ACKNOWLEDGEMENT

I have great pleasure to express my heartfelt thanks to my guides Dr. J. Sundara Rajan, Joint Director, Central Power Research Institute, Bangalore and Dr. B. Ramachandra, Professor and Head of the Department, Electrical & Electronics Engineering, PES College of Engineering, Mandya for their inspiring guidance, encouragement and constant monitoring of the progress throughout the course of this work.

My sincere thanks to the authorities of the Central Power Research Institute, Bangalore for their kind permission to register for this course and also for providing all the facilities to undertake this work. In particular, I would like to thank Shri N. Murugesan, Director General, CPRI for his encouragement and constant drive for acquiring higher qualification through continuing education programme of CPRI.

My sincere thanks to the authorities of PES Research Centre, PES college of Engineering Mandya for their kind permission to register for this course and also for providing all the facilities to undertake this work.

I wish to acknowledge with thanks M/s Bharat heavy Electricals Limited, Haridwar for their all support in manufacturing the Generator sample bars used in this study and also permitting to use of their research facilities at Haridwar.

I also wish to acknowledge with thanks M/s Lakshmanan Isola, Bangalore for providing the laminate samples for use in this study.

I acknowledge with thanks for the encouragement I have received from Dr. R.S. Shivakumara Aradya, Additional Director, Central Power research Institute. I also wish to thank the officers and my colleagues in Diagnostic Cables and Capacitors Division, Polymer Laboratory and Materials Technology division for their help and encouragement during the course of this study.

Thanks are also due to Dr. Channakeshava, Ex Director General, CPRI for his valuable guidance in preparing this manuscript.

I am extremely thankful to my father Shri. B. Krishna Murthy for his constant encouragement and special thanks to my wife Smt. B. Madhumati, Daughters B. Ashwini and B. Rachita for their sacrifice in bearing the agony of periods of my absence from home due to continuous spells of occupation in this research work.

Finally, I wish to acknowledge the benefits I have derived directly or indirectly from various technical publications, journal and text books.

25th April 2014

B. Nageshwar Rao
Joint Director
Central Power Research Institute, Bangalore
SYNOPSIS

Electric Power System comprise of a large number of power equipments like high voltage generators, motors, transformers, cables which are quite expensive and form a significant portion of plant assets. More importantly, they are vital components for reliable delivery of electric power. However, the reliability of these equipment depends to a large extent on the healthy condition of their insulation. Failure of the insulation, directly or indirectly, will result in failure of power equipment, which in turn results in forced outages, reduced reliability and increased maintenance and repair costs. Insulation systems for power equipment are a complex combination of materials and have undergone changes in the last few years. Insulating materials do comply with the required performance at the beginning of their life, though during their course of operation ageing and deterioration occur due to the effects of various stresses. The insulation of these equipment ages under thermal, electrical, mechanical (vibration) and thermo-mechanical stresses, environmental stresses during service and one of them may be predominant depending on the type of the equipment. The ageing processes are complicated and take place under stresses simultaneously or sequentially and may result in deterioration of physical / chemical properties. Therefore dielectric diagnosis plays a vital role in assessing the insulation condition of the power equipment and also in trend analysis regarding the extent of degradation ensuring reliability of power equipment.

Dielectric diagnosis is the application of suitable procedures and measurements to evaluate insulation degradation and deterioration caused by service conditions. The deterioration criteria are either tailored to the material or to the equipment and may be classified as direct or indirect. The direct criteria are connected with the properties like electrical strength, flexural strength etc. while indirect criteria have a relationship with properties required in service like loss angle, insulation resistance, partial discharge, moisture content, non-ohmic behavior etc. The other criteria are specific to one kind of material or one type of equipment. During ageing the insulation undergoes structural changes both at molecular level and macroscopic level and can be studied by thermo analytical & spectroscopic techniques. However, its correlation with parameters obtained by diagnostic tests, is not fully explored which is an absolute necessity to achieve reliability of the system. CIGRE Working group 33/15.08 [1] has emphasized that there is need to apply the physical / chemical tools like structural, morphological and spectroscopic procedures which have not been in extended use for dielectric diagnosis.
In the present research investigation a study is made on the dielectric diagnosis of stator windings of high voltage rotating machines based on structural changes due to ageing. Stator windings of high voltage machines like generators and motors are considered.

A critical survey of the existing literature revealed that though there are several diagnostic test methods, there is no conclusive evidence to show that the available tools provide reasonable estimate of the remaining life of the insulation. The progressive deterioration of high voltage machine insulation is assessed through nondestructive techniques like measurement of Insulation Resistance, Polarization Index, Dissipation factor, Loss angle and Capacitance, Partial Discharge (PD) measurements, mainly for trend analysis. However, from these quantities determination of remaining life is the most difficult part of analysis because of lack of well defined deterioration models, lack of adequate data, multiplicity of failure mechanisms which are not well understood in quantitative form and their dependence on environmental and operating factors. The existing methods are inadequate for reasonable evaluation and hence there is a need for considering other methods of analysis of deterioration mechanism of stator winding insulation. Due to various degradation processes, the insulating material undergoes structural changes which can be studied by Spectroscopic and analytical techniques and correlated to parameters obtained by diagnostic evaluation for reasonable and comprehensive understanding of state of electrical insulation of stator winding of high voltage rotating machine. The application of Dielectric spectroscopy, thermo analytical techniques and Recovery voltage measurement for assessment of stator winding insulation has been very rarely used. The need for a comprehensive study with the application of all the techniques for stator winding degradation is always felt and is even recommended by CIGRE Working group 33/15.08 [1]. Physical / chemical tools like structural, morphological and spectroscopic procedures have not been in extended use for dielectric diagnosis and as such this approach is very much necessary to increase the reliability of measurements for better condition assessment of the stator winding insulation.

The principal goal of this research investigation is to make a detailed study of the subject by reviewing the ageing mechanisms of stator winding insulation leading to failure, and then understand the symptoms and causes for insulation deterioration. The investigation also proposes to review the various diagnostic evaluation techniques currently employed worldwide to assess the ageing of stator winding insulation and bring out their limitations and possibly suggest thermo analytical and spectroscopic methods to supplement the dielectric parameters.
In the present research programme, the stator winding insulation prepared under resin poor and resin rich processes were studied. Investigations were undertaken to study the deterioration mechanisms of stator winding insulation under accelerated electrical and thermal ageing. Two types of Class F insulation (155° C class) system viz. epoxy – mica: resin rich and resin poor systems were studied. Sample generator bars and laminates made of resin poor epoxy mica and motor coils and laminates made from resin rich epoxy mica insulation system were evaluated in the present investigation. The dielectric diagnostic techniques like IR/PI, Tan δ and Capacitance measurements both in time domain and frequency domain and PD measurements were suitably adopted for insulation condition assessment. Laboratory studies were undertaken to understand the dielectric response of thermally degraded stator winding insulation at lower frequencies. The dielectric diagnostic methods of capacitance and tan δ measurements at different frequencies (dielectric spectroscopy, a frequency domain method) and Recovery voltage (time domain) method have been adopted to study the dielectric response of epoxy mica insulation. Low voltage measurements at 140 volts peak were made in the frequency range of 1 mHz to 1 kHz using Dielectric spectroscopy. The Recovery voltage measurement technique was adopted to investigate the slow polarization process in the dielectric and to assess the insulation ageing based on the analysis of polarization spectrum.

In addition, spectroscopic techniques like Fourier Infrared Transform Spectrometry, x-ray energy spectrum analysis for the study of structural / chemical changes are used. To supplement the results, thermo analytical techniques like Differential Scanning Calorimetry, Thermo Gravimetric Analysis, Thermo Mechanical Analysis were used for the understanding of chemical kinetics.

Studies were also conducted on several motors and generators in service located in different industries, hydro, thermal and nuclear power stations. Non-destructive techniques like measurement of Insulation Resistance, Polarization Index, Dissipation factor, Loss angle and Capacitance, Partial Discharge (PD) measurements were used to assess the insulation condition.

Structure of thesis
The thesis is presented under nine chapters. An introduction to the topic of Research is presented in chapter 1. A bird’s eye view of the various electrical test methods for evaluation are summarized. Various spectroscopic and thermal analysis techniques that can be used for the study of structural and changes that the insulation undergoes during ageing are also discussed in Chapter 1. For good understanding of different dielectric
response, details of evaluation methods are discussed in Chapter 2. The literature survey, the aims, objectives and the approach followed in the research investigation are presented in Chapter 3. The details of experimental setup, procedures are presented and discussed in chapter 4.

The results obtained on ageing studies under thermal, electrical and combined stresses of epoxy-mica stator winding insulation using conventional diagnostic techniques are presented and discussed in chapter 5. The results obtained using spectroscopic and thermo analytical techniques are presented and discussed in chapter 6. The Studies with Dielectric spectroscopy and Recovery voltage measurement technique to investigate the slow polarisation process in the dielectric and to assess the insulation ageing based on the analysis of polarization spectrum are presented and discussed in chapter 7.

Finally, based on Insulation theory and laboratory results using electrical techniques, studies were also carried out on in-service machines like generators and motors at various power stations. The effect of presence of moisture in stator winding, effect ageing of insulation, refurbishment etc., are presented and discussed to illustrate the usefulness of measurements on the stator winding of rotating machines chapter 8. In chapter 9 the conclusions drawn from this investigation are summarized & key indicators of ageing of stator winding insulation are recommended as guidelines for failure analysis and condition assessment of epoxy mica stator windings.