The Journal of CPRI,
Vol. 6, No. 1, March 2010 pp. 61–76

Assessment of Stator Winding Insulation

Part 1 - Review of Deterioration Mechanisms and Condition Monitoring Techniques

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This paper reviews the main ageing and failure mechanisms of stator winding and methods for extending the useful life of the machine. The symptoms for each failure mechanism are discussed and an overview of various electrical diagnostic techniques for condition assessment of stator winding insulation is presented

Keywords: *Stator Winding Insulation, Degradation, Condition Monitoring Techniques*

1.0 INTRODUCTION

High voltage rotating electrical machines represent vital key components of power plants. They are quite expensive, form significant portions of the plant assets and their reliability depends to a large extent on the healthy condition of the insulation. The insulation systems of high voltage (HV) rotating machines are a complex combination of materials and have undergone few changes in the last few decades. In the past, natural binding materials were employed as stator insulation of HV rotating machine. However, with the advent of synthetic materials (Polyester, Epoxy, Silicone resins, etc.) the development of generator with larger capacity became possible. Epoxy-mica is used as ground wall stator insulation of large generators since 1960 [1,2]. These materials used in stator winding do comply with the required performance at the beginning of their life, but due to various stresses during service condition, undergo ageing and deterioration. The progressive deterioration of high voltage machine insulation is assessed through non destructive techniques like measurement of Insulation Resistance, Polarization Index, Dissipation Factor, Loss Angle and Capacitance, Partial Discharge (PD) measurements, mainly for trend analysis [3-9]. Whilst reliable assessment of insulation condition cannot normally be achieved by a single test, a reasonable indication of the overall condition can be assessed by obtaining the results of a number of tests. In order to identify the ageing mechanisms and diagnostic measures for the assessment of degradation, long time accelerated ageing studies of stator insulation models of HV machines in the laboratory have been carried out by several researchers. Life models for insulation ageing under accelerated electrical, thermal and mechanical multistress have been proposed in literature [10-14]. Further the failure mechanism due to combined stress have been described based on empirical models [15]. A new structured methodology developed through CIGRE WG 15.11 "Service Aged Materials" [16] has been proposed to link the evidence obtained from forensic studies of failed plant with the theoretical failure modes developed from laboratory studies.

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1.1 Insulation System

To fully understand and predict the electrical behaviour of insulation and ageing characteristics, one must have knowledge of the chemistry of materials used: the atomic-molecular arrangement and the nature of the chemical bonds. The stator winding of rotating machine usually comprises of mica with organic reinforcing, bonding and impregnating materials [1]. Mica paper / synthetic resin combinations (polyester, epoxy, silicone resins, etc.) are employed almost exclusively in the form of tapes, which are wrapped around the conductor, impregnated and cured. Mica's unique combination of physical, thermal and electrical properties and its ability to be split into very thin, incompressible sheets while maintaining flexibility, toughness and high tensile strength find wide applications in high voltage machines. The two classes of mica most commonly used in electrical applications are muscovite [$KAl_2(Si_3Al)O_{10}(OH,F)_2$] and phlogopite [$KMg_3$ $(Si_3Al)O_{10}(OH,F)_2$] respectively [17]. Mica minerals comprise of layers of silicates separated by alternating layer of metal oxides and metal ions. Fig. 1 shows the cross-section of muscovite mica showing the silicate metal oxide-silicate layers where one of every four silicon atoms is replaced by an aluminium atom. Each three layer structure is separated by a layer of potassium ions.

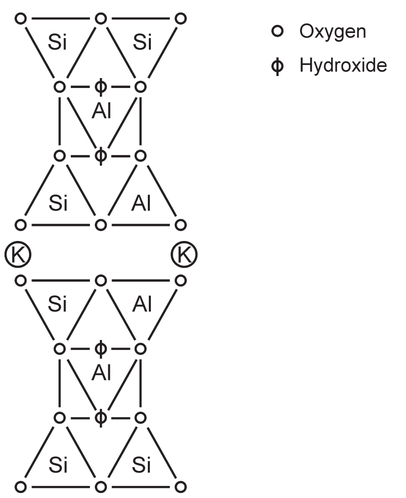

FIG. 1 CROSS-SECTION OF MUSCOVITE MICA

Epoxy resins are valued for their high strength, good adhesion to most materials including metals, and resistance to moisture, solvents, and other chemicals. Epoxies take their name from the epoxide functional group (three-membered oxygen containing ring) which forms part of the epicholorohydrin molecule, one of the two reactants to make the resin. The molecular structure of basic epoxy resin prepolymer is as shown in Fig. 2. The other component most commonly used is dipheyl propane, often called Bisphenol A. Many different curing agents are used to bring about cross linking of thermosetting epoxy resins.

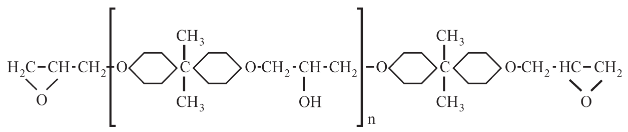

FIG. 2 MOLECULAR STRUCTURE OF BASIC EPOXY RESIN PREPOLYMER

2.0 DETERIORATION MECHANISMS

The epoxy/mica insulation in a generator stator winding ages under the conditions of thermal, electrical, vibration and thermo-mechanical stresses during service [2]. In addition to the operating stresses, the stator is subjected to unforeseen stresses during transient over voltage conditions. Steep fronted over voltages generated during switching actions, system disturbances or direct on line starting etc., propagate through the winding and have deleterious effects on the insulation. Ageing process is complex in general and takes place under stresses simultaneously or sequentially. Thermal ageing is a chemical process like molecular decomposition and oxidation of organic materials. It will lead not only an increase of internal gas pressure and decrease of adhesive strength of epoxy to mica surface, but also results in delamination at the interface between mica and epoxy [18-20]. Delamination further aggravates under thermo-mechanical force. Small cracks are likely to be generated in epoxy rich areas due to thermal ageing which could trigger electrical trees.

Electrical stress causes Partial Discharge in defects, which erode insulating materials [21].

Partial discharge occurring with occluded cavities in the epoxy resin of the insulation can lead to breakdown of the insulating system and the degradation results from a complex synergistic action of electronic and ionic surface bombardment, of ultra violet radiation and of electro chemical reactions. Among the leading causes responsible for premature failure of machine insulation are slot discharges which are characterized by extremely large pulses. In the past 10 – 20 years significant progress has been made on research in the area of partial discharge induced ageing of epoxy-mica insulation. The amount of literature on partial discharge (PD) and partial discharge induced degradation is vast [18-27]. Several researchers have attempted to correlate a number of parameters such as discharge amplitude with dielectric damage [23] or pulse repetition rate with surface deterioration [24]. Studies based on partial discharge test for observing delamination and cracks in the insulation are reported [25]. Neural networks / pattern recognition techniques has been applied to recognize PD problems. [27].

The physical and chemical nature of the degradation products formed on the surfaces of the epoxy resin are also reported in literature. Insulation condition can also be affected by various factors such as thermally decomposed byproducts, moisture absorption, oxidation, electrolytic effects of leakage currents, attack by electrical discharges and their chemical byproducts, thermo mechanical stress and mechanical wear and abrasion [25]. Thermal analysis techniques have been used to characterize a mica/glass fiber-reinforced composite. Furthermore, optical microscopy and SEM are used to examine surface morphology of the insulation.

The various degradation mechanisms [2] leading to failure are

2.1 Thermal Ageing Processes

The thermal stress on the insulation occurs due to the continuous I^2R loss in the conductor and sometimes due to thermal shock in the event of a short circuit. The insulation inside the slot is surrounded by large amounts of iron whose heat capacity is very large as compared to air. However in deep slotted machines the temperature rise in the middle of the slot could be 180°—185°C, because of low thermal conductivity of the surrounding insulation and localized runaway condition may be reached.

The various causes of thermal ageing are

- Chemical changes in binder and backing materials due to operating temperature and with time, ingress of moisture and contaminants during periods of shut down, overhaul, relative motion between conductor and core due to thermal cycling, inadequate cooling due to dead spots, poor distribution and reduction in heat transfer, loss of volatiles.

The common symptoms and failure mode due to thermal ageing are

- Burning smell and change in colour and texture, strand separation, powdering, puffiness, embitterment flaking and delamination of insulation, tape separation, cracks and sponginess, flow of insulation in case of bitumen, increase in PD activity, flashover of surfaces or gaps under electrical stress due to nearby arcing or extremely high metal temperatures in the presence of contaminated gas.

2.2 Electrical Ageing Processes

The electrical stresses occur due to the operating voltage. Enhanced electrical stresses can occur at certain local points due to voids, imperfections and defects. The insulation being composite in nature, it is very likely that hollow cavities are present within the system. The partial discharges in these cavities are always a source of degradation. The occurrence of PD in rotating machine stator insulation is a very common phenomenon and the origin of failure in many instances has in fact been traced to this. In addition, two other types of degrading phenomena can occur in the insulation, namely the slot discharges and discharges in the end region, called end discharges.

2.2.1 Partial discharges

Partial discharges are caused by local breakdown of insulating media. As a result of a high local electric field, charge carrier swarms are generated in the dielectric and may produce local decomposition of the insulation.

The most significant locations where this can occur are

- Voids enclosed in the slot insulation material or at its boundary with the copper conductor
- Between the semi-conducting paint on the bar and the iron core (slot discharges).
- At the damaged spot of the paint i.e. where the electric field along the surface becomes too high.
- Where the stator bar emerges from the slot and no special stress control is present.
- Between the non-linear and highly resistive stress grading paint at slot entry and the low resistance coating on the bar.

2.2.2 Slot discharges

The discharge between the main ground insulation of high voltage coil and the slot wall is termed as the slot discharges. One can easily distinguish between mechanical slot discharges caused by the stator bar movement in the slot, and electrical slot discharges caused by poor contact between the semi-conducting layer of the stator bar insulation and the stator iron core.

Causes of discharge damage

Various causes which are responsible for damage are:

Inadequate resistivity of outer coil surface and that of any slot fill material whenever used, coil damage, clearance between coil side and slot wall, level of distribution, loss of effective electrical contact of coil surface to ground, thermal cycling etc.

Each individual factor plays its own role and finally a few combined effects lead to damage of insulation.

Various causes of electrical ageing are:

Effect of high dielectric stress during over voltages, effect of operating dielectric stress over a period of time, electrical tracking due to surface build up of moisture, oil, carbon dust treeing and corona, insufficient insulation on leads.

The following are the common symptoms and failure mode

Damage to bar armour and insulation surface, White or brown discoloration and powdering due to corona specially between phases, near blocking and underneath wedges, dark or black discoloration and powdering due to arcing and burning along creapage paths and along stress control coatings, higher temperature due to increased dielectric losses, flashover and ground fault.

2.3 Mechanical Ageing Processes

During operation of the machine, the firm contact of the bar with the slot walls is disturbed due to core vibrations, thermal expansion and contraction of the winding and forces imposed on the winding due to sudden short circuits.

The mechanical stresses occur due to the load changes. These stresses may be amplified many times during a short circuit. In very large capacity generators, the conductor overhangs (in spite of being rigidly supported) are subjected to enormous vibrations and embrace each other upon a severe short circuit. Due to the fact that the heat capacity of the surrounding medium (air) near the conductor overhangs is very less, the insulation in the conductor overhangs is subjected to tearing stress due to differential thermal expansion and contraction. Due to the load changes, the temperature of the conductor increases or decreases quite rapidly, giving rise to thermal expansion and contraction. The insulating materials over the conductors cannot sustain these sudden expansions or contractions and cracks on the surface of the insulation may be formed, which may become a site of PD. Performance under mechanical stress is one of the most important aspects in deciding the materials for rotating machine insulation.

The probable causes of insulation ageing due to mechanical stresses are

- End winding vibration due to magnetic forces between phase belts, resonance and mechanical support, inadequate support and axial restraint of end winding, deterioration of radial support in slots, wedges, springs and packing.

The common symptoms and failure mode are

- Loosening of slot wedges, strand separation and cavitations, rubbing and looseness at end winding blocking, higher temperature due to bar bouncing and consequent reduction in heat transfer especially at cross over-leading to flashover and ground fault

2.4 Ageing Due to Environmental Influence

Machines operating in aggressive atmosphere e.g. cement and chemical plants, rubber factories etc. would suffer rapid deterioration of their insulation system, if not designed properly. Further hazard from which majority of stator windings get affected is the surface deposition of chemicals, dust etc and ingress of moisture.

Electrochemical failure will occur if the electrolyte concentration within the insulation is high enough. Poor electrical design or the inclusion of gas pockets in the insulation can lead to erosion of the insulation by discharges and to subsequent failures.

2.5 Causes of Failures of Windings of the Machines during Manufacture Stage

Quality deficiencies of the insulating materials (mica tapes, varnishes, enamels etc.)

- Improper storages, defective method of application (loose taping, causing voids and formation of wrinkles), non-uniform pressing of insulation during baking and curing, non-adherence to established process of regimes with reference to temperature and time, inclusion of foreign particles during application of insulation, development of cracks, sharp corners, mechanical damage caused while inserting the winding into the slots, sharp edges / burrs in the stator slots, mishandling of the machine during manufacture, overheating of insulation during brazing of end joints, loose core causing vibration and damage, magnetic particles inside stator, inadequate corona protection, defective inter-turn insulation, lack of or inadequate quality control and different manufacturing stages

3.0 EVALUATION OF DAMAGE DUE TO DIFFERENT AGEING PROCESSES

Periodic tests are generally conducted to monitor ageing of the insulation, diagnose the problems, or provide some assurance that the stator winding has a minimum level of insulation strength. Test methods like measurement of Insulation Resistance, Polarisation Index, Dissipation Factor, Loss Angle and Capacitance, Partial Discharge measurements for condition monitoring of high voltage machine insulation were proposed among others by Stark. K.H [6], Kelen A [4,41], Kurtz [5], G.Stone [8], A. Wichman [28], Schuler and Liptak [29,30], H. Yoshia and Y Inoue [31], etc. The main features of the electrical methods are summarized below.

3.1 Electrical Techniques

IEEE standards and procedures are widely used by Motor and Generator manufacturers and utilities to commission windings in new machines as well as to evaluate the condition of the winding insulation in operating machines. The tests can be broadly classified as

A. Over Voltage tests
   - 1 Proof tests
   - 1.1 50 Hz
   - 1.2 Direct Voltage
   - 1.3 0.1 Hz
   - 1.4 Half Wave
   - 1.5 Impulse

B. Direct Current tests
   1. Insulation resistance
   2. Polarization Index
   3. Polarization / depolarization versus time
   4. Cameron

C. High Voltage AC bridges
   1. Delta tan delta, capacitance tip-up
   2. Integrated Partial discharge energy (DLA)
   3. R*C
   4. Goffaux
   5. Terase

D. Pulse and HF Measurements
   1. Partial Discharge detectors
   2. Neutral connection signal analysis
   3. R F Slot probe, manual
   4. R F Slot probe automatic
   5. Partial Discharge analyzer
   6. Stator slot coupler (SSC)

3.1.1 Over voltage tests

Over voltage tests are carried out on full stator windings and individual phases. These proof tests simulate two conditions. The permanent stressing of the insulation by power frequency, and the action of switching surges. IEEE standard 56 [32] is an extensive guide for various tests on stator windings and also discusses the maintenance AC hipot test. A hipot test is a “high potential” applied to the winding and is normally higher than what the winding experiences in service. Any gross flaws in the windings is detected during the test and if the winding does not fail as a result of high voltage test, the winding is not likely to fail when put into service.

A large transformer is required to test the winding of a large machine at power frequency. The DC tests were introduced to overcome the difficulty of portability of testing transformer. The objective of many investigators was to determine the ratio between DC/AC test voltage which would produce the same probability of insulation failure, or the same revealing power with regard to weak spots. However, it was realized that failures occurring during AC and DC testing respectively were not always of the same kind; end winding failures were more frequent in DC tests. This is due to the fact that the electrical stress distribution over a winding is governed by resistivity in the case of direct voltage and permittivity in the case of AC voltage.

In order to attain a realistic stress distribution over the winding and the influence of the dielectric parameters, very low frequency [30] tests were introduced and frequency on the stress distribution is analysed. Another approach is the power frequency half wave test.

Alternatively a resonance power frequency voltage generator is used in place of portable voltage test equipment. The advantage is that when an insulation failure occurs the limited available power causes much less destruction to the insulation. The voltage wave has a very low harmonic distortion, which is extremely important for correct partial discharge tests.

Impulse voltage testing of multi-turn windings will produce a realistic simulation of the stresses produced by surge voltages, but damping will confine stresses to a small portion of the winding near the energized terminal.

3.1.1.1 Non-linear analysis

This is carried out by means of application of AC voltage on the stator and the leakage current frequency is monitored [33]. It allows the assessment of insulation ageing and or degradation status and the ionic activities intensity inside the slots casued by the presence of voids between the stator core and the winding. This current spectrum tends to be displaced from the fundamental frequency to higher harmonics along the time indicating the presence of ionic activity.

3.1.2 DC tests

To avoid damage due to overheating and intense partial discharges of the insulation during the high voltage AC tests, international practice is to subject the windings to DC over voltage tests. A variety of direct voltage (DC) testing techniques have been devised to monitor and assess the condition of stator winding insulation systems. These methods range from the simple withstand or proof tests to more refined rampled voltage test in which the DC high voltage is applied as a linearly increasing ramp function and the current response is recorded.

3.1.2.1 Evaluation of deterioration by hipot method

The DC hipot tests are performed by several methods. DC test sets being of lower capacity are portable and power consumption is much less. The ratio between DC and AC tests varies between 1.2 and 2.5. Often a value of 1.6 is chosen usually for the machines in operation. The disadvantage to DC testing is that actual service conditions are not simulated during this test as stress distribution is governed by resistivity and the insulation is unevenly stressed. On the basis of extensive tests Rushall and Simons [34] have also concluded that the high voltage DC testing method has no valid basis for non-destructivity indicating the serviceability of the insulation of HV machines. IEEE standard 95 [35] gives the guidelines for conducting DC tests and 2002 version highlights a new variation of the DC hipot test called DC Ramp test.

(a) Conventional DC hipot

In this method a suitable high voltage is applied quickly to stator winding terminal and held for either 1 or 5 minutes and after this time the voltage is gradually reduced to zero. If the insulation is sound, there will be no high current surge and power circuit breaker will not trip. If the power circuit breaker trips then it is likely a puncture of insulation has occurred.

(b) Step stress hipot

In this method the applied DC voltage is increased in 1 kV steps, with each voltage level being held for 1 minute before it is increased again. The DC current is measured after the end of each step and current plots are obtained with voltage. The trend is generally a line with a gentle upward curve. An abrupt increase in current is an indication of weakened insulation.

(c) DC Ramp hipot

In this method, the DC voltage is smoothly and linearly increased at a constant rate, usually 1 or 2 kV/minute and there are no discrete steps in voltage or current. The current vs voltage plot is automatically graphed and displayed. The advantage of this method is that it is by far the most sensitive way to detect when a current instability is occurring, since the capacitive charging current is not changing with time. However the disadvantage is that it does not duplicate the voltage stresses applied across the insulation when it is in operation [36].

3.1.2.2 Insulation resistance

IR tests are made to determine current leakage through insulation and over its surfaces under specific conditions of voltage and time. DC insulation resistance also provides information on humidity, contamination and certain types of mechanical damage of insulation. This is probably the most widely used test for stator windings of motors and generators. This test is performed as per IEEE-43-2000 standard [35] "guidelines and the minimum acceptable corrected insulation resistance (in MÙ) to be equal to the kilovolt rating of the insulation system plus one", that is $R_{min} = V_{LL} + 1$.

3.1.2.3 Polarisation index

Determination of current to earth and its rate of change with time: A commonly used characteristic is the PI, the ratio of observed currents at two times i.e. the ratio of the observed currents at two times 1 min and 10 min. PI is a recognized criterion for judging the insulation dryness or humidity, contamination, cure and physical integrity of a new winding or after a service interruption. A low value of PI indicates a humid insulation. IEEE std. 43-2000 recommends a polarization index greater than or equal to 2 for class F insulation.

The variation of polarization or depolarization current with time follows a power law in most of the cases. The value of the exponent might provide useful information on the state of the insulation or contaminated with oil, dirt, etc.

An attempt at producing a general judgement of the state of the ageing of insulation in terms of its remnant breakdown voltage (RBDV) has been based on measurements of the current during an over-voltage DC test [9]. The stationary current at each step of DC test is plotted against voltage; instability is predicted from an upward curving slope. A forecast of the RBDV of the insulation is derived from the current voltage characteristic at voltages exceeding the normal test levels.

3.1.2.4 Recovery voltage

Recovery or return voltage measurements (RVM) have been used to evaluate the polarization and discharge characteristics of an insulation system since these processes are strongly influenced by the quality and condition of the dielectric materials. This technique is widely used for determination of moisture and the extent of ageing of oil-paper insulation in transformers and cables. Experience using RVM on rotating machine insulation is very limited and no guidelines or standards exist for this application. Some preliminary work on stator winding using RVM techniques are reported [38, 39] The principle of the measurement is as follows:

1. A DC voltage of 2 kV charges the insulation under test for a predetermined time of t_c sec.
2. The test object is short circuited for pre-selected time of t_d.
3. Open the short circuit and allow the residual polarization to build up recovery voltage across the test object.
4. Measure the maximum recovery voltage and its rise time. Under this condition the test object discharges through its own DC resistance. These parameters are strictly related to the polarization processes and their intensities.
5. Changing t_c and t_d in a time range of 20msec to 10,000 sec. while $t_c/t_d = 2$, constant, a series of values V_r and t_r are obtained.

3.1.2.5 Surge comparison

Surge comparison test is used to determine 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.

3.1.3 HV AC bridge measurements of dielectric loss

Discharge measurements provide a sensitive, non destructive means of detecting minute defects in insulation. The successful application of discharge technique depends on the following; The conditions at which discharges occur, factors which affect the discharge magnitude, recurrence frequency, and the various mechanisms of deterioration and breakdown by discharges.

The Schering bridge and modifications of HV AC bridge circuit represents the next step of development which branches in several, slightly different directions, mostly with the purpose of revealing the extent of PD activity.

3.1.3.1 Dissipation factor tip-up (Delta tan delta)

Dissipation factor, also called tan delta is a measure of dielectric losses in the insulation. It is the property of the insulating material used. IEEE 286-2000 [40] gives the guidelines for measurement of power factor tip-up of electric machinery coil insulation. For a given insulating system the tan delta 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 delta and capacitance of the stator winding.

Dissipation factor is determined at several levels of the test voltage. The first test voltage is usually 0.2 times the rated phase to phase voltage Vph where PD is just below inception level and is taken as the reference value (tan δo). The inception voltage may decrease due to reversal of charges or presence of homopolar charges at the interface or on the system or due to a single large void. Tan δ and capacitance measured at low voltage are a function of the state of the cure of the resin, the presence of moisture or contamination in the windings, loss of contact of the coil outer surface with the core due to erosion of slot discharge preventing coating, non linear effect of slot end stress grading systems, the influence of inter winding capacitances and losses, besides other factors [35]. The higher levels often in steps of 0.2 Vph are interpreted as revealing the gradual ignition of PD in voids and imperfections [41]. These measurements are performed by balancing the bridge with appropriate earthing and guard circuitry. The settings of a balanced bridge give values of the capacitance of the test object as well as the dissipation factor. Information about PD activity is contained not only in Delta tan δ but in capacitance tip-up as well. Different shapes of the voltage wave will at constant amplitude produce different values of delta tan delta for a particular test object.

Capacitance tip-up is another important diagnostic tool. A change in capacitance may occur due to change in the size, shape or distance between the two conductors. As insulation system cures or ages, the dielectric constant may change causing a change in the measured capacitance.

3.1.3.2 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. Partial discharges in stator windings are manifest by positive and negative current pulses of a few nanoseconds in duration. IEEE std. 1434 – 2000 [42], "Guide to the Measurement of Partial Discharges in Rotating

Machinery" describes typical systems for conducting off-line partial (PD) measurements on individual form-wound coils.

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.

3.1.3.3 Integrated partial discharge energy

Another method of deriving more direct information on PD activity is by dielectric loss analyzer (integrating capacitance bridge) developed in UK [43]. This bridge is balanced at a voltage below PD inception. A signal proportional to the test voltage is connected to the X-Plates of an oscilloscope and the signal across the bridge detector to Y-Plates. When the test voltage is increased above PD inception lissajou figure on the oscilloscope screen opens up to a loop typically in the form of a parallelogram. Information is derived from the dimensions and shape of this figure as a function of the test voltage. An overall judgement is expressed in terms of dissipated loss power per microfarad of winding capacitance and per AC cycle. This test is becoming obsolete now.

3.1.3.4 R*C

The product of the insulation resistance of one minute and the capacitance of the winding at 0.2 V_L is another diagnostic tool. It has the dimension of time, the insulation time constant. It decrease with time in service is sometimes interpreted to indicate deterioration.

3.1.3.5 Goffaux

Modification of the traditional AC bridge diagnostics has been proposed by Goffaux [44]. Band-pass bridge detectors tuned to two frequencies above power-frequency are used in addition to the 50 Hz detector. Based on a physical model of polarization and conduction in sound and damaged insulation, the variation of different recorded signals with voltage are interpreted. The usefulness of this method depends on the response of the insulation to PD pulses, rather than the PD pulses themselves.

3.1.3.6 Terase

Another approach has been developed by Terase [45]. The slope of the active current versus AC voltage reveals the well known bend when PDs ignite. By increasing the voltage beyond the value used in ordinary over voltage tests, a second bend is often observed, which is stated to permit the prediction of the RBDV. The newly defined parameter Y, measured in this method equal tan delta plus γ, where γ closely relates to void volume in a sample.

A new apparatus to measure Y automatically is also developed, which shows experimentally several advantage in a practical test Y-V patterns and γ-V patterns by this method are verified to correlate well to insulation condition and residual breakdown voltage of a sample.

3.1.4 Pulse and High Frequency

More recently, advances in digital electronics have made microprocessor based measuring and analysis techniques possible. Much progress has been made in the development of partial discharge instrumentation in terms of bandwidth selection, calibration and pulse discrimination.

Partial discharges generate short duration current pulses propagating from the origin towards both ends of the winding and takes place in

- a series mode like a travelling wave on a transmission line with frequency dependent attenuation and reflections.
- and in a parallel mode mainly by inductive and capacitance coupling between the windings.

Direct observation of PD activity by means of straight or balance circuits, band-pass filters with selected characteristics have been widely used. Development in this field continuing in particular with regard to noise discrimination are signal averaging and differential detection with discrimination by logical circuitry between PD signals and noise signals.

Electrical signals in the neutral connection of a winding are subjected to frequency analysis in the range from tens of KHz to tens of MHz. The signals obtained by means of a coupler in the neutral connection of a winding are reported to produce information on various deleterious conditions.

If any of the methods which have been mentioned so far indicates a dangerous level of PD activity, the geometrical location of its source is important to plan the required maintenance. Looking at the energized winding by means of RF or ultra–acoustical devices is frequently resorted to. This requires access to the winding.

3.1.5 Electromagnetic Probes

A more precise location is achieved by means of the electromagnetic probe which is an inductively coupled detector. Capacitively couple detector probes have also been used. The latter is less safe and less accurate because of difficulty in reproducing the capacitive coupling. The E M probe is an insulating rod carrying a sensor which is isolated axially to scan one slot after another while the stator winding is energized. The sensor is in principle, a small radio receiver and enables the precise localization of PD activity and slot corona. A modification of this method is the permanent installation of miniature RF receivers on the rotors at various axial locations; suitable signal processing enables a continuous scanning for slot PD activity.

PD pulse distributions from the winding of operating generator are analysed and presented using specially developed electric circuitry, Phase resolving pulse distribution analysis (PRPDA). This new technique records amplitude distributions of PD pulses. The PDA test has not been applied to turbine generators since the electrical noise is much greater in turbine generators.

Analysis and interpretation of partial discharges is still a subject of intense research. The PD are 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.

3.1.6 Online Monitoring Techniques

3.1.6.1 Stator slot coupler

Off late a new PD sensor called the stator slot coupler (SSC) is developed by the Canadian Electrical association [45,46] which is able to differentiate between the PD in the winding and all types of electrical interference and permit online test for turbo generators. The new sensor requires no HV connection to the winding, and is easily installed in the stator slot, underneath the wedges.

The SSC is essentially a directional electromagnetic coupler and consists of a ground plane and a sense line with co-axial output cables at each end. The SSC yields an output pulse from each end whenever an electromagnetic wave propagates along the SSC near the sense line. The dual port nature of the SSC permits determination of the direction of PD pulse travel using instrumentation that can indicate which end of the SSC has detected the signal first.

3.1.6.2 Passive Rotor Temperature Sensor [PRTS]

The PRTS is a device to measure the temperature at specific locations on the rotor of a turbine generator [47]. The PRTS uses an optical temperature measurement technique. The surface of the rotor is painted with a special florescent paint that, when illuminated with ultra violet (UV) light (via a fibre optic cable in the stator that focuses the UV light on the rotor), will floresec a temperature decay time. Higher the temperature faster the decay time.

3.1.6.3 Electronic Rotor Temperature Sensors (ERTS)

Electronic Rotor Temperature Sensors is an alternative means of measuring rotor temperature at specific locations [48].

3.1.6.4 Others

Thermal life indicator, insulation sniffer, global motor monitor are some of the other sensors for online monitoring of generators [48].

4.0 LIFE EXTENSION OPTIONS

Some of the techniques for condition assessment and life extension options for generator components are given in Table 1 [49].

5.0 CONCLUSION

This paper reviews the various deterioration mechanisms of stator winding insulation during ageing and presents a birds eye view of the various electrical test methods for evaluation of health and remaining life of insulation. There are several off-line and on-line techniques for condition assessment of stator winding insulation of Generators and motors.

The progressive deterioration of high voltage machine insulation is assessed through non destructive techniques like measurement of Insulation Resistance, Polarization Index, Dissipation Factor, Loss Angle and Capacitance, Partial Discharge (PD) measurements, mainly for trend analysis.

Based on the literature survey it is concluded that though there are several diagnostic test methods, the study of structural and chemical changes, that insulation undergoes during ageing is limited, and not fully explored. It is absolutely essential and for proper estimation of remaining life of insulation.

6.0 ACKNOWLEDGEMENT

The authors thank the management of CPRI for giving permission to publish this paper.

TABLE 1

PLANT COMPONENTS, DAMAGE/FAILURE MECHANISM, CONDITION ASSESSMENT AND LIFE EXTENSION OPTIONS: GENERATOR COMPONENTS

Component Damage/Failure Mode	Condition Assessment/Detection	Life Extension Options / Prevention
1. Core/winding insulation		
(1) Overheated and shorted strands. Change in appearance and colour of inter turn insulation.	Infrared detection end winding contamination.	Manufacturing quality control.
(2) Turn to turn failures.	High frequency tests.	Cut and replace failed coils. Voltage surges, switching surges to be minimized. Manufacturing quality control.
(3) Ground wall insulation failure.	At the time of installation and when in service AC and or DC electrical tests for insulation resistance/ polarization index, diagnostic tests like PD measurement etc followed by visual inspection.	Proper positioning of coils in the slots. Periodic diagnostic testing and maintaining tight packing of coils and packing materials in the slot. Ensure firm contact between ground insulation with slot walls to prevent corona and partial discharges.
(4) Internal corona	PD tests, power factor tip-up test.	Remove failed coil or parallel circuit with failed coil. Manufacturing quality control.
(5) Corona in slot entry and grading paint not adhering.	Extensive visual inspection.	Ensure correct length of semi conductive coating paint from slot and proper overlapping. Care to be taken while handling.
(6) Coil vibration, slot discharge and worm semi-conducting paint.	Slot corona and PD may indicate loose coils, visual inspections during operation and hollow sounding wedges when tapped. Sound variation during operation. Migration of wedges or packing materials.	Prevent coils from becoming loose by installing coils sufficiently tight. To establish complete mechanical stability and electrical contact repack and rewedge.
(7) Slot corona and partial discharge.	Corona probe test.	Injection of semi-conductive material in liquid or semi-liquid form between insulation and slot may be required. Repack and rewedge to establish electrical contact between insulation surface and slot surface.
(8) Semi conducting paint not adhering.	Visual inspection corona probe test. Ohm meter resistance coil to core.	Prevention of coil vibration in service. Recoat with semi conducting paint as completely as possible.
(9) Loose wedges. Material dust deposits.	Wedge mapping tests. Visual inspection for insulation damage.	Periodic inspection Re-tightening of wedges.
(10) Loose wedge packing	Inspection for insulation damage.	Periodic inspection. Use of spring type filler.

Component Damage/Failure Mode	Condition Assessment/Detection	Life Extension Options / Prevention
(11) Loose side packing.	Visual inspection.	Slots with loose side packing should be replaced and rewedged.
(12) Loose coil separator and bottom stick.	Same as wedge packing.	-
(13) Blocking and lashing loose.	Inspection.	Periodic inspection broken or loose lashings to be retied. Blocking should be mechanically locked in a place.
(14) Connection open circuit or high resistance.	Comparison of resistance of parallel circuits.	Insulation quality control. Re-insulation and re-brazing.
(15) Stator lamination.	Visual inspection. Core Loss (ring) test using infra-red scanning to detect hot spots.	Periodic inspection of core for ferrous oxide deposits. Re-torque loose clamping studs. Separate shorted laminations with mica sheets or by stacking to prevent localized heating.

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