CHAPTER 1

INTRODUCTION

1.1 GENERAL

The reliability of the high voltage equipments depend to a large extent on the quality of insulation. The bulk of the insulation has to withstand very arduous working conditions such as thermal stress, electrical stress, mechanical stress and environmental stress. The combination of these stresses causes deterioration of the insulation and hence the life of the equipment.

Experience with power equipment in service all over the world has indicated, invariably, that insulation is the weakest link. With the increase in rating of the power equipment and escalation in cost, any unplanned outage of the equipment in service will have adverse financial implications and social unrest. A number of surveys made in different parts of the world have shown that the cost of outage represents a significant percentage of initial capital cost of the equipment. It is therefore the aim of the user to plan outages and avoid complete shutdown of the plant (IEEE std 56-1997). One way of minimizing the problem is introduction of periodic non-destructive measurements to detect significant changes in the state of the insulation.

High Voltage (HV) machines are widely used in power stations, steel mills, cement mills, sugar mills etc. Thus monitoring the condition of such machines are vital to ensure continuous production/power generation and to avoid breakdown and there by production losses. The purpose of the
diagnosis is to check the condition of the equipment in service in order to
detect defects, anomalies and mal-functioning which may eventually lead to a
failure. In essence, diagnosis is the ultimate and perhaps most decisive action
to achieve the reliability of equipment and installations (Stefan Grubic et al 2008).

In this thesis, it is proposed to conduct various diagnostic tests like
Insulation Resistance, Polarization Index, Leakage Current, Capacitance,
Dissipation Factor and Partial Discharge magnitude on the stator winding of
three phase high voltage motor and generator. These test parameters are
analyzed using Back Propagation Neural (BPN) network, Fuzzy Logic, BPN
network with slope parameter and Proportional, Integral and Derivative (PID)
controller concept and Adaptive Neuro Fuzzy Inference System (ANFIS)
approach. From the above test results, the condition of the stator winding is
predicted.

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.
(Stone and Vicki Warren 2006). 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 (Lloyd et al 1991).

In addition to the above test, some other tests are normally carried out to check the condition of insulation of the stator winding and they are briefly explained in this chapter.

1.2 CONDITION ASSESSMENT PROGRAMME

Condition assessment programme generally consists of the following steps:

- Visual Inspection and Examination.
- Conducting diagnostic tests on the machine.
  i. Collecting operating history of the machine.
  ii. Analysis of the data
  iii. Identification of the deteriorating factor
  iv. Recommendation of appropriate remedial measures to enhance reliability and availability

1.2.1 Visual Inspection and Examination

The visual inspection is generally considered to be a very important step in the diagnosis programme. It requires a 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.

### 1.2.2 Diagnostic Tests

Over the years the following diagnostic tests have proved to be effective in condition monitoring of Turbo/Generators and large AC motors in service (Vicki Warren and Stone 1998; Stone 2005).

i. Insulation Resistance (IR) and Polarization Index (PI) measurement

ii. Leakage current measurement

iii. Dielectric loss angle or Dissipation Factor (tan δ) test

iv. Partial Discharge (PD) test

v. Surge Comparison test

#### 1.2.2.1 Insulation Resistance and Polarization Index Measurement

It is a routine method of checking of the stator insulation. The test provides an indication of presence of cracks, contamination and moisture in the insulation. The Polarization Index (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 (IEEE 43-2000).

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 and PI values, steps shall be taken to thoroughly clean and dry the winding.

1.2.2.2 Leakage Current Measurement

Measurement of leakage current by applying DC voltage in steps is 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, held for a fixed interval of time at each step so that the influence of polarization effects of the insulation is proportional to the voltage applied. The use of Direct Current (DC) voltage instead of Alternating Current (AC) results in different stress distribution in the stator winding when compared with service conditions and this needs to be taken into account when selecting the DC test voltage.

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. The leakage current of the high voltage rotating machine can be measured by both DC voltage and AC voltage with power frequency.

1.2.2.3 Dissipation Factor Test

Dissipation factor, also called Tan Delta (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 Schering bridge or transformer ratio arm bridge is used to measure the \( \tan \delta \) and capacitance of the stator winding (IEC std-60894).

The stator winding needs to be disconnected from the cables on both neutral sides for conducting the \( \tan \delta \) test. When the measurement is conducted on one phase section the other two phase sections are shorted and grounded to the stator frame. The \( \tan \delta \) is measured in steps up to a maximum of rated phase to ground voltage. The \( \tan \delta \) 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 \( \tan \delta \) is only dependent on the kind, temperature, humidity, degree of polymerization, ageing, contamination, etc. of the insulation (Mohsen Farahani et al 2005). As the test voltage increases, \( \tan \delta \) increases due to partial discharges in voids occluded in the insulation.

Therefore, the change in \( \tan \delta \) with voltage is a measure of the gaseous losses in the winding insulation. The slope of the \( \tan \delta \)-voltage curve is proportional to the volume of air or gas voids short circuited by discharges at the test voltage. Thus, \( \tan \delta \) measurements provide a good indication of the average condition of insulation of the stator (IEEE 286-2000).

Machine manufacturers use \( \tan \delta \) test as a quality control test for new stator bars and coils. 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 higher than normal increase in the \( \tan \delta \) when the voltage is increased.

The parameters that can be derived from this test are \( \tan \delta \) at low voltage (usually 0.2 V where V is the rated line voltage), \( \tan \delta \) tip-up (\( \Delta T \)) (average change in \( \tan \delta \) between 0.2 V and rated phase voltage) and
Capacitance tip-up (ΔC) (percentage change in capacitance while raising the voltage from 0.2 V to the phase voltage).

1.2.2.4 Partial Discharge Test

Partial Discharge (PD) test is another important diagnostic test for HV machines as it is capable of revealing incipient faults in the stator winding structure (IEEE 1434-2000).

In the HV electrical rotating machines, three types of discharges can be identified.

i. Internal discharges that occur in voids blocks in the bulk volume of the winding insulation.

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

iii. End winding discharges that occur at the extremity of the conductive 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 with in 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 (pC).
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 the 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 is 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 the recent times, with the advent of computers and data acquisition systems, sophisticated PD detectors and analyzers have been developed (Kurtz et al 1984). 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 PDs are 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 (Stone 2005).

1.2.2.5 Surge Comparison Test

The 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 (IEEE 522-1992). 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 (Gupta et al 1995).

1.3 LITERATURE REVIEW

Allison (2000) described the importance of using the correct conductive and stress grading tapes in high voltage rotating machines. Conductive materials must be chosen with regard to their performance both before and after processing and must be applied according to the machine operating voltage, the processing methods and the operating conditions.

Braun and Brown (1990) described the operational performance of the generator condition monitoring system under field conditions and to perform a comparison of heated and unheated ion chambers.

Campbell and Stone (2000) described that the random wound stator winding in motors would fail, when exposed to the fast-rise time voltage surges. These surges could create partial discharges and these discharges eventually destroy the turn-to-turn and/or phase-to-phase insulation, resulting in premature motor failure. The failure of stator windings in low voltage motors had been observed due to PD created between turns. The root cause of the PD is the high inter turn voltage that could occur when the fast-rise time and high magnitude surges are produced.

Dombi (1990) discussed about the extraction of different demands and determine the rational class of the membership functions. He also showed the connections between the operators of the evaluation and membership functions, which gives the generalization of this concept in a more general form.
Emery (2004) described a tutorial on dissipation factor measurements on high voltage stator bars and coils, the most commonly used measuring techniques and typical equipment setup used to make this measurement, although measured values were a function of the coil insulation system.

Geethanjali and Mary Raja Slochanal (2008) described about optimal design of the over current relay using the ANFIS. The ANFIS simulated results are quite encouraging than the fuzzy models and will be useful as an effective tool for modeling.

Stone et al (2004) described about the machines rated at 1kW or more, much of the information on insulation system design, failure and testing procedure for high voltage rotating machines.

Gupta et al (1987) dealt the failure of many large AC motors in generating stations caused by failure of the turn insulation on the stator winding and eventually lead to a motor ground fault.

Gupta et al (1995) discussed about the condition assessment of stator insulation in motor and generator. It was an important part of the life extension process for the generating station. Various electrical tests including AC and DC hipot tests that can be used to determine whether the stator insulation is in serviceable condition or to be replaced. The measured AC and DC breakdown voltages are compared to with-stand specification, in various standards in order to determine the effectiveness to AC and DC hipot tests in detecting a weakness in the insulation. The AC hipot test is more searching than the DC hipot test.

Haack (1979); Charles Elkan (1993); Zadeh (1965) and Bandler and Kohout (1980) described the Fuzzy sets began as a generalization of
conventional set theory. They stated a crisp set has a unique membership function, whereas a fuzzy set can have an infinite number of membership functions to represent it.

IEEE 43 (2000) described the procedure for measuring the insulation resistance and polarization index of the stator winding in high voltage rotating machines.

IEEE 95 (1977) described the procedure for analyzing the variations in the measured current. So that any possible relationship of the components of these variations to the condition of the insulation can be more effectively studied.

IEEE 286 (2000) guide described the power factor and power factor tip-up of the coil insulation and to specify test procedures for their measurement.

IEEE 522 (1992) guide makes suggestions on testing the dielectric strength to the insulation separating the various turns from each other within multi turn form-wound coils to determine the acceptability of the coils.

IEEE 56 (1997) guide presents information necessary to permit an effective evaluation of the insulation systems of large alternating current rotating electrical machines. Such an evaluation can serve as a guide to the degree of maintenance or replacement which might be deemed necessary, and also offer some indication of the future service reliability of the equipment under consideration.

IEEE 930 (2004) standard deals with statistical methods to analyze times to breakdown and breakdown voltage data obtained from electrical testing of solid insulating materials, for purposes including characterization of
the system, comparison with another insulator system and prediction of the probability of breakdown at given times (or) voltages.

Jang (1993) described the architecture of adaptive network based fuzzy inference systems with type-3 reasoning mechanisms. By employing a hybrid learning procedure, the proposed architecture can refine fuzzy if-then rules obtained from human experts to describe the input-output behaviour of a complex system.

Jinkyu Yang et al (2007) presented that the insulation quality assessment is an important issue for pulse width modulation inverter-fed machines. This can be performed by standard OFF line tests namely capacitance, dissipation factor and insulation resistance tests. The above tests give the solutions that are capable of monitoring the insulation condition and from that to prevent forced outages and safety risks due to motor insulation breakdown.

Jusso (1999) described the different combinations of fuzzy logic and neural networks provide various ingredients for smart adaptive applications. Linguistic Equation (LE) approach originating from fuzzy logic is an efficient technique for highly complex systems. The LE approach is also successfully extended to dynamic simulation and used in intelligent controller design.

Passino and Yurkovich et al (1998); Klir and Boyuan (2000) and Timothy (2000) stated the fuzzy logic is ideal for controlling non-linear system and for modelling complex systems where an inexact model exists or systems where ambiguity.

Lamarre and David (2006) suggested the measurements conducted in the time domain can be presented for modern epoxy mica winding insulation technology. The influence of the temperature is investigated and a correction procedure for insulation resistance for epoxy mica insulation system for stator bars.

Laurence Fausett (2004); Zurada (1997); Freeman and Skapura (2000); Hornik (1993) and Chin et al (1996) described about various neural network techniques which are used to solve problems in many areas. The main aim is to train the network to achieve a balance between the ability to respond correctly to the input patterns that are used for training.

Lloyd et al (1991) reported the development of an expert system to assist rotating machine maintenance personnel in assessing the insulation condition of their machines.

Mohsen Farahani et al (2005) described the defects in the stator insulating system maybe created by combined thermal, mechanical, electrical and environmental stresses during their operation, resulting in gradual deterioration. The results indicate sufficient sensitivity of PD measurements to changes within the insulation caused by thermal and thermo mechanical stresses. Those stresses also cause an increase in the dissipation factor, depend on test voltage. The change in the PD and tan δ, and the trend in the changes can be used as a sensitive parameter for the evaluation of this type to aging in the insulation system.

Muhammad Arshad et al (2004) dealt with the major factors for stator winding insulation degradation and accelerated aging are due to electrical, mechanical, thermal and environmental stresses. In winding insulation systems, the energy discharge mainly occurs on the surface, slot, end winding, inter-turn and between bars. Effective monitoring will reduce
the life cycle cost with improved reliability and better asset management. The partial discharge (PD) dissipation factor (DF), insulation resistance (IR) and polarization index (PI) are the key tests to determine the stator winding insulation assessment.


Rux (1997) described the principles of DC testing with an emphasis on the measured stator insulation current response versus voltage. Although no single diagnostic test can successfully detect all types of stator winding insulation deterioration, routine high voltage DC ramp testing has proven to be an effective means for reducing in-service failures.

Sang Bin Lee et al (2005) presented to measure the differential leakage currents of each phase winding from the terminal box in a noninvasive manner to assess the insulation condition of stator winding. With high performance current sensors to measure the leakage current with higher accuracy, indicators for insulation condition such as the capacitance and dissipation factor are calculated based on the measurement.

Sivanandham et al (2003) and Paulraj (2001) described about the Stability of Back propagation neural network system using various activation functions. Also improvements in BPN network using slope parameter has been analyzed which gives the basic idea to introduce the PID function with the BPN network.
Sood et al (1994) described the operational behavior of the individual Neural Network controllers and by compares the behaviors of the traditional Proportional-Integral controller and Neural Network controller.

Stefan et al (2008) presented testing and monitoring techniques that diagnose the condition of the turn-to-turn insulation of low voltage machines. The offline surge test is not only able to identify a fault but also capture a weakness in the turn insulation prior to a fault.

Stone (1998) described about PD measurement on new motor and generator winding. The machine manufactures accept the power factor tip-up test as PD acceptance test, which is an indirect PD test. The tip up test is sensitive to PD sources when testing individual coils. In rotating machines the PD is often just a symptom of insulation deterioration by thermal or mechanical means. PD is not necessary the main ageing mechanism and its importance depend on the ageing process with which it is associated.

Stone (2005) dealt the power factor tip-up test and PD test for a new or rewind stator as a factory Quality Acceptance (QA) test. Most of the machine manufactures and rewind shops currently use the power factor tip up test as QA test. The tip-up test is an indirect PD test that is very effective in identifying problems in the stator winding.

Stone and Maughan (2008) described the ground wall insulation of the stator winding may erode due to the normal loose coil, slot discharges and vibration sparking between the surface of the stator bar and the core. This spark erosion can happen anywhere in the winding. This discharge can be detected through off-line (or) on-line mechanism. If the presence of vibration sparking in a stator winding is significant, repair may be difficult.
Tanaka (1995) discussed stability analysis of Fuzzy Neural linear control systems. The stability conditions for ensuring stability of the systems in the sense of Lyapunov. The stability criteria are reduced to the problem of finding a common Lyapunov function for a set of Lyapunov in equalities.

Tanaka (1996) discussed stability of Neural Networks (NN) based control systems using Lyapunov approach. The dynamics of NN systems can be represented by a class of nonlinear systems treated as Linear Differential Inclusions (LDI). Stability conditions for the class of non linear systems are derived and applied to the stability analysis of single NN systems and feedback NN control systems.

Vicki Warren and Stone (1998) prescribed to determine the condition of stator winding insulation systems and recent improvements in test instrumentation; it is useful to reexamine the various tests. No single test is sensitive to all insulation problems. Many test methods are available to determine the condition of the stator winding insulation.

Wolmarans and Geldenhuys (1991) described regular diagnostic measurements on the stator insulation of high voltage rotating machines. Statistical analysis of typical insulation parameter, eg. Tan delta, distribution provides reference values against which future measurement results can be evaluated. From the nature of faults which could be diagnosed through measurement, it would appear that faults are immediately evident to the experienced test engineer.

Zhu et al (2005) presented the OFF-line and ON-line tests on a hydro generator. OFF-line testing is a well known method to assess the stator winding insulation. The voltage is applied to the entire stator winding. From that PD sites can be accurately located. The off-line testing is a good
complement to on-line testing to verify insulation problems and assess insulation conditions.

1.4 OBJECTIVE OF THE THESIS

The performance of the insulation of the new or rewound stator winding of high voltage rotating machine can be determined by many tests like Insulation Resistance, Leakage current, Capacitance, Dissipation Factor, Partial Discharge test, Surge comparison test and High Potential test. The test parameters show whether the insulation is in good condition or not. In this work, an attempt is made to use the test parameters, to predict the status of the insulation using BPN, Fuzzy Logic, BPN with PID concept and ANFIS.

The main objectives of this research are, to obtain the status of the insulation through

i. Back Propagation Neural Network algorithm

ii. Fuzzy Logic approach

iii. Back Propagation Neural Network with PID controller concept


1.5 OUTLINE OF THE THESIS

This thesis is composed of seven chapters. The overall organization of rest of the chapters is as follows:

**Chapter 2** describes about to conduct various diagnostic tests like Insulation Resistance, Polarization Index, Leakage Current, Capacitance, Dissipation Factor, Partial Discharge magnitude and Surge Comparison test on the stator winding of high voltage rotating machine.
Chapter 3 deals the analysis of the performance of stator winding insulation using Back Propagation Neural Network algorithm.

Chapter 4 describes the analysis of the performance of stator winding insulation using Fuzzy Logic system.

Chapter 5 deals the analysis of the performance of stator winding insulation using Back Propagation Neural Network with slope parameter and PID controller concept.

Chapter 6 deals the analysis the performance of stator winding insulation using Adaptive Neuro Fuzzy Inference System.

Chapter 7 discusses the main points of the work completed with the results to justify the direction taken in the research. Conclusion on the main body of the work, including the applicability, use and effectiveness of the intelligent techniques for analyzing the insulation status of the high voltage rotating machine which are outlined in this chapter.