor," includes values less than 2 MΩ. An insulation resistance in this category indicates significant deterioration of the rotor insulation, requiring immediate corrective action to avoid potential short-circuit or system failure risks. These observations, based on the data presented in Figure 4, highlight the importance of regularly monitoring insulation resistance to ensure rotor safety and efficiency.

Results and Discussion

The measured values of the short-circuit current and voltage of the alternator windings, as well as the rotor insulation resistances, are presented in three tables that are essential for evaluating the performance of the alternator. **Table 1** shows the measured current and voltage values at the rotor of group 6 at an ambient temperature of 23 °C. For each assembly, the table shows the current intensity (I_{sc}) in amperes and the potential difference (d.d.p.) in volts. **Table 2** provides similar measurements for the stator of group 6 at an ambient temperature of 29 °C. It details the currents and voltages for the three phases (UX, VY, and WZ). **Table 3** shows the rotor insulation resistance values, measured at 23 °C, with values expressed in megaohms (MΩ) for time intervals ranging from 1 to 10 minutes. The resistance increased slightly from 3.85 MΩ to 3.95 MΩ, indicating insulation stability. The index of 1.03 allows these performances to be placed in relation to expected standards. These tables provide a detailed overview of the electrical performance of the alternator, providing crucial data for a complete analysis of its operating condition.

Table 1. Short-circuit current and voltage measured at the rotor

Group 6 Rotor	**Ambient Temperature to 23 °C**	
Assembly No.	Intensity I_{cc} (A) (5%)	d.d.p. V_{cc} (V) (5%)
1	0.843	0.103
2	1.240	0.155
3	2.393	0.298
4	4.414	0.551
5	6.138	0.766

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

Table 2. Short-circuit current and voltage measured at the stator

Group 6	Ambient temperature at the stator enclosure 29 °C		
Stator	Assembly No.	Intensity I_{cc} (A) (5%)	d.d.p. V_{cc} (V) (5%)
UX Phase	1	0.841	0.003
	2	1.249	0.005
	3	2.433	0.009
	4	4.660	0.018
	5	6.568	0.003
VY Phase	1	0.839	0.003
	2	1.248	0.005
	3	2.430	0.001
	4	4.612	0.019
	5	6.511	0.026
WZ Phase	1	0.839	0.003
	2	1.246	0.005
	3	2.426	0.010
	4	4.595	0.019
	5	6.504	0.026

Table 3. Group 6 alternator rotor insulation resistance values

Group 6 Rotor	Room Temperature 23 °C										
Time (min)	1’	2’	3’	4’	5’	6’	7’	8’	9’	10’	Index
R (MΩ)	3.85	3.85	3.87	3.88	3.92	3.94	3.95	3.94	3.94	3.95	1.03

According to the work of SIEMENS, a subcontractor for the National Electricity Company, the following resistance values of the windings of the alternator in group 6, corrected to a temperature of 20 °C, were obtained before commissioning in 1982. The resistance values recorded after the 2016 accident can be found in **Table 4** and **Table 5**. However, insulation measurements were not conducted by these experts.

Table 4. Measured rotor resistances after accident, 2016 to those of commissioning in 1982

Group 6 Rotor Assembly No.	Resistance after 2016 accident (Ωm) at 23 °C	Resistance before commissioning 1982 (Ωm) at 20 °C
1	122.183	110.600
2	125.000	
3	124.529	
4	124.830	
5	124.796	

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

Table 5. Resistances measured at the stator after accident from 2016 to those of commissioning in 1982

Group 6	**Resistances measured at the stator in (Ωm)**		
Stator	Assembly No.	2016 accident at 29 °C	Before commissioning 1982 at 20 °C
UX Phase	1	3.567	3.20
	2	4.003	
	3	3.699	
	4	3.863	
	5	0.457	
VY Phase	1	3.576	3.20
	2	4.006	
	3	0.412	
	4	4.119	
	5	3.993	
WZ Phase	1	3.576	3.20
	2	4.013	
	3	4.122	
	4	4.134	
	5	3.997	

Table 6. Calculated resistances of the rotor windings reduced to 75°C of the rotor after accident in 2016 to those of commissioning in 1982

Group 6 Rotor	**Measured resistances reduced to 75 °C (Ωm)**	
Assembly No.	After accident 2016	Before commissioning 1982
1	146.856	134.502
2	150.243	
3	149.678	
4	150.038	
5	149.998	

Table 6 and **Table 7** below show the measured resistances of the rotor and stator windings of the alternator, reduced to a standard temperature of 75 °C, and allow the values after the 2016 accident to be compared with those recorded during commissioning in 1982.

A student's t-test was performed at a 5% threshold to compare the resistance measurements of the rotor and stator windings, as well as the rotor insulation, before the 1982 commissioning and after the 2016 incident on the excitation panel of the turbine-generator group 6 of the Inga 2 hydroelectric power plant in **Table 8, Table 9, Table 10, and Table 11**.

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

Table 7. Calculated resistances of the stator windings reduced after the accident in 2016 to those at the 1982 commissioning

Group 6	**Measured resistances reduced to 75 °C (Ωm)**		
Stator	Assembly No.	After 2016 accident at 29°C	Before commissioning 1982
UX Phase	1	4.189	3.892
	2	4.702	
	3	4.344	
	4	4.537	
	5	0.537	
VY Phase	1	4.200	3.892
	2	4.705	
	3	0.484	
	4	4.838	
	5	4.690	
WZ Phase	1	4.200	3.892
	2	4.714	
	3	4.842	
	4	4.856	
	5	4.695	

Table 8. Student test of calculated resistances of rotor windings reduced to 75°C from 2016 to those of 1982

After accident 2016 (Ωm)		**Before commissioning 1982 (Ωm)**	**ddl**	**t**	**p-value**
146.856 150.243 149.678 150.038 149.998	Mean 149.363	134.502	4	23.471	0.0000***

Since the p-value is much lower than the chosen significance threshold (usually 0.05), it can be concluded that the mean of the resistances measured after the 2016 accident (149.363) is statistically different from the resistance measured before commissioning in 1982 (134.502). The 95% confidence interval shows that the actual mean value is between 147.605 and 151.121.

The p-value being greater than the chosen significance threshold (usually 0.05), as well as the mean of the resistance measured after the 2016 accident (3.662), is not statistically different from the resistance measured before commissioning in 1982 (3.892). The 95% confidence interval shows that the actual mean value is between 1.479 and 5.844.

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

Table 9. Student test of calculated phase resistances UX of stator windings reduced to 75 °C from 2016 to those of 1982

After accident 2016 (Ωm)		Before commissioning 1982 (Ωm)	ddl	t	p-value
4.189 4.702 4.344 4.537 0.537	Mean 3.662	3.892	4	-0.293	0.784

Table 10. Student test of calculated phase resistances VY of stator windings reduced to 75 °C from 2016 to those of 1982

After accident 2016 (Ωm)		Before commissioning 1982 (Ωm)	ddl	t	p-value
4.200 4.705 0.484 4.838 4.690	Mean 3.783	3.892	4	-0.131	0.902

The p-value being significantly higher than the chosen significance threshold (usually 0.05). as well as the mean of the resistance measured after the 2016 accident (3.783) being statistically different from the resistance measured before commissioning in 1982 (3.892). The 95% confidence interval shows that the actual mean value is between 1.474 and 6.093.

Table 11. Student test of calculated WZ phase resistances of stator windings reduced to 75°c from 2016 to those of 1982

After accident 2016 (Ωm)		Before commissioning 1982 (Ωm)	ddl	t	p-value
4.200 4.714 4.842 4.856 4.695	Mean 4.661	3.892	4	6.419	0.003**

The p-value being lower than the chosen significance threshold (usually 0.05). as well as the mean of the resistance measured after the 2016 accident (4.661). is statistically different from the

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

resistance measured before commissioning in 1982 (3.892). The 95% confidence interval shows that the actual mean value is between 4.329 and 4.994.

For the rotor insulation resistances reduced to 20° calculated by expression (3), we have retained the largest, which was taken at 10 minutes and is worth 5 MΩ corresponding to 56 poles or 107.1 rpm of the operating curves (Figure 4) which is in the mediocre zone.

The analysis of the consequences on the rotor and stator of the alternator, as well as the possibility of replacing the excitation panel in group 6, reveals several important points.

Concerning the rotor, it was observed that the average resistance of the windings increased significantly after the accident in 2016, compared to the period before commissioning in 1982. This increase is probably related to additional losses and significant heating of the rotor following the incident. This excessive heating may have caused thermal damage or even cracks in the massive parts of the rotor. The degradation of the rotor windings negatively affects the overall performance of the alternator, particularly in terms of efficiency, power delivery, and stability. In addition, the insulation resistance of the rotor is at the lower limit of the insufficient zone, which indicates the beginning of deterioration. It is therefore imperative to regularly monitor these resistance measurements to detect any negative developments at an early stage.

Regarding the stator, the resistances of the UX and VY phases did not show significant variations between the commissioning in 1982 and after the accident in 2016, suggesting that these parts were not affected by the incident. The electrical characteristics of these phases therefore seem to be preserved. However, the resistance of the WZ phase increased considerably following the accident, indicating a degradation of this part of the stator, probably also due to losses and excessive heating. This heating may have led to thermal damage or cracks in the stator. The degradation of the stator windings also impacts the efficiency, output power, and stability of the alternator.

As for the possibility of replacing the digital excitation panel of group 6, it appears that the main problems come from the rotor and the WZ phase of the stator. Therefore, replacing the excitation panel would probably not be the best solution. It would be more advisable to focus on repairing or replacing the rotor and stator WZ phase to restore the overall performance of the alternator.

Conclusions

The analysis conducted reveals a significant increase in the resistances of the stator and rotor windings of turbine-generator unit 6 following the 2016 incident, compared to the measurements taken before its commissioning in 1982. This rise in resistance, coupled with a notable decrease in insulation resistance, indicates substantial degradation of the electrical components. These findings suggest that the abrupt shutdowns of the plant have accelerated the aging of equipment in unit 6. Specifically, the average resistance of the rotor winding increased significantly after the 2016 accident, which may be associated with additional losses and excessive heating. Currently, the rotor insulation resistance is at the lower limit of the "lean" zone, indicating a level of degradation that necessitates closer monitoring. For the stator winding, the resistances of the UX and VY phases have remained stable since 1982, suggesting they were not severely impacted by the incident. In contrast, the WZ phase exhibited a significant increase in resistance, pointing to degradation linked to losses and excessive heating that could result in thermal damage. These

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

results underscore the importance of enhanced monitoring and the implementation of predictive maintenance strategies for unit 6 to detect early signs of degradation. While the introduction of a new digital excitation board may offer some benefits, prioritizing the repair or replacement of the rotor and WZ phase stator components would be more effective in restoring the generator's performance. This study provides valuable insights into the effects of emergency shutdowns on generator aging, which can inform future maintenance strategies at Inga 2. By applying this analytical approach to other units, we can evaluate the impact of similar incidents across the entire plant, thereby enhancing the reliability and safety of operations.

ACKNOWLEDGMENTS

We would like to thank the National Electricity Company of Inga 2 hydroelectric power plant for its valuable support in carrying out this study.

Reference:

[1] J. Warner, S. Jomantas, E. Jones, M. S. Ansari, and L. de Vries, “The fantasy of the Grand Inga hydroelectric project on the River Congo. Water 11: 407.” 2019.

[2] G. J. Anders, J. Endrenyi, G. L. Ford, and G. C. Stone, “A probabilistic model for evaluating the remaining life of evaluating the remaining life of electrical insulation in rotating machines,” *IEEE Trans. Energy Convers.*, vol. 5, no. 4, pp. 761–767, 1990.

[3] A. M. Nzita, E. P. Phuati, R. M. Ngimbi, G. D. Ngoma, and N. M. Mavungu, “Investigation of Lateral Vibrations in Turbine-generator Unit 5 of the Inga 2 Hydroelectric Power Plant,” 2024.

[4] H. K. Bahati, A. Ogenrwoth, and J. I. Sempewo, “Quantifying the potential impacts of land-use and climate change on hydropower reliability of Muzizi hydropower plant, Uganda,” *J. Water Clim. Chang.*, vol. 12, no. 6, pp. 2526–2554, 2021.

[5] A. Atef and D. Bristow, “Capturing the spatial and operational interdependencies among building systems using building information modelling,” *Struct. Infrastruct. Eng.*, vol. 15, no. 12, pp. 1613–1629, 2019.

[6] E. L. Alberti *et al.*, “New concept on 100.74 kWp floating solar photovoltaic plant and a real mechanical failures assessment: Case of study at Santa Clara hydroelectric power plant reservoir in southern Brazil,” *Sustain. Energy Technol. Assessments*, vol. 60, p. 103455, 2023.

[7] O. T. T. Roger, “Qualité de tension-creux de tension et coupures brèves,” *Tech. l’ingénieur*, p. P2, 2002.

[8] C. Della Vedova, “Introduction to data analysis with R software,” vol. 2, no. 3, pp. 165–174, 2019, doi: https://doi.org/10.25796/bdd.v2i3.21313.

[9] H. Srivastava, A. Kaushal, H. Kumar, A. Tripathi, and A. K. Sharma, “A design and development of baggage sorting robotic system at the airport,” 2022.

Computational and Experimental Research
in Materials and Renewable Energy (CERiMRE)
Volume 7, Issue 2, page 78-92
eISSN : 2747-173X

Submitted : July 27, 2024
Accepted : October 3, 2024
Online : November 22, 2024
DOI : 10.19184/cerimre.v7i2.51268

[10] F. Z. H. Pacha, A. Herizi, W. Amri, and A. Ben Amor, “Design and Diagnosis of current faults in electrical power systems of permanant magnet synchrones machine,” in *2022 5th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, 2022, pp. 204–209.

[11] S. Akbar, T. Vaimann, B. Asad, A. Kallaste, M. U. Sardar, and K. Kudelina, “State-of-the-art techniques for fault diagnosis in electrical machines: advancements and future directions,” *Energies*, vol. 16, no. 17, p. 6345, 2023.

[12] D.-H. Cho, H.-K. Jung, T.-K. Chung, and C.-G. Lee, “Design of a short-time rating interior permanent magnet synchronous motor using a niching genetic algorithm,” *IEEE Trans. Magn.*, vol. 36, no. 4, pp. 1936–1940, 2000.

[13] I. Khalid, “A Brief Review on the Electrical Resistivity Of Aluminium Alloy and its Nanoparticles at Low Temperature,” *Comput. Exp. Res. Mater. Renew. Energy*, vol. 5, no. 2, pp. 133–141, 2022.

[14] M. Cohen *et al.*, “Pronostic des infections liées à une voie veineuse centrale (VVC) dans une population de patient en nutrition parentérale à domicile (NPAD),” *Nutr. Clin. Métabolisme*, vol. 36, no. 1, pp. S10–S11, 2022.

[15] F. Edition and S. J. Chapman, “Electric machinery fundamentals,” 2012.

[16] G. C. Stone and M. Kurtz, “Interpretation of Megohmmeter Tests on Electrical Apparatus and Circuits,” *IEEE Electr. Insul. Mag.*, vol. 2, no. 1, pp. 14–17, 1986.

[17] J. L. Chaneliere, *Protection des lignes et des câbles de transport et de répartition*. Ed. Techniques Ingénieur, 2009.