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(RESEARCH ARTICLE)

Experimental investigation of insulation resistance for turbo generator digital protection

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Abstract

Insulation of all electrical machinery is practically in the form of organic compounds that contain water as part of their make-up. Excessive temperature tends to dehydrate and oxidize the insulation and make it become brittle and disintegrate under vibration and shock. The insulation lifespan of turbo generators deteriorates slowly at low temperatures and more rapidly at high temperature. Economic factors, such as initial cost, replacement cost, obsolescence, and maintenance, are of prime importance when determining the years of useful service desired for the electrical insulation. Generator digital protection- fault diagnosis test was carried out to find out the cause of insulation breakdown on the turbo generator unit 411G3. The experimental procedure consists of an insulation resistance test, meggering (time-resistance absorption test), and pendulum over-speed test. A thorough investigation was conducted to identify all the stator bars that constituted the Red phase and other connections. Voltage drops on these stator bars were measured and values were used to detect ground faults which were rectified via an intelligent protection scheme.

Keywords: IR Testing; Meggering; Phasor Data; Polarization Index; Thermal Insulation.

1. Introduction

Electrical insulation testing involves dielectric strength testing and insulation resistance measurement. Dielectric testing is a destructive test employed for fault finding (breakdown testing), while insulation resistance measurement is non-destructive under normal test conditions.

Dielectric testing measures insulation ability to withstand a medium-duration voltage surge without spark-over occurring. Dielectric testing is a destructive test performed in the event of a fault on a power transmission line as a result of voltage surge due to lightning or induction. This test is performed using a hippo tester to measure the applied AC voltage to ensure compliance to construction rules concerning leakage paths and clearances have been followed on new or reconditioned equipment.

The purpose of insulation around a conductor is to resist current and keep the current on its path along the conductor. Any problem with the integrity of the electrical insulation results in loss of current, and affects the performance of electrical installations in military aircraft panels, submarine circuit breaker panels, and commercial wiring harnesses.

Turbo generators are thermally protected with insulation resistance materials in the form of organic compounds that contain water as part of their make-up. Excessive temperatures dehydrate and oxidize insulation; make the insulator brittle and disintegrate under vibration and shock. Insulation deteriorates slowly at low temperatures and more rapidly at high temperatures [7]. The addition of modified varnish with a high thermal conductivity coefficient to the insulation material does not yield any deterioration of its electrical properties. In the 21st century, a lot of the research has

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concentrated on improving existing off-line diagnostic tests and on-line monitoring such as temperature and insulation thermal insulation. However, some newer tests such as polarization/depolarization current, dielectric spectroscopy, and on-line leakage current monitoring have been introduced [6].

During preventive maintenance is important to identify the possible causes of insulation performance deterioration and implement corrective measures. There are five causes of insulation failure namely: electrical stresses, mechanical stresses, chemical stresses, temperature variations stresses, and environmental contamination. The superimposition of these five failures leads to insulation breakdown and equipment failure and must be forestalled.

These tests and monitoring systems are reviewed. Tests and monitoring systems for rotor winding insulation and stator winding insulation are addressed separately. The permissible power ratings of machines, as indicated on the nameplate, are determined and standardized by the allowable temperature rise dictated by economic considerations [10]. Exceeding the load rating of the machine heats the insulation above the allowable limit and hastens its deterioration, whereas operating below the rating prolongs the insulation useful life. Available statistics indicate the life expectancy of insulation to be approximately halved with each 10^0C rise in operating temperature [8]. The electrical air-gap torques as well as the shaft torques are calculated for a variation of fault clearing times (FCT) of a 3-phase closed circuit [12].

Windings are disconnected from all bus-work to test deterioration of insulating resistance caused by moisture and dirt. Experiments reveal that when all Resistance Temperature Dictators (RTDs) are short to the ground, insulating materials have negative resistance characteristics. The resistance of the insulation decreases greatly with increasing temperature. Insulation resistance readings taken at different operating temperatures are compared with the reference temperature of 40^o Cf. The insulation resistance test was designed to detect ground, phase, three-phase faults, and any combinations of them. Performance of the instantaneous protection function of this test is dependent on the polarization index (P.I) is also measured to provide a quantitative appraisal of the condition of the insulation for moisture and other contaminants [4, 16]. [1, 2] works reveal the electro-physical properties of a new type of high-efficiency heat conducting insulation for turbo generators with air and hydrogen cooling. They further stated that the addition of modified varnish with a high thermal conductivity coefficient to the insulation material does not yield any deterioration of its electrical properties.

Higher turbo power generation depends mainly on the maximum availability of current in the stator windings. The development of insulation systems with improved heat transfer properties is required for high power turbo generators. The insulation frame acts as a heat barrier for the transfer of heat generated in the through stator walls. The specific heat conductivity of insulation materials like mica paper, the binder, and the substrate is characterized by excellent electrical insulation properties. The thermal insulation coefficient of the modern mica-based composite ranges between 0.25 and 0.30 W/(m K), while copper and steel are 1500 and 300 greater respectively [5]. This implies that mica based insulation acts as a heat barrier resulting in limiting the efficiency of the cooling system and, consequently, the specific power carrying capacity of an electric machine. Heat transfer in the stator winding system can be improved by either decreasing the frame insulation thickness; or increasing the allowable operating temperature of the frame insulation; or by increasing the thermal conductivity coefficient of the frame insulation [13, 15].

1.1. Insulation Resistance (IR) Test

Insulation resistance is a measure of opposition offered to current by the insulating materials. The insulating resistance is affected by moisture and dirt and is therefore a good indicator of deterioration from such causes. Before the test, the windings should be disconnected from all bus-work, surge arresters' or protection capacitors while shorting all Resistance Temperature Dictators (RTDs) to the ground. Insulating materials have a negative resistance characteristic; that is, the resistance of the insulation decreases greatly with increasing temperature. Hence, if insulation resistance readings taken at different operating temperature are to be compared, the reading should be corrected to a common reference temperature / usually 40^o C [14].

$$R_{40} = K_t \times R_t \qquad (1)$$

R_{40}, the insulation's resistance corrected to 40 ^{0}C

R_t, the measured insulation resistance at t ^{0}C

K_t, the correction factor.

A sixty-second insulation resistance test is recommended for comparison with previous records. The recommended minimum insulation resistance for field and armature windings is determined from the following employing a 500 V Megger: -

$$R_m = \frac{KV}{I} \qquad (2)$$

$R_{m,}$ Recommended minimum I.R corrected to 40 ^{0}C and I, Current (amperes)

KV, Rated machine voltage, kilovolts

1.1.1. Polarization Index

The Polarization Index (PI) provides a quantitative appraisal of the condition of the insulation for moisture and other contaminants. The index is obtained by taking the ratio of the 10 - min to the 1 - min insulation resistance measurements or current leakages. However, for the sixty seconds insulation resistance measurement, the 15 to 60 seconds measurement ratio gives you a good idea. For large windings such as in Shiroro, an index of less than 2.0 is unacceptable [9].

During the annual maintenance High-potential test (AC and DC) which is generally used for a go/no-go evaluation of electrical insulation is not conducted. Even though these tests provide a considerable amount of data useful for evaluating the condition of the insulation, they are still considered unnecessary during this preventive maintenance because the test is considered to be additional stress on the windings. The main leads connections and those of the Neutral from within the generator housing that is the generator terminals are to be properly checked for tightness with at least 50 Nm Torque. All inspection manholes along the main leads up to the Unit transformer are to be carefully inspected, cleaned with a vacuum cleaner and dry rags while the bolts and nuts are checked at 35 Nm torque wrench. The moisture absorber (silica-gel) of the main leads is fired to recondition it. The insulation resistance of all the leads is measured during the maintenance. The earthen transformer (single phase dry type 12.025 / 0.230 KV) should be cleaned with a vacuum cleaner and all bolts and nuts checked for proper tightness. Thereafter, the insulation resistance of the winding is measured. The earthen resistor network (0.30Ω) is also to be cleaned during this exercise while bolts and nuts checked for tightness. The self-excitation transformer (dry type 16 / 0.565 kV, 2 MVA) is maintained as obtained in the standard procedure of dry transformers as is the case with the earthen transformer above. The Generator surge arresters and protection capacitors are dusted and cleaned with a vacuum cleaner and all nuts checked for tightness [3, 11].

Digital fault recorders (DFR's) installed on power generator plants with data and communication gadgets records sampled waveforms of voltage and current signals, the status of relays, and other digital quantities related to the generator circuit. Oscillography record system using phasor data analysis module (PDAM) from DFR is employed to map out the sequence of events (SOE) for delays. A delay that is appreciable amounts of time spent delaying data does not express any fault or abnormal situation, delay load rejection, faults, or overload. The manufacturer's recommendation for insulation Resistance is a minimum of 10 Mega-Ohms per phase. Test result for any phase of stator winding less than specified indicates leakage as a result of insulation breakdown. The Generator surge arresters and protection capacitors should be dusted and cleaned with a vacuum cleaner and all nuts checked for tightness. Before the test the windings should be disconnected from all bus-work, surge arresters' or protection capacitors while shorting all Resistance Temperature Dictators (RTD's) to ground. Insulating materials have a negative resistance characteristic; that is, the resistance of the insulation decreases greatly with increasing temperature. Hence, if insulation resistance readings taken at different operating temperatures are to be compared, the reading should be corrected to a common reference temperature usually 40^o C [17].

2. Experimental

Generator digital protection- fault diagnosis test was carried out to find out the cause of breakdown/fault on unit 411G3. The materials needed were collected from the electronics and main stores. The mechanical auxiliary department removed all top covers and air deflectors –top and bottom. The electrical/protection control department disconnect the generator main leads and star- point bars. Then Megger test of the windings for Insulation Resistance (IR) was carried out and the result of the tests was recorded. Both rotor and stator windings were thoroughly cleaned with rags soaked in electro clean-2 safety cleaning solvent (halogenated hydrocarbon blend-C_2HC_{13}). The generator brakes were pneumatically released for circumferential cleaning of the rotor whole surface from dirt, soothes, and other foreign bodies. Finally, extensions, caps ring of the stator winding were cleaned. After the cleaning exercise, the winding was left over-night to dry. The following day, the generator heaters were switched on; set the thermostat to a minimum of

27^{0}C and a maximum of 70^{0}C for 2 hours to ensure the winding and its environment was completely dry of any liquid. After 2 hours the heaters were switched off and the generator was left to cool down till the following day and Insulation Resistance (IR) test was conducted.

2.1. Fault diagnosis test

A thorough investigation was conducted to identify all the stator bars that constituted the Red phase and other connections. The installation / original diagram was studied and the red phase connecting bars were identified and marked. To narrow down the particular area of the problem, voltage drops on these stator bars were measured at the marked points. The test result of segments 1 and 2 meggering shows that Ground Fault has occurred at some point of segment 2. Segment 2 was further broken up and meggered to pin-point the exact location of the fault. The readings show that the Ground Fault occurred between 6g and 199d (*12 Nos. of bars)*. Voltage drop tests and meggering was done to locate the problem between *stator bars Nos. 6g and 264d*. A further test reveals that the faulty bar was the *stator bar No. 6g* – (*the upper –Bar) in slot No. 6*, of the stator winding. The cause of insulation breakdown was traced to the *upper (top) part of the bar (6g*). The portion had direct contact with the Stator- core and some oil sediments were found at the lower portion of the bar and the surface of the bottom air deflectors. The bar 6g had a small crack at the bottom portion that was responsible for the ground fault.

2.2. Fault Rectification

Complex systems require improved protection to ensure system reliability and stability. Experiments conducted on real-life turbo generators are designed to identify and detect faults for improvement aspect to be achieved in the reliable inter-turn fault detection. Thus a new upper Stator was prepared for installation. The insulation on the fingers-tips (33 × 2 = 66 fingers) of the stator bar was burnt - off with oxy-acetylene gas flame. After heating, the wire brush was used to brush-off the insulation. The *generator* Stator-Slot No. 6 was well examined. The lower portion was wire-brushed to remove dirt particles and the slot was cleaned with electro clean-2 safety cleaning solvent (halogenated hydrocarbon blend-C_2HC_{13}). The new Stator bar was wrapped with another insulating black paper and slotted in place using the powerhouse overhead crane. Insulating wedges and insulating separators were used to hold the bar firmly in place. After this, all the stator bars and connecting bars that were separated for sectionalising the problem and meggering tests were brazed back perfectly. Stator, slip-ring chamber, and rotor core were cleaned with a vacuum cleaner. The slip-ring chamber was thoroughly cleaned with rags soaked in electro clean-2. All carbon deposits and foreign matters were removed. The cover was lifted up to gain access to the speed sensor damper rubber that was worn out for replacement with a new stator. The rotor core and whole generator housing area were cleaned with the top and bottom air deflectors. The star-point bars and generator main leads were connected back firmly. The instrument cables on the current transformers (CT's) were also reconnected. The top covers and slip-ring chamber were cleaned and assembled back to their normal positions.

2.3. Time-Resistance Absorption Test

Instantaneous Fault Detection test was carried out to achieve optimum protection and accurately detect faults inherent as quickly as possible. Turbine oil and Lower Combined Bearing (LCB) sump oil was topped to a normal 300 mm level after which the pendulum test was re-conducted. The generating unit was commissioned to ensure lifting of all isolations on Unit 411 G3. Cooling water lines were test-run to ensure no leakage. Finally, the mechanical test-run of a 72 hours' reliability test- the run was carried out and the unit was synchronized to the National Grid.

3. Results and discussion

Insulation Resistance (IR) test of the Stator conducted with AC Powered–Series 1megger; 1000V injected; 390C Star-Point disconnected condition for fault is shown in table 1.

The results reveal IR test is very effective in detecting ground faults in turbo generators. These values indicate leakage as a result of insulation breakdown, hence segments 1 and 2 were merged and meggering carried out with result presented in figure1.

Intelligent protection is required to instantly detect ground faults in MGs with high-impedance grounding. Ground fault protection could be done by using neutral overvoltage relays. Oscillography record system using phasor data analysis module (PDAM) from DFR was employed to map out the sequence of events (SOE) for delays. The result of the feature extracted data was used to plot the segmented phasor graph shown below in figure 1.

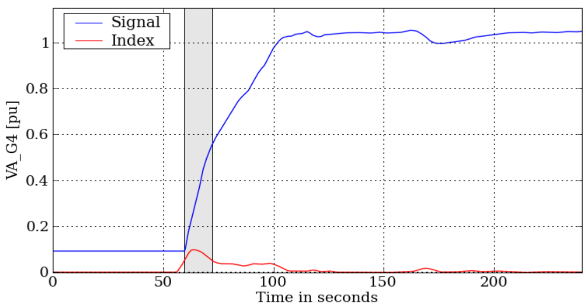

Figure 1 Segmented Phasor Graph

Table 1 Insulation Resistance (IR) Test of the Stator

Test No.	Connection Segment	15 Seconds MΩ	60 Seconds MΩ	P.I	Remarks
Test 1	R – YBG	0.4MΩ	0.4 MΩ	1.0	Not OK
	Y – RBG	100MΩ	1000MΩ	10.0	OK
	B – RYG	400MΩ	920 MΩ	2.3	OK
Test 2	Phase to Ground				
	Red to Ground	0.21 MΩ	0.21 MΩ	1.0	Not OK
	Yellow to Ground	300 MΩ	960 MΩ	3.2	OK
	Blue to Ground	300 MΩ	940 MΩ	3.1	OK
Test 3	Between Phases				
	Red to Yellow	300 MΩ	1000 MΩ	3.30	OK
	Red to Blue	320 MΩ	1000 MΩ	3.125	OK
	Blue to Yellow	700 MΩ	2000 MΩ	2.88	OK

AC Powered–Series 1megger; 1000V Injected; 39⁰C Star-Point Disconnected.

In table 2, test 1 shows that the resistance measured in 15 seconds and 60 seconds were fractional 0.4mΩ for R- YBG connection, and the phase of stator winding was just 1.0 P.I.

Table 2 Result of Meggering of Segments (1 and 2)

S/No	Connection	15 seconds MΩ	60 seconds MΩ	P.I	Remarks
1	Red to YBG	3.000	>100,000	33.33	Ok
2	Yellow to RBG	3,000	>100,000	33.33	Ok
3	Blue to YRG	3,000	>100,000	33.33	Ok

Koncar Megger; Voltage Selected 5,000V; Ambient Temp: 27⁰C

Pre-Diagnostic Expert System (PDES) results in energization as each phase was fired and the mean voltage signal before disturbance is < 0.1 pμ and after > 0.9 pμ. In figure 1 the current remains near zero. The delay of time does not express any fault or abnormal situation, delay load rejection, faults, or overload. During the execution of the No-Fault Expert System (NFES) the rule Normal Operation was fired because there was no relevant protection or circuit breaker operation within the sequence of events (SOE) list during the oscillography time interval. Thus, the final diagnosis is normal operation as the voltage sequence of RMS values gradually increased to its nominal value (1 pμ) and the current, in this case, remains near zero. Special cases representing unusual generator protection configuration can be specified by the NFES. Finally, the system can identify common faults where the oscillography data can be automatically archived.

IR test of the Stator conducted with AC Powered–Series 1 megger; 1000V injected; 390C Star-Point disconnected condition for fault diagnosis is shown in table 3.

Table 3 Insulation Resistance (IR) Test of the Stator

Test No.	Connection Segment	MΩ (15 Seconds)	MΩ (60 Seconds)	P.I	Remarks
Test 1	R – YBG	0.4MΩ	0.4 MΩ	1.0	Not Ok
	Y – RBG	100MΩ	1000MΩ	10.0	Ok
	B – RYG	400MΩ	920 MΩ	2.3	Ok
Test 2	Phase To Ground				
	Red to Ground	0.21 MΩ	0.21 MΩ	1.0	Not Ok
	Yellow to Ground	300 MΩ	960 MΩ	3.2	Ok
	Blue to Ground	300 MΩ	940 MΩ	3.1	Ok
Test 3	Between Phases				
	Red to Yellow	300 MΩ	1000 MΩ	3.30	Ok
	Red to Blue	320 MΩ	1000 MΩ	3.125	Ok
	Blue to Yellow	700 MΩ	2000 MΩ	2.88	Ok

AC Powered–Series 1megger; 1000V Injected; 390C Star-Point Disconnected

In table 4, *tests* 1 result also show that the resistance measured in 15 seconds and 60 seconds was fractional 0.4mΩ for R- YBG connection, and the phase of stator winding was just 1.0 PI. Polarization Index (PI) is a measure of quantitative appraisal of the condition of insulation for moisture and dust contamination. Sports Reading test result where a mega ohmmeter was connected across the insulation of the windings gives a test voltage applied for a fixed period of 60 seconds at winding temperature of 20 ºC was used to plot insulation resistance variation curve shown in figure 2.

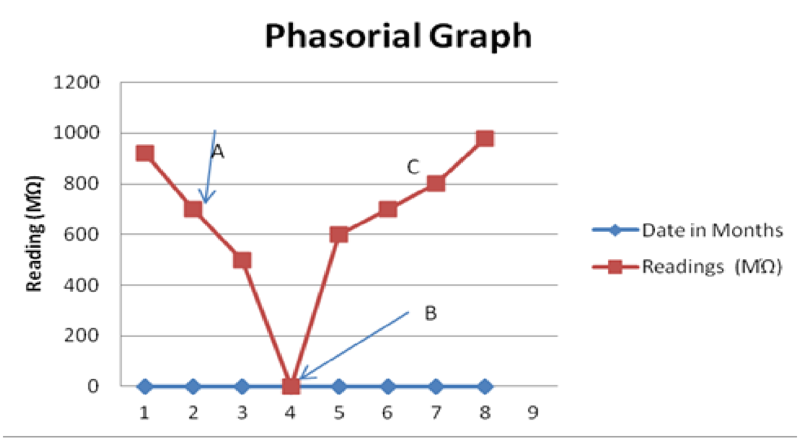

Figure 2 Insulation Resistance Phasor Variation Graph

A- The curve showing a downward trend indicates a loss of IR (insulation deterioration) due to conditions such as moisture, dust, dirt, or oil accumulation.

B- A sharp drop indicates insulation failure.

C- A continual increase in IR value after the maintenance test shows good insulation.

Table 4 Result of Meggering of Segments (1 and 2)

S/No	Connection	15 seconds MΩ	60 seconds MΩ	P.I	Remarks
1	Red to YBG	3,000	>100,000	33.33	OK
2	Yellow to RBG	3,000	>100,000	33.33	Ok
3	Blue to YRG	3,000	>100,000	33.33	OK

Koncar Megger; Voltage Selected 5,000V; Ambient Temp: 270C

Successive readings at specific times (60 seconds) were taken and used to plot a graph. Figure 3 gives a clear picture of the 60 seconds test for good or bad insulation. The series of tests with high operating voltage reveals insulation damage or good insulation was used to plot the segmented absorption test curve.

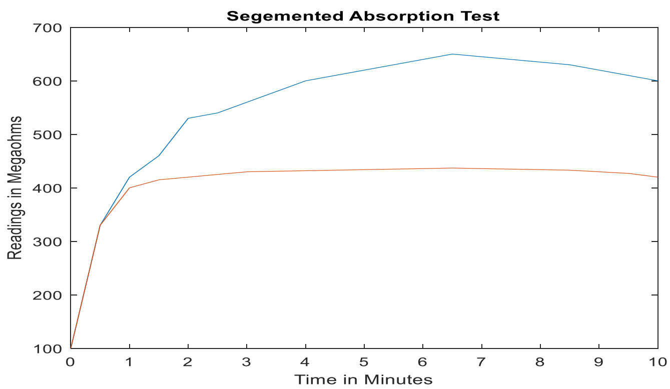

Figure 3 Segmented Absorption Test Graph

i. Curve D shows insulation with excellent polarization index PI>2.0. Insulation is thoroughly dry, clean and without physical damage thus it provides increasing resistance values despite changes in test voltage levels.

ii. Curve E shows a substantial potential decrease when tested at higher voltage levels. This serves as a warning that the insulation quality may be deteriorating due to dirt, moisture, cracking, excessive heat, or aging.

4. Conclusion

Insulation resistance of lagging material decreases with increasing temperature. For large winding such as in Shiroro the 60 seconds IR measurement for which PI < 2.0 is unacceptable as recommended by the manufacturer. Also, any IR < 10 MΩ indicates current leakage as a result of the insulation breakdown of lagging material that causes excessive heat within the turbo generator. Therefore, test 1 R-YBG with IR of 0.4 MΩ and PI of 1.0 value indicates leakage as a result of insulation breakdown, hence segments 1 and 2 were merged and the result presented in Table 4. This result shows clearly that IR values for 15 seconds and 60 seconds were 3,000 MΩ and 100,000 MΩ far above 10M Ω indicating no more current leakage. Also in tests, 1 to 3 PI was 33.33 greater than the recommended minimum of 2.0 PI. Time-Resistance Test (Absorption Test) results gives conclusive information without records of past tests. Data were based on the absorption effect of good insulation compared with moist or contaminated insulation.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest.

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