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Diagnostic Testing of Hydro and Turbo Generators and Large AC Motors in Service

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Majority of the generating sets operating in our country are turbo generators contributing nearly 70 % of the total electrical power generated. Many of these generators are about 30–40 years old and have already come to the end of their notional design life. The important components that have direct bearing on the operational reliability and life of the machine are: (1) Stator winding, (2) Stator core, and (3) Rotor winding. The stator winding is the most important and expensive part of the generator, where full power is generated. The life of the stator is affected by one or more combinations of various stresses, like electrical, thermal, mechanical and environmental, at any point of time during operation of the machine. Since the mechanical stresses are relatively higher in turbo generators, many of the stator winding failures are mechanically induced electrical failures. Some of the degradation processes include loosening of wedges and coils, slot and end-winding discharges, erosion of stress grading and corona shielding coatings, de-lamination of insulation, de-bonding of copper from insulation, etc.

Keywords: *Degradation processes, Insulation resistance and polarisation index, DC Leakage current measurement, Dielectric loss angle, Partial discharge, Surge comparison, Wedge tightness detection, Electromagnetic core imperfection detection.*

1.0 INTRODUCTION

Majority of the generating sets operating in our country are turbo generators contributing nearly 70 % of the total electrical power generated. Many of these generators are about 30–40 years old and have already come to the end of their notional design life. In recent times, with the ever-growing demand for power, high cost of new equipment and paucity of funds, there is an increasing trend to upgrade and extend the life of older generating sets. It has been recognized that with the advent of new technologies, there is a scope for upgrading of generating capacity of the generators. In the light of this knowledge of integrity of these machines and their remaining service life would be of great interest. In this endeavor, there is a strong incentive for condition assessment of various components of these machines. Over the years, many diagnostic tests have been suggested for condition monitoring of different components of the machines. The data obtained from these tests provide much needed information regarding present state and condition of the components.

2.0 LIFE EVALUATION PROGRAMME

The important components that have direct bearing on the operational reliability and life of the machine are: (1) Stator winding, (2) Stator core, and (3) Rotor winding.

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The stator winding is the most important and expensive part of the generator, where full power is generated. The life of the stator is affected by one or more combinations of various stresses, like electrical, thermal, mechanical and environmental, at any point of time during operation of the machine. In addition to these stresses, the stator insulation is also subjected to unforeseen stresses during transient over-voltage conditions. Steep fronted over voltages generated during switching actions and system faults propagate through the winding and have deleterious effects on the insulation. Since the mechanical stresses are relatively higher in turbo generators, many of the stator winding failures are mechanically induced electrical failures. Some of the degradation processes include loosening of wedges and coils, slot and end-winding discharges, erosion of stress grading and corona shielding coatings, de-lamination of insulation, de-bonding of copper from insulation, etc.

3.0 DEGRADATION PROCESSES

In addition to the operating stresses, the stator winding is subjected to unforeseen higher stresses during transient over voltage conditions. Steep fronted over voltages generated during switching actions, system disturbances or direct on-line starting propagate through the winding and have deleterious effects on the insulation. Some of the degradation processes associated with these stresses are coil looseness, vibration, erosion of stress grading and corona shielding coatings, slot discharges, end winding discharges, de-lamination, embrittlement, de-bonding of copper from the insulation etc. Therefore, there is a strong incentive from the point of view of preventive maintenance to carry out certain non-destructive diagnostic tests on the stator winding to detect any significant changes in the state and condition of the insulation. As condition assessment is based on trend analysis, the diagnostic tests need to be conducted periodically and generate data. The data obtained over the years would help to initiate appropriate remedial measures to avoid forced outages and increase reliability and availability of the machine. A systematic condition monitoring/diagnostic testing programme would go a long way in enhancing the service life of the machines.

4.0 CONDITION ASSESSMENT PROGRAMME

Condition assessment programme generally consists of following steps:

- Collecting O and M history of the machine
- Visual inspection and examination
- Conducting diagnostic tests on the machine
- Analysis of the data
- Identification of deteriorating factors
- Recommendation of appropriate remedial measures to enhance reliability and availability

4.1 Historical Data

Collection of historical data is a critical step to select the kind of tests and inspections which are sensitive to the likely failure mechanisms. Careful analysis of the data can warn of the problems, which are of generic as well as develop over the years due to aging.

The historical data include:

- Age of the equipment
- Running hours
- Number of starts and stops
- Load levels
- Over loading
- Major electrical disturbances and faults
- Vibration and temperature abnormality
- Record of repair and replacement of components, etc.
- O and M practices
- Design documents

4.2 Visual Inspection and Examination

Before carrying out the electrical tests, the equipment must be thoroughly inspected and examined for visible symptoms of deterioration. Symptoms of electrical tracking, corona, surface discharges, surface erosion, abrasion, time temperature effects and deformation can be easily detected through visual inspection, tapping, touching and feeling by hand.

4.3 Diagnostic Tests

Over the years, following diagnostic tests have been proved to be effective in condition monitoring of Turbo Generators and large AC motors in service [1].

1. Insulation resistance (IR) and Polarisation index (PI) measurement
2. DC leakage current measurement as a function of DC voltage
3. Dielectric loss angle test
4. Partial discharge test
5. Surge comparison test
6. ELCID Test on Stator core
7. Wedge tightness test
8. Tests on rotor

4.5.1 Visual Inspection and Examination

The visual inspection is generally considered to be a very important step in the diagnosis programme. It requires very good knowledge of machine construction and experience. Before conducting any electrical test, the stator winding must be thoroughly inspected and examined for visible symptoms of deterioration. Sometimes, mechanical damage to coil surface and end winding, looseness of coils and wedges, deterioration due to thermal effects, etc. cannot be readily detected by electrical tests. Such symptoms can be found relatively easily through visual inspection, tapping, touching and feeling by hand.

4.3.2 Insulation Resistance and Polarisation Index Measurement

It is a routine method checking the stator insulation. The test provides an indication of presence of cracks, contamination and moisture in the insulation. The PI is defined as the ratio of IR after ten minutes to the IR after one minute of voltage application. It is regarded as the index of dryness and cleanliness of the insulation.

The IR depends mainly on the temperature and humidity of the winding. To monitor the changes in IR values over time, it is essential to perform the test under the same humidity and temperature conditions.

If the stator winding is moist and dirty, the IR values will be low and PI approaches unity. Therefore, PI is a direct measure of the dryness and cleanliness of the insulation. In the event of low IR/PI values, steps shall be taken to thoroughly clean and dry the winding.

4.3.3 DC Leakage Current Measurement

Measurement of leakage current by applying DC voltage in steps is also frequently used. Variation of leakage current as a function of test voltage gives an indication of status of the winding. The test voltage is applied in steps, and held for a fixed interval of time at each step so that influence of polarization effects of the insulation is proportional to the voltage applied. The use of DC voltage instead of AC results in different stress distributions, in the stator winding compared with service conditions, and this needs to be taken into account when selecting the DC test voltage.

In some countries, the high voltage test either AC or DC is still a controversial matter because of the risk of causing prior damage or weakening of the insulation. To overcome this, over voltage testing at low frequency (0.1 Hz) but 1.6–1.8 times the line-to-line voltage has been adopted.

In most countries, the AC voltage test is the preferred method for finding localized weak points. Because of the reduced capacity and size of the apparatus, DC testing at 1.6 times the AC test voltage level has gained acceptance alternative to power frequency testing.

If there is a weakness in the ground wall insulation, a sudden nonlinear increase in current will precede a breakdown as the voltage is increased. An experienced operator can interrupt the test when the first indication of warning occurs.

4.3.4 Dielectric Loss Angle Test

Dissipation factor, also called tan δ, is a measure of dielectric losses in the insulation. It is the property of the insulating material used. For a given insulating system, the tan δ shall be as small as possible. An AC bridge such as a Schering bridge or transformer ratio arm bridge is used to measure the tan δ and capacitance of the stator winding.

For conducting the tan δ test, the stator winding needs to be disconnected from the cables on both neutral sides. When the measurement is conducted on one phase section, the other two phase sections, are shorted and grounded to the stator frame. The tan δ is measured in steps up to a maximum of rated phase to ground voltage. The tan δ at low voltage (at 20 % of the line voltage) is generally below the ionization threshold level of the voids in the stator winding insulation, and tan δ is only dependent on the kind, temperature, humidity, degree of polymerization, aging, contamination, etc. of the insulation. As the test voltage increases, tan delta increases due to partial discharges in voids occluded in the insulation. Therefore, the change in tan δ with voltage is a measure of the gaseous losses in the winding insulation. The slope of the tan δ-voltage curve is proportional to the volume of air or gas voids short circuited by discharges at the test voltage. Thus, tan δ measurements provide a good indication of the average condition of insulation of the stator.

Machine manufacturers use tan δ test as a quality control test for new stator bars and coils [2–4]. A general weakness in the bulk insulation normally caused by incorrect composition or insulation that is not fully cured is indicated by an abnormally high dissipation factor. Excessive voids occluded in the insulation involve in discharge activity at the operating voltage resulting in a higher than normal increase in the tan δ when the voltage is increased. The parameters that can be derived from this test are tan δ at low voltage (usually 0.2 V, where V is the rated line voltage), tan δ tip-up (average change in tan δ between 0.2 V and rated phase voltage) and capacitance tip up (percentage change in capacitance while raising the voltage from 0.2 V to the phase voltage) [5].

4.3.5 Partial Discharge test

Partial discharge test is another important diagnostic test for HV machines, as it is capable of revealing incipient faults in the stator winding structure. In HV electrical rotating machines, three types of discharges can be identified.

(a) Internal discharges that occur in voids occluded in the bulk volume of the winding insulation.

(b) Slot discharges that occur in the air gaps between the core laminations and adjacent coil sides in the slots.

(c) End winding discharges that occur at the extremity of the conducting coating outside the end of the slot where there is an interface on the coil surface between ground and high voltages.

The slot and end winding discharges are known to be more detrimental to the insulation than internal discharges. The internal discharges cause slow but gradual deterioration of the insulation in the course of service. The slot and end winding discharges are severe and can cause deterioration and eventual breakdown of the insulation within the span of few months.

The PD test involves energizing the individual phase winding to phase to earth voltage from an external source. The blocking capacitor C_b blocks the power frequency high voltage and allows the high-frequency current impulses of PD to be coupled to the discharge detector. The magnitudes of PD are calibrated in pico coulombs.

The AC test voltage is raised gradually until PD pulses are observed on the detector. The voltage at which PD starts occurring is called discharge inception voltage (DIV). The test voltage is increased up to the maximum of phase to earth voltage and magnitude of the PD pulses is noted down. As the test voltage is decreased, the voltage at which the PD pulses disappear is recorded. This voltage is called discharge extinction voltage (DEV) and is usually lower than the DIV.

Analysis and interpretation of partial discharges are still a subject of intense research. The PD is highly stochastic in nature. Their magnitude, repetition rate and phase angle of occurrence on supply waveform change continuously depending on the local conditions such as temperature, pressure and chemical composition that exist in the voids. In recent times, with the advent of computers and data acquisition systems, sophisticated PD detectors and analysers have been developed. With the available techniques, it is possible to detect the presence of slot and end winding discharges. However, there is no general agreement on the acceptable levels of PD magnitude, DIV and DEV. As the PD is known to cause chemical and mechanical destruction of the surrounding insulation, it is desirable that magnitude of PD shall be as small as possible and the DIV and DEV shall be as high as possible. The most useful method of interpreting the PD test results is performing the test at regular intervals and monitoring the trends.

4.3.6 Surge Comparison Test

Surge comparison test is used to determine the condition of inter-turn insulation of the stator winding. An impulse voltage of appropriate magnitude is applied synchronously to the two winding sections. The resultant damped oscillatory waves are superimposed on an oscilloscope. The two waveforms will be identical if both the phase windings are electrically identical and free from faults. Any discrepancy in the two waveforms indicates inter-turn fault in one of the windings.

4.3.7 Wedge Tightness Detection

The stator bars are tightly fixed/held in the stator slots of the core by wedging system. Excessive vibration in the machine may cause loosening of the wedges in the slots. The loose stator wedges lead to excessive vibrations and erosion of stator insulation and stress control coating in the generators. In the extreme cases, the loose wedges cause failure of the stator winding. Therefore, it is vital to detect tightness of the wedges in the slots.

The stator wedges are traditionally tested for tightness by tapping them with a hammer and listening to the hallow sound produced. However, it is a crude method and the assessment is highly subjective depending on the experience of the operator.

Electronic stator wedge tightness detection is faster, more accurate, provides consistent results than traditional hand tapping method and the test procedure is repeatable. The tightness data can be stored electrically for trend monitoring at future date. The tightness of each wedge is measured electronically and compared to all other wedges in the winding, the wedges of another winding or an absolute external reference. The data can be stored for trend analysis to determine when maintenance will be required.

The hand-held probe consisting of a magnetic hammer is small, light and can fit most slot widths and depths. The probe is moved from wedge to wedge and each wedge is tapped 29 times in three seconds. The accelerometer gathers the data and transmits this information to the signal processing circuitry in the electronic case. These processed signals are sent to the computer for final analysis and presentation in a map.

The status and position of problem stator wedges can be read off on this map immediately.

4.3.8 Electromagnetic Core Imperfection Detection

The stator core of a typical generator is built from thousands of thin steel sheets (laminations) and the winding is formed from electrically insulated copper conductor bars which are embedded in slots between teeth around the bore. The core is held together by steel building bars, usually on its outside.

The laminations are coated with a thin layer of electrical insulation to prevent eddy currents being induced between them by rotating magnetic flux produced by the spinning rotor.

Defects in the inter-laminar insulation cause fault currents to flow locally in the core. These currents can produce dangerous local overheating or hot spots in the damaged areas and the damage to the core may become progressively worse. In extreme cases, sufficient heat is generated to melt small parts of the core and even modest rises in core temperature adjacent to the winding can result in the premature failure of the winding insulation. Clearly, hot spots should be detected and repaired during routine machine overhauls. Early test methods known as full ring flux testing required the core to be executed to near its normal working level for a period of time. The temperature rise of hot spots due to the core fault was then measured.

An alternative method of detection of faults in core inter lamination insulation by electromagnetic means was developed by the Central Electrical Research Laboratory of the UK C. E. G. B. (now National Power plc). Instead of the previous full flux working level, the ELCID method uses only a small fraction of rated excitation to generate fault currents within the core body which are sensed by a pick-up coil. This avoids the testing problems usually found with high excitation, yet gives an accurate indication of damaged area along tooth tips and walls, as well as possible sub-surface damage.

The ELCID equipment tests a core for faults by exciting the core using a toroidal winding to produce a ring flux similar to the conventional method, but only to 4% of its normal working level of excitation.

4.3.9 Electrical Tests on Generator Rotor

The following tests are carried out on the generator rotor.

(i) **Insulation Resistance/Polarisation Index (IR/PI):** IR/PI test between slip rings and the body is carried out to check the integrity of the pole sleeve insulation of the rotor.

(ii) **DC Resistance test:** The DC resistance of the field winding is measured to identify defective clamps/brazings of conductors.

(iii) **Field Winding Impedance Measurements:** The impedance of the field winding is determined by measuring the AC voltage drop across winding on passing a known current. The inter turn short in any pole is reflected by the change in the measured impedance. Normally, up to 5 % variation in the measured impedance value is acceptable. Any variation over 5 % reflects shorted turns in the pole winding.

(iv) **Recurring Surge Oscillogram Test:** Rotor winding insulation inter-turn and earth faults are detected using the recurrent surge oscillograph (RSO) method. The test is very sensitive and will give an indication of the early stages of an interturn fault.

A DC voltage step is applied to each end of the rotor winding in turn. Each reflected wave at the input end of the winding is monitored and the two waveforms are superimposed automatically and monitored on a single channel oscilloscope. As the half windings in a rotor are identical, the two waveforms monitored at each end of the rotor will also be identical for a healthy winding. A winding with a fault will cause different voltages to be monitored at the two ends for a winding with an inter-turn fault.

4.4 Significance of Test Parameters

The test parameters used for condition assessment may be classified in to four groups:

(i) IR & PI, tan delta and capacitance at low voltage relate to degree of polymerization, cabonisation, contamination and moisture absorption;

(ii) Tan delta tip up, capacitance tip up, PD energy represent total void content in the insulation;

(iii) PD magnitude, DIV and DEV are capable of revealing severe local or abnormal degradation in the insulation;

(iv) ELCID test detects faults in the core. Wedge mapping test detects loose wedges and loose stator bars.

As there is no unique test method that can provide complete information on the actual condition of the stator windings and the operational reliability, a combination of several tests needs to be carried out.

4.5 Field Experience

CPRI has been undertaking the diagnostic tests on high-voltage machines in service for various utilities, power stations, petrochemical plants, industries over the last two decades. The test parameters cited above have been monitored and the field data so obtained are analyzed in depth. The assessment based on these parameters has enabled to predict the condition of the stator insulation and helped the user companies to initiate corrective measures to enhance the useful service life of the machines.

5.0 CASE STUDIES

5.1 12 kV, 220 MW Generator

The diagnostic tests were carried out on this 32-year-old generator in order to the assess the status of its insulation system. Figure 1 presents tan δ–voltage characteristics obtained on the stator winding of the generator. As it can be seen in the figure, the tan δ values lie in the normal permissible range for healthy machine. The characteristics do not exhibit steep slope with test voltage. These results indicate normal dielectric losses in the stator winding insulation. The IR values are high. The PI values are higher than the minimum permissible value of 2.0 according to the IEEE 43 standard.

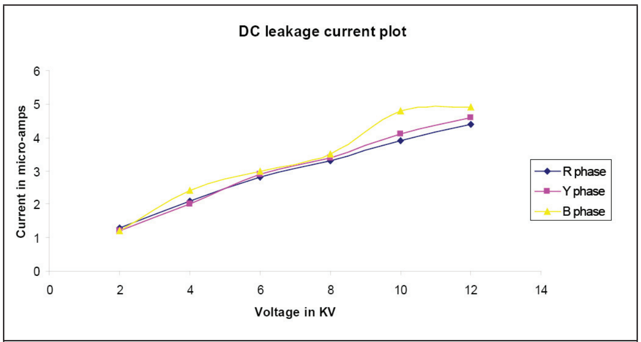

FIG. 2 DC LEAKAGE CURRENT PLOT

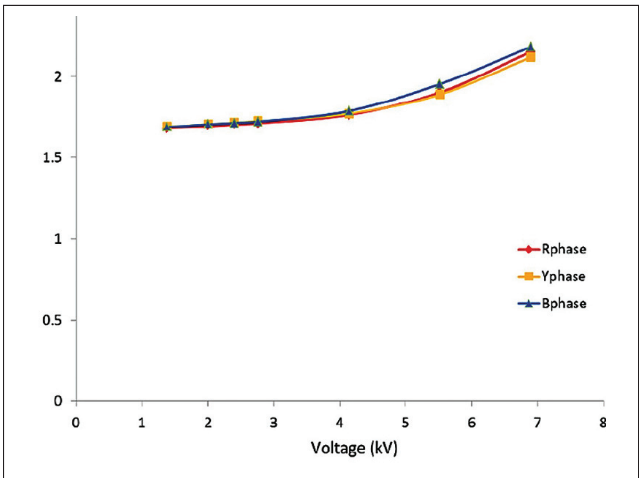

FIG. 1 TAN δ VS VOLTAGE CHARACTERISTICS

Figure 2 presents the DC leakage current-voltage characteristics obtained on the stator winding sections. The DC leakage current characteristics do not exhibit steep slope with test voltage indicating healthy condition of the overhang portion of the stator winding.

The partial discharge test results show low intensity of partial discharge activity in the stator winding insulation. The peak magnitude of partial discharges are 2000 pC, 3000 pC and 2000 pC, respectively, for the three-phase sections of the stator winding. These results indicate low void content in the stator winding insulation.

Figure 3 presents representative data of the ELCID. The ELCID data show that the fault current in the core is quite low indicating healthy condition of inter-lamination insulation system of the core. Figure 4 presents representative data of the wedge mapping tests obtained on the stator winding. The wedge mapping statistics in Figure 5 show that the percentage of loose wedges is quite low (0.2 %). These results indicate that wedging system of the stator winding is healthy.

From the analysis of the diagnostic test data, it can be inferred that stator winding insulation structure of the generator is healthy.

The condition monitoring tests were conducted on 25-year-old 11 kV, 110 MW, 27-year-old 13.8 kV, 120 MW and 20-year-old 11 kV, 5 MW Turbo generators; and 27-year-old 6.6 kV,

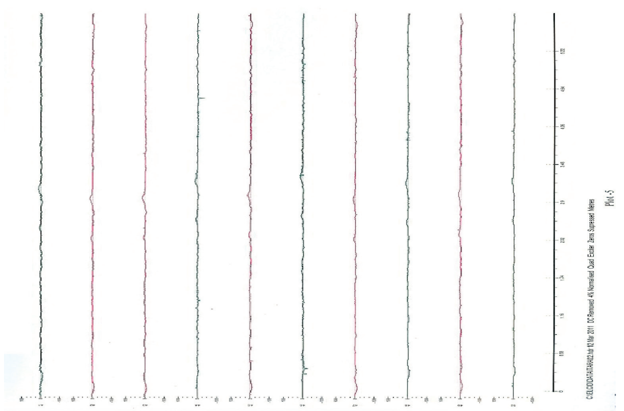

FIG. 3 ELCID PLOT

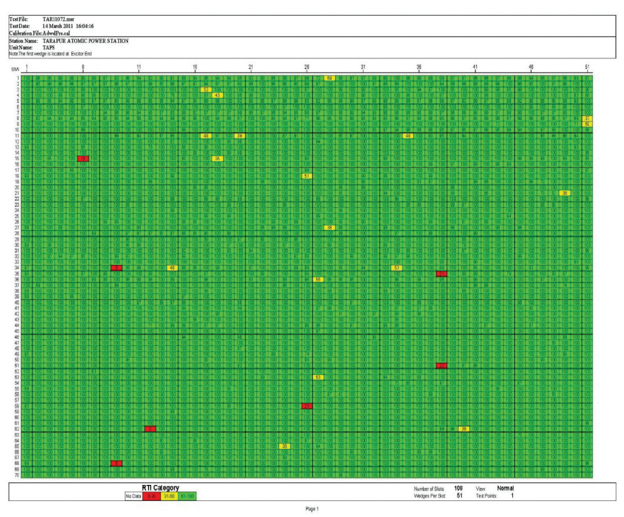

FIG. 4 WEDGE MAPPING

Test File: TAR11072.msr
Test Date: 14 March 2011 16:04:16
Calibration File: AdwelPre.cal
Station Name: TARAPUR ATOMIC POWER STATION
Unit Name: TAPS
Note: The first wedge is located at Excitor End

WEDGE TIGHTNESS REPORT [%]

Slot #	No Data	0-30	31-60	61-100
1	0.0	0.0	2.0	98.0
2	0.0	0.0	0.0	100.0
3	0.0	0.0	2.0	98.0
4	0.0	0.0	2.0	98.0
5	0.0	0.0	0.0	100.0
6	0.0	0.0	0.0	100.0
7	0.0	0.0	0.0	100.0
8	0.0	0.0	2.0	98.0
9	0.0	0.0	2.0	98.0
10	0.0	0.0	0.0	100.0
11	0.0	0.0	5.9	94.1
12	0.0	0.0	0.0	100.0
13	0.0	0.0	0.0	100.0
14	0.0	0.0	0.0	100.0
15	0.0	2.0	2.0	96.1
16	0.0	0.0	0.0	100.0
17	0.0	0.0	0.0	100.0
18	0.0	0.0	2.0	98.0
19	0.0	0.0	0.0	100.0
20	0.0	0.0	0.0	100.0
21	0.0	0.0	2.0	98.0
22	0.0	0.0	0.0	100.0
23	0.0	0.0	0.0	100.0
24	0.0	0.0	0.0	100.0
25	0.0	0.0	0.0	100.0
26	0.0	0.0	0.0	100.0
27	0.0	0.0	2.0	98.0
28	0.0	0.0	0.0	100.0
29	0.0	0.0	0.0	100.0
30	0.0	0.0	0.0	100.0
31	0.0	0.0	0.0	100.0
32	0.0	0.0	0.0	100.0
33	0.0	0.0	0.0	100.0
34	0.0	2.0	3.9	94.1
35	0.0	2.0	0.0	98.0
36	0.0	0.0	2.0	98.0
37	0.0	0.0	0.0	100.0
38	0.0	0.0	0.0	100.0
39	0.0	0.0	0.0	100.0
40	0.0	0.0	0.0	100.0
41	0.0	0.0	0.0	100.0
42	0.0	0.0	0.0	100.0
43	0.0	0.0	0.0	100.0
44	0.0	0.0	0.0	100.0
45	0.0	0.0	0.0	100.0
46	0.0	0.0	0.0	100.0
47	0.0	0.0	0.0	100.0
48	0.0	0.0	0.0	100.0
49	0.0	0.0	0.0	100.0
50	0.0	0.0	0.0	100.0
51	0.0	2.0	0.0	98.0
52	0.0	0.0	0.0	100.0
53	0.0	0.0	2.0	98.0
54	0.0	0.0	0.0	100.0
55	0.0	0.0	0.0	100.0
56	0.0	0.0	0.0	100.0
57	0.0	0.0	0.0	100.0
58	0.0	2.0	0.0	98.0
59	0.0	0.0	0.0	100.0
60	0.0	0.0	0.0	100.0

Summary (average of all slots)

108	0.0	0.2	0.5	99.3

RTI Category: No Data | 0-30 | 31-60 | 61-100

Number of Slots: 108 View: Normal
Wedges Per Slot: 51 Test Points: 1

Page 1

FIG.5 WEDGE TITENESS REPORT

3500 kW BFP motors, 6.6 kV, 570 kW ball mill motors at various Thermal Power stations in order to assess state and condition of their stator insulation systems.

5.2 11 kV, 110 MW Turbo Generator

1. Historical data: Year of commission: 1979; Stator winding rewound in 1986; Class F

5.2.1 Stator Winding

Visual inspection and examination:

- The Stator winding was cleaned by site Engineers using CRC solution. No varnish was applied.
- No deformation of the end winding and overhang portions.
- No embrittlement of the insulation was found.
- No discoloration of the insulation has been observed.

TABLE 1				
IR AND PI VALUES				
Phase	**IR (GΩ)**	**P I**	**DC leakage current at 9 KvDC (μA)**	**Conductor Resistance (mΩ) at 30° C**
R	4.19	4.32	1.2	1.901
Y	4.41	4.26	1.0	1.902
B	3.71	3.99	1.2	1.902

- No white/brown powder formation on the surface of the stator.
- No symptoms of arcing or surface discharges.
- No symptoms of mechanical damage to the stator winding.
- No migration of wedges.
- No loose lashes/space bars were found.

6.0 ELECTRICAL TESTS

The results of IR, PI, DC leakage current measurements and conductor resistance obtained on the Stator winding are presented in Table 1.

Referring to Table 1, IR and PI values are quite high. Since PI is regarded as the index of dryness of the insulation, it can be inferred that the stator winding is clean and dry. For a clean and dry insulation, the PI shall be higher 2.0.

The variations in DC leakage current against DC voltage obtained on the stator winding are satisfactory. The leakage currents increase gradually with test voltage and no sudden change in the slope has been observed. These results indicate that there are no weak points in the overhang portions of the stator winding.

TABLE 2			
RESULTS OF TAN δ AND CAPACITANCE TESTS			
Phase	**Tan delta (%)**	**ΔT (%)**	**ΔC (%)**
R	0.739	0.045	0.097
Y	0.719	0.032	0.070
B	0.784	0.038	0.0862

The stator conductor resistance values are comparable with the factory value with due consideration to the temperature at the time of measurement. From these results, it can be observed that the stator conductor joints are in good condition.

The results of tan δ and capacitance tests obtained on the three phases of the stator winding are presented in Table 2.

The tan δ test parameters lie in the normal acceptable range for an in-service machine. From these results, it can be inferred that the dielectric losses in the stator winding insulation are quite low. Tan δ tip up (ΔT), and capacitance tip up (ΔC), indicate that the void content in the stator insulation system is low.

The results of partial discharge (PD) are presented in Table 3.

The magnitude of PD at phase voltage are quite low for a 15-years-old stator winding (Rewound in 1986). The void content in the Stator winding insulation is low. The consolidation of the stator winding insulation is satisfactory. There are no symptoms of end winding or slot discharges.

TABLE 3		
RESULTS OF PARTIAL DISCHARGE (PD)		
Phase	**Voltage**	**Discharge magnitude**
R	6.35 kV	Less than 500 pC
Y	6.35 kV	Less than 500 pC
B	6.35 kV	Less than 500 pC

6.1 Stator Core

The ELCID test has been carried out on the Stator winding to detect imperfections/faults and hotspots in the Stator core. The ELCID test has been carried out by passing an AC current (Excitation Current) of 6.35 A. through 07 turns of loop around the Stator frame. The traces show the variations in the fault current as a function of the core length. The core laminations are coated with a thin layer of electrical insulation to prevent eddy currents being induced between them by the rotating magnetic field. Any defect in the inter-laminar insulation causes fault currents to flow locally between the laminations. These currents can produce dangerous local overheating at the damaged areas and the damage to the core may become progressively worse. In extreme cases, sufficient heat is generated to melt small parts of the core which will ultimately lead to failure of the winding insulation. Generally, for a good inservice machine, the currents induced in the core are flat to within 50 mA. The maximum limiting value of this fault current is 100 mA. Results of the ELCID test indicate that there are no imperfections or hot spots in the stator core.

6.2 Rotor Winding

6.2.1 Visual inspection and examination

Low contamination on the rotor winding, No deformation of the retaining rings.

6.2.2 Electrical Tests

Results of the IR, PI, Conductor Resistance, AC field impedance and Surge Comparison tests are summerised in Table 4.

As it can be seen in Table 4 the IR and PI values are quite high. These results indicate that the Rotor winding is clean and dry. Normally, the PI value shall be higher than 2.0.

TABLE 4		
IR, PI, CONDUCTOR RESISTANCE, AC FIELD IMPEDANCE AND SURGE COMPARISON TESTS		
IR (GΩ)		2.74
PI		3.5
Conductor resistance (mΩ)	Measured value at 28ºC	214.5
Field impedance (Ω)	Measured value	6.99
Surge test		No abnormality

The Conductor Resistance of the Rotor winding is in the permissible range with due consideration to the temperature of the conductor. The Surge Comparison test indicate that there are no inter-turn faults in the Rotor winding.

On the basis of the data, it can be inferred that the insulation conditions of the Stator winding, Rotor winding and Stator core are healthy. However, it is recommended to repeat the condition monitoring tests after three years with a view to monitor state and condition of the Generator.

6.3 13.8 kV, 120MW TURBO GENERATOR

Class B insulation, Year of commission: 1974

6.3.1 Stator winding

Visual inspection and examination of the stator winding revealed damage to two bars (bar nos. 48 and 49) on their overhang portions at the exciter end. The damage has caused a big hole in the insulation on each stator bar.

TABLE 5

RESULTS OF THE IR, PI, DC LEAKAGE CURRENT AND CONDUCTOR RESISTANCE MEASUREMENT

Phase	IR-GΩ 60 sec.	PI	DC Leakage current at 1 (kVDC)	Conductor Resistance (mΩ) at 32°C	Previous value (mΩ)
R	1.16	4.16	5.2	1.290	1.296
Y	1.07	4.08	6.0	1.288	
B	1.25	4.10	5.5	1.291	

Results of the IR, PI, DC leakage current and conductor resistance measurement obtained on the three stator winding sections of the generator are presented in Table 5.

Referring to Table 5, the IR and PI values lie in the normal range for an inservice machine. Normally, for a clean and dry class B winding, the PI value shall be higher than 1.5. Since PI is regarded as index of dryness of the insulation, the stator winding appears to be clean and dry.

The DC leakage current characteristics. DC test voltage are satisfactory. The leakage currents increase gradually with the test voltage and no sudden change in the slope has been observed.

The measured CR values are comparable with the previous data. These results indicate that there are no abnormalities with the conductor joints in the stator winding.

Results of the tan δ and capacitance tests obtained on the three phases of the stator winding are presented in Table 6.

The tan δ test parameters lie in the normal acceptable range for an inservice machine. From these results, it can be inferred that the dielectric losses in the stator winding insulation are low. The tan δ tip-up (ΔT) and capacitance tip-up (ΔC) indicate that void content in the stator insulation is quite low.

The partial discharge tests revealed that there are no partial discharges in the stator winding insulation up to the phase voltage (7.97 kV) of the machine. These results supplement the tan δ test results indicating low void content in the stator winding insulation.

TABLE 6

TAN δ AND CAPACITANCE TESTS OBTAINED ON THE THREE PHASES OF THE STATOR WINDING

Phase	Tan delta (%)	ΔT (%)	ΔC (%)
R	2.747	0.034	0.088
Y	2.728	0.022	0.066
B	2.440	0.013	0.068

6.3.2 Stator Core

The ELCID test has been carried out on the stator winding to detect imperfections/faults and hot spots in the stator core. The ELCID test has been carried out by passing an AC current (excitation current) of 4.38 A. through 07 turns of loop around the stator frame. The ELCID data are presented in test results.

The core laminations are coated with a thin layer of electrical insulation to prevent eddy currents being induced between them by the rotating magnetic field. Any defect in the inter-lamination causes fault currents to flow locally between the laminations. These currents can produce dangerous local overheating at the damaged areas and the damage to the core may become progressively worse. In extreme cases, sufficient heat is generated to melt small parts of the core which ultimately lead to the failure of the winding insulation.

In the present context, the fault currents are lower than the maximum permissible level of 100 mA. From these results, it can be inferred that the core insulation system is homogeneous and healthy.

Analysis of field data indicate that insulation condition of the stator winding is healthy and insulation condition of the stator core is also healthy.

However, in view of damage to the stator bars bearing Nos. 48 and 49, it is recommended to replace them.

It is also recommended to repeat the tests after 3 years in order to monitor the status of the insulation and structural integrity of the stator winding.

6.3.3 Rotor Winding

Visual inspection and examination revealed no abnormalities in the rotor winding.

Results of the IR/PI, winding impedance, conductor resistance and surge comparison tests are summarized in Table 7.

The IR and PI values lie in the normal acceptable range for an inservice class B insulation. For a healthy, clean and dry class B insulation, the PI shall be higher than 1.5.

TABLE 7

TEST PARAMETER MEASURED VALUES

IR-MΩ 60 sec.	697	
P.I	1.56	
Winding impedance (Ω)	6.83	
Conductor resistance at 38°C (mΩ)	Measured value	188.2
	Previous value obtained at site	184.8

The rotor impedance and conductor resistance values shall be comparable with that of the commissioning test data. Normally, these values shall not deviate by more than 5 % from their initial values.

Insulation condition of the rotor winding is healthy. However, it is recommended to repeat the tests after three years.

6.4 3.11 kV, 5 MW Turbo Generator

The the results of diagnostic test data obtained on the stator winding of this 20-years-old generator are presented in Table 8.

Referring to Table 8, the IR and PI values of the R-phase section of the stator winding are too low.

The corresponding DC leakage relatively higher. These results can be related to heavy contamination of this portion of the stator winding. As it is evident in the table, the tan δ test results indicate significant changes in the deterioration levels of the stator winding

TABLE 8

RESULTS OF THE IR/PI, WINDING IMPEDANCE, CONDUCTOR RESISTANCE AND SURGE COMPARISON TESTS

Phase	IR(GΩ)	PI	$I_{d\,(\mu A)}$	Tan δ (%)	ΔT(%)	ΔC(%)	$V_{i\,(kV)}$	PD magnitude (pC)
R	0.166	1.23	28.0	4.71	0.28	4.51	2.20	46,000
Y	1.06	1.64	4.2	4.37	0.05	1.60	3.40	3680
B	1.80	2.41	3.4	5.26	0.086	4.16	3.75	5980

insulation. While R-phase section of the winding is exhibiting higher level of deterioration of the insulation, the Y-phase section appears to be in good condition. The PD test also revealed higher level of deterioration in the R-phase section. As the PD was asymmetric and their magnitudes were extremely high, it was suspected that the motor was suffering from slot and end winding discharges, especially in the R-phase section of the winding. On the basis of these results, it was recommended to withdraw the machine and thoroughly inspect the stator winding for symptoms of slot/end winding discharges, loose or damaged wedges, erosion of stress grading coating and presence of heavy contamination. On physical inspection, it was found that the stator winding was heavily contaminated, 2 nos. of stator wedges were missing and most of the wedges in the slots were loose and deteriorated. Subsequently, the user company initiated action for re-wedging of the stator winding.

6.5 6.6 kV, 3500 kW, BFP Motors (2 no.s)

Motor A: Class B, year: 1975; Motor B: Class B; year 1975.

The results of PI, DC leakage current (I_d) and tan δ tests obtained on the stator winding of the motor are presented in Table 9.

The IR and PI values of all the motors are in the normal acceptable range. The tan δ tests indicate low dielectric losses in the insulation. The void content in the stator insulation systems of the motors is also low. There are no inter-turn faults in the stator windings as revealed by the Surge Comparison test.

The insulation conditions of the stator windings of both the motors are healthy. However, it is recommended to repeat the measurements after 3 years.

6.6 6.6 kV, 570 kW, BALL MILL MOTORS (2 No's)

Motor A:Cls F insulation; Date of commission: 1992; Motor B: Class B insulation.

The results of PI, DC leakage current (I_d), and tan δ tests obtained on the stator windings of the motors are presented in Table 10.

The ball motor B is exhibiting higher tan δ values due to the presence of heavy contamination. However, the tan δ tip up and capacitance tip up values are quite low, indicating low void content in the stator winding insulation. The stator conductor resistance values are comparable and in the normal range.

Insulation Condition of the stator windings of both the motors is healthy. However, it is recommended to thoroughly clean and dry the stator windings and varnish be applied to prevent any possible degradation of the structural

TABLE 9

RESULTS OF PI, DC LEAKAGE CURRENT (I_D) AND TAN δ TESTS

Test parameters	Motor A	Motor B
	All the phases are shorted	All the phases are shorted
IR (GΩ)	4.14	5.69
PI	3.48	3.50
I_d(μA)	0.8	0.8
Tan δ(%)	2.245	2.250
ΔT (%)	0.093	0.086
ΔC (%)	0.211	0.160
Surge test	Stable smooth and identical pattern	Stable smooth and identical pattern

integrity of the motors due to heavy deposits of contamination.

TABLE 10		
RESULTS OF PI, DC LEAKAGE CURRENT (I_D) AND TAN δ TESTS		
Test parameter	**Motor A**	**Motor B**
IR (MΩ)	1150	1810
PI	1.62	3.18
I_d at 5 kV DC (μA)	3.62	2.45
Tan δ (%)	4.747	9.608
ΔT (%)	0.01	0.07
ΔC (%)	0.141	0.26
Stator Conductor resistance (mΩ)	759.0 758.8 758.4	1102 1105 1105

7.0 CONCLUSIONS

Progressive deterioration of the stator insulation system of inservice HV machines can be assessed by monitoring certain non-destructive test parameters. As each test parameter can be related to certain information regarding condition of the insulation, it is preferable to monitor as many relevant parameters as possible to enable to arrive at a realistic assessment. The data of the diagnostic tests obtained over the years enable to initiate appropriate corrective measures to avoid forced outages and hence to enhance remaining useful service life of the machines.

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