Diagnostic Tests and Condition Monitoring of Electrical Machines

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1.0 INTRODUCTION

When a restricted earth fault relay or other protective device trips equipment, do you try to get the circuit back in? Do you carry out special tests to minimise further outages? Good maintenance practice is built around linking knowledge of equipment design, application, rate of fault development and timely diagnosis of symptoms. What tests do you undertake to identify and investigate those weak links?

The objective of this paper is to give a brief description of the available diagnostics testing and condition monitoring techniques for electrical machines i.e. generators and motors. There are basically two methods, offline and online testing.

2.0 OFF-LINE TESTING

2.1 STATOR

2.1.1 Insulation resistance

Insulation Resistance testing is carried out by applying a d.c. voltage from an insulation tester at voltage levels dependent on the rated voltage of the equipment.

Rated voltage	Test voltage
LV below 1 kV	500V dc
HV up to 4.6 kV	2500V dc
HV above 4.6 kV	5000V dc

For correct comparative interpretation of test data, subsequent IR tests should be carried out at the same voltage level as the initial test.

The measured resistance (IR) value is dependent on the temperature of the insulation and shall be corrected with the use of a nomogram. As a guide, the Insulation Resistance of windings reduces by approximately 50% for each 10 °C rise in temperature.

2.1.2 Polarisation Index

Also known as DC absorption test, the Polarisation Index (PI) is the ratio between the insulation resistance measured after one minute and after 10 minutes of continuous testing at the appropriate voltage ($PI = R_{10\ min}/R_{1\ min}$). After 10 minutes, the capacitive current, the leakage current over the surface of the insulation and the dielectric absorption current will have stabilised.

The PI obtained gives an indication of the condition of the winding insulation with regard to its dryness and cleanliness; the PI will be lower for a dirty, wet chemically contaminated winding insulation. Below are some typical curves for variations of insulation resistances and the values for the Polarisation Index.

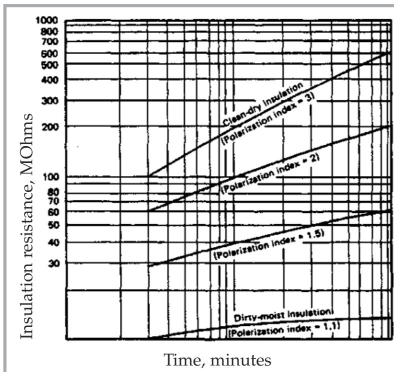

Figure 1

2.1.3 RC measurement

The product of the measured Resistance and Capacitance values, RC gives a value specific to the properties of the insulation. The value is independent of the thickness or area of the insulation being measured. It is a measure of the resistivity and permitivity (dielectric constant) of the insulation material.

For polyester resin impregnated insulation (coil VPI), the value should exceed 30 while for epoxy resin impregnated insulation, (global VPI), it should exceed 100.

2.1.4 Tan delta

When an AC voltage is applied to a dielectric, the total current I will lag the capacitive charging current I_C by an angle δ which is known as the loss angle. Readings of $\tan\delta$ are taken as the test voltage is increased up to a maximum of the rated phase voltage. The value of $\tan\delta$ can be seen to increase as the test voltage is increased. The test voltage is then decreased and readings of $\tan\delta$ are again taken. The two sets of readings should be about the same.

The value of $\tan\delta$ is an indication of the surface contamination (e.g. by dust, moisture) and the value at 2 kV should not exceed 8 for most types of dielectric material.

2.1.5 Surge test

A pulse generated by the test equipment is applied to the stator of the machine under testing. The pulse can be applied one phase at a time. This produces waveforms on the instrument display. If there is no current leakage between turns or phases or to the ground, the waveforms will be stable and identical. If there is a turn-to-turn or phase-to-phase weakness, the wave patterns will separate and appear unstable. This is an indication of imminent failure. If a motor with a turn-to-turn fault stays in service, circulation currents may produce hot spots and the groundwall insulation will eventually fail.

2.1.6 Partial Discharge (PD)

The term partial discharge and corona are frequently used interchangeably in the industry. According to IEEE 1434-1999, a partial discharge is an incomplete or partial electrical discharge that occurs between insulation and either insulation or a conductor. This is in contrast to a full discharge that spans the gap between two conductors, otherwise known as insulation failure. Corona occurs when the gas adjacent to an exposed conductor ionizes and produces visible partial discharges. Corona or PD does not involve insulation.

The first step of most insulation failure is the creation of gas-filled voids. The voids are the result of degradation of the impregnated resin and may be internal to the insulation system or on the surface of the coil. Once a void is created within the bulk or on the surface of insulation, a potential difference will build across it. The magnitude of this voltage will depend upon the applied voltage and the capacitance of the insulation and the gas in the void. A discharge can only occur when the electric stress exceeds the electrical breakdown point for the gas e.g. 3kV/mm for air.

The pulse from a PD has an extremely fast rise-time and short pulse width. Most PD detection devices only detect the initial pulse that has a rise-time of 1 – 5 nanoseconds which corresponds to the frequency range of 50 – 250 MHz.

Off-line PD measurement involves the application of a voltage up a maximum of the rated phase voltage. The PD is picked up by a detector which measure it in pC (picoCoulombs). Typical, normal values are less than 10,000 pC.

Other methods involve the use of transformer ratio arm bridge with appropriate coupling capacitors. The PD pulse patterns are analysed with regard to pulse count, pulse magnitude, polarity dependence and phase to identify the nature of the discharges, which can be classified as:-

- internal discharges
- surface discharges
- slot discharges.

2.1.7 Ring flux test

A number of turns of insulated flexible cable is wound toroidally around the core. A transformer of suitable rating will charge the cable. Flux will be generated in the stator core by means of these external loops and hot-spots or any abnormal temperature rise in the core can be determined. Parameters like current, core losses, ampere-turns, volts/turn, etc. can be measured at various flux levels and recorded for future reference. At flux density of not less than 1 Tesla, the stator will be kept under observation for about one hour, noting the temperature at various locations at various interval of time, in order to identify the presence and location of any hot-spots.

2.1.8 Electrical Core Imperfection Detector (ELCID) test

Around 5% flux is created in the stator core with the help of a loop wound toroidally around the core. A pick-up coil will be used to access the leakage fluxes that bridge adjacent teeth. Phase shifting due to eddy currents generated at the site of 'hot-spots' or shorted laminations between the accessed leakage fluxes and the exciting fluxes will be noted to detect the shorted laminations.

2.1.9 Polarisation-Depolarisation Current Analysis

A D.C. step voltage of 2500V is applied to the windings using a highly regulated electronic power supply. The voltage is maintained for a time period of not less than 1000 seconds. The current flowing through the insulation is monitored during the charging period. After all the relevant data is obtained, the windings are discharged through a micro ammeter and discharged currents are monitored after the initial windings capacitance discharge (< 5 secs), over a total time period that will not be less than the charging time period. The charging and discharging currents are plotted on a log-log scale and analysed in the time and frequency domains.

The following parameters are computed from the measurements performed:-

- Ion migration time constant
- Slow relaxation time constant
- Interfacial polarisation time constant
- Ageing factor / mobility index of the binding resin
- Ion concentration index
- Dispersion ratio

On the basis of the above, an assessment of the winding insulation can be made with regard to:-

- General insulation quality
- Sensitivity of the insulation system to moisture absorption
- Presence of contamination in the windings
- Condition of the binding resin
- Extent of electrical contact of the coil with the slot.

2.1.10 Wedge looseness check

The stator slot wedges are checked for looseness by tapping on them with a small hammer and listening for the hollow sound of looseness. The results are recorded and from the percentage of loose wedges is a row or slot, re-wedging is carried out by knocking out the loose wedges and replacing them with new wedges and re-varnishing the slots.

2.2 ROTOR

2.2.1 Insulation Resistance, Winding Resistance and Polarisation Index

Insulation and PI measurements are carried out on the rotor windings using 500V megger. The winding resistance is measured to find any inter-turn shorts and breaks or for high resistance joints. The resistance values obtained are compared with earlier measured values.

2.2.2 Polarization-Depolarization Current Analysis

The test is conducted the same way as for PDCA measurements on the stator windings at test voltages not exceeding 500V. From the test results, it can be determined whether any suspected leakage is localised (damage related) or global (contamination related).

2.2.3 Recurrent Surge Oscillograph (RSO)

A steep fronted step voltage is repeated applied to the rotor windings using a Recurrent Surge Oscillograph (RSO) and the terminal voltage is examined for reflections from shorted turns. This test is very sensitive and will give an indication of the early stages of an inter-turn fault or earth fault.

2.2.4 Dye Penetrant test

The rotor ratainging rings are subject to huge forces during operation. A dye penetrant test is conducted at the retaining rings to check for cracks. The rotors of older synchronous machines may be made from 18Mn-5Cr material which is susceptible to stress corrosion cracking and periodic checks should be carried out. For the long term, replacement of the retaining rings may be considered.

3.0 ON-LINE TESTING

Condition monitoring (also known as Predictive Maintenance) is rapidly being accepted as the best way to minimise overall maintenance costs in capital-intensive equipment that is usually highly reliable such as motors and generators. Condition monitoring is an approach to planning maintenance, where equipment is removed from service when and only when an on-line monitor gives an indication that some failure mechanism is imminent. Thus equipment shutdowns are not based on operating hours or the elapsed time since the last maintenance shutdown.

Having confidence in planning maintenance based on the actual condition of the machines involves the following prerequisites:-

- The monitors must be able to detect most of the failure mechanisms that are likely to occur.
- There must be few false alarms. That is, if a monitor indicates a problem, an actual problem must exist.
- The monitor itself should not lead to a failure and the monitoring cost must reflect a small fraction of the machine cost.

Over the past 20 years, extensive research has refined and/or developed several technologies that can detect most rotor and stator windings problems in machines during normal service. These new monitoring technologies include:-

- The reliable measurement of stator winding partial discharge
- The detection of shorted turns using magnetic flux monitoring in synchronous machine rotor windings
- The detection of broken rotor bars in induction motor rotors using Current Signature Analysis (CSA).

Together with conventional vibration and temperature monitoring, the majority of winding problems can be detected and addressed well before in-service failures occur.

3.1 On-line PD monitoring

On-line PD monitoring involves the permanent installation of sensors on the machines. The sensors are periodically monitored via a specialised portable instrument or permanently connected monitoring system. The type of sensor, its mounting location and the instrument technology used for the measurement are dependent on the machine to be monitored.

Analysis of the measurements provides an insight into insulation aging or deterioration mechanisms such as loose windings, degrading semi-conductive paint in the slot, delamination of groundwall insulation, separation of the tape layers from the copper due to thermal cycling and possible contamination or tracking in the end winding area.

Industrial and utility motors rated 3.3kV and above are monitored for PD activity using 80pF epoxy mica capacitive couplers installed at the high voltage terminals of the machines. Typically only three sensors are installed because most motors are connected to significant lengths of power cable which attenuates and distorts any noise pulses from the power system making it improbable to mistake with PD signals. The sensors are fitted inside the motor termination box and the coaxial cables from the sensors are terminated in a separate enclosure to be used in conjunction with either a portable PD analyzer or directly plugged into a continuous monitor.

Turbine generators rated less than a few hundred MW are typically fitted with at least six 80pF epoxy mica capacitors. A set of three sensors is installed at the terminals of the machine and a second set of three sensors is installed at a short distance along the bus towards the switchgear or the transformer. The 'directional' installation on each phase of the generator takes advantage of the physics of pulse propagation of high and low frequency pulses through the bus, connecting the generator and the system. After a calibration of the set-up during an outage, the installation is optimized to help determine the source of the pulses recorded by the instrument. The sensors are connected by calibrated coaxial cables to an enclosure where they can be monitored either periodically or continuously.

Machines rated over about 150MW provide a unique challenge to PD monitoring due to the risks of internal noise which can be attributed to multiple sources of arcing and sparking within the stator. To overcome this problem, stator slot clouper (SSC) are used. These act as high bandwidth antennae which are installed during a rotor pull or at the factory during assembly of the stator. The SSC sensor is inserted under the wedge of the line-end coil of each parallel or between the top and bottom bars in the same slot during assembly or a rewind. The SSC's are custom-made to fit the slot width of individual machines. They are made from materials similar to those used in slot packing/filling. The SSC's are not connected directly to any high voltage component within the machine. For hydrogen-cooled generators, the coaxial cables from each sensor are fed through a hermetically-sealed penetration.

3.2 Magnetic flux monitoring

Turbine generator rotors are a critical component to the overall reliability of the equipment. Rotors age due to high electrical, mechanical and thermal stresses under which they operate. In addition, as they are rotating components, on-line condition monitoring can prove to be difficult. One proven technology for monitoring turbine generator rotor winding insulation integrity is on-line magnetic flux monitoring. Utilising specialised sensing coils fixed to the stator, the flux of the rotor slots can be measured. Shorted turns in the rotor winding will result in a perturbation in this flux pattern. Shorted turns result in:-

- Decreased generator output power and efficiency
- Mechanical vibration due to rotor thermal unbalance.

3.3 Current spectrum Analysis

Motor current signature analysis is widely used to diagnose rotor problems in three-phase squirrel cage induction motors. By measuring current spectra from the motor supply, sidebands in and around the fundamental supply frequency can be used to detect broken rotor bars. The spectra is analysed by software algorithms to directly indicate the number of broken rotor bars accurately. Other rotor conditions like rotor eccentricity may also be determined.

4.0 Conclusion

Machine reliability and availability are becoming more crucial as many industries strive to 'sweat the asset'. A good programme of diagnostic testing and condition monitoring is required to ensure that equipment utilisation and maintenance cost are optimised by means of 'just-in-time' intervention. ■