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Guide for the Monitoring, Diagnosis and Prognosis of Large Motors

Working Group A1.26

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GUIDE FOR THE MONITORING, DIAGNOSIS AND PROGNOSIS OF LARGE MOTORS

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GUIDE FOR THE MONITORING, DIAGNOSIS AND PROGNOSIS OF LARGE MOTORS

1. Introduction

1.1 Purpose

This guide is intended for the following purposes:-

- To summarise all monitoring systems and on-site diagnostic techniques presently used to assess the condition of in-service electrical motors, both on-line as well as off-line. Type tests and factory routine tests are not included.
- To provide useful guidance in techniques used for effective fault diagnosis so that proper repair prognosis can be predicted and formulated.
- To encourage the establishment of routine and uniform data collection so that valuable facts are kept for future reference.
- It includes a survey summary of international experiences on the use of different techniques. This will assist users to identify the most popular techniques for monitoring, diagnosing and prognoses of faults.

1.2 Scope of the guide

The focus of this guide is on large motors which ratings exceed 1,000V and 800 kW and have been more or less service-aged.

1.3 Contents

The major contents are in these three sections:-

Section 1: Guideline for the Condition Monitoring of Large Motors
Section 2: Guideline for diagnosing problems in Large Motors
Section 3: Guideline for fault prognosis of Large Motors

2. Section 1: Guideline for the Condition Monitoring of Large Motors

2.1 Introduction

Various condition monitoring techniques exist to allow effective monitoring of large electrical motors. Some are being used since the inception of the electrical machine and others are only recently being made possible by the development of signal processing equipment. Each technique has its own benefits as well as downfalls when it comes to the identification of certain problems. Great focus is placed these days on reliability centred maintenance which has as its focus on the reduction of maintenance cost and at the same time the improvement of reliability. These techniques can only be helpful if proper and effective condition monitoring is done to ensure correct preventative maintenance practices from being successful. Ideally, all maintenance, repairs and replacements are done based on the condition motors. Induction machine failure surveys [25] indicate that mechanical failures represent a large portion of large motor failures. From the Electra published report it is also clear that electrical originated failures contribute significantly to the unreliability of large motors.

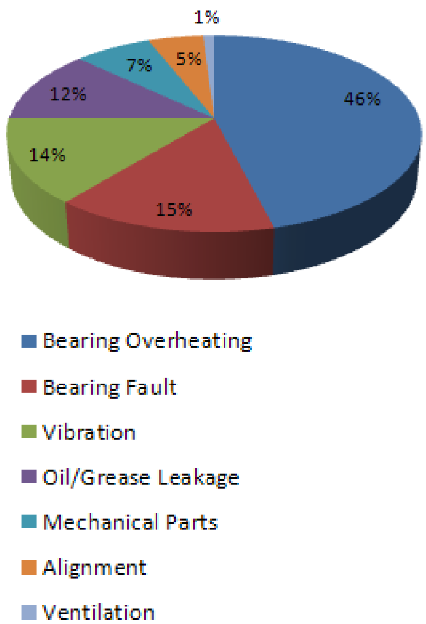

Fig 1: Mechanical motor failures [25]

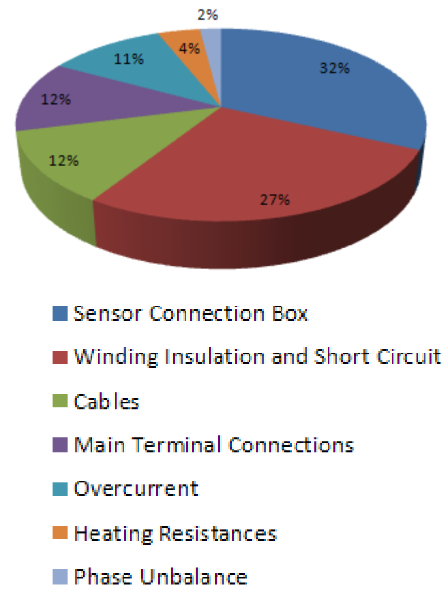

Fig 2: Electrical motor failures [25]

From Fig 1 it is clear that bearing related problems play a significant role in motor failures. Bearing vibration condition monitoring equipment is very advanced and used by the majority of users of large motors. Although motor winding failures contribute significantly to electrical related failures (Fig 2), some condition monitoring of the electrical integrity of motor windings is available but not used very often. Performing fault diagnostics from these available winding condition monitoring techniques is also very complex and can mostly only be done by experts (Partial discharge, Polarisation Depolarisation Current, current signature analysis and stator winding flux analysis).

A questionnaire was distributed to users of large motors across the world. More than 800 motors by 10 users from 8 different countries over 5 continents were covered by the questionnaire. Although it is not representative of all the countries, sufficient data was gathered to perform an effective conclusion with regards to techniques used in different countries as well condition monitoring philosophies and practices in use by the different users.

This guideline will assist users of motors with basic and intermediate knowledge of motor condition monitoring to decide on which practices and principles to use when deciding on techniques to be used for motor condition monitoring as well as for decision making on fault diagnosis and repair prognosis. For the experts in condition monitoring a large number of papers and documents exists which are referenced in this guideline. The guideline is written in an easy to read format to allow all users of motors and condition monitoring equipment to learn from it. It should be used as a basic guideline from which users should further expand their knowledge by reading the referenced papers and reports.

2.2 Effective condition monitoring system for motors

In the ideal world effective condition monitoring will prevent all failures. That is the aim of condition based maintenance. Unfortunately in reality we have a significant shortcoming in effective monitoring techniques. Most of the more known techniques are only available off-line. Newer methods that could pick up developing problems on-line are still unknown to the majority of users and the effectiveness and repeatability of these techniques not yet proven.

If on-line condition monitoring can be developed and proven to be very reliable and the fault diagnoses done effectively, a monitored machine can theoretically run for its full life cycle and no unplanned downtime will be experienced and no unnecessary maintenance will be performed. As condition monitoring technology stands presently, huge successes are achieved by using a combination of various methods to identify developing problems. Experts are still used to perform the analysis, therefor expertise is essential to ensure effective diagnosis of problems. If these processes can be streamlined and optimised, and even automated, huge margin for cost savings on maintenance budgets are possible. EPRI has developed an extensive and detailed on-line monitoring cost benefit guide [4] and technical report on on-line monitoring systems [16] that can be very useful for users motivating the implementation of on-line monitoring systems.

Table 1 contains a list of most monitoring systems and on-site diagnostic techniques for the assessment of “General Health” and “Dielectric Health” and are listed in the first column. The second column gives the section number where the details of each monitoring item can be found within this document. The check box in the other columns provides the type of condition monitoring systems as follows:-

- Continuous on-load monitoring systems
- Periodic on-load condition monitoring systems
- Periodic off-line tests

Table 1:
Condition monitoring systems for large motors

Condition monitoring systems	Details in Appendix	Continuous on load	Periodic on-load	Periodic off-line
General Health				
- External visual inspection	A1	X	X	X
- Internal visual inspection	A2			X
- Stator volt/current monitoring & analysis	A3	X	X	
- Temperature monitoring of bearing, winding, core and cooling water/air	A4	X		
- Shaft volt/current measurement & analysis	A5	X	X	
- Monitoring of cooling water flow	A6	X	X	
- Vibration monitoring of bearing	A7	X	X	X
- Vibration monitoring of shaft	A8	X	X	
- Measurement of leakage flux	A9		X	
- Infrared thermography	A10	X	X	
- Ultrasonic acoustic measurement	A11	X	X	
- Conductor resistance measurement	A12			X
- Dye penetrant test	A13			X
- Lube oil analysis	A14	X		
- Winding ground detection test	A15			X
- Other health detection	A16			X
- Motor intelligent health diagnostic test	A17			X
Dielectric Health				
Local problem in dielectric:				
- Partial discharge measurement	B1	X	X	X
- Corona probe test	B2			X
Global health of dielectric:				
- Insulation resistance, Polarisation index (P.I.) and time constant, RC	B3			X
- Polarisation Depolarisation Current (PDC) with its evaluation of tan delta & capacitance	B4			X
- Capacitance & Dielectric Dissipation Factor (DDF) in term of tan delta or power factor including - power factor tip-up	B5			X
- Hi-pot test (DC & AC)	B6			X
- Turn-to-turn insulation test (surge test)	B7			X
- Stator core low energy test	B8			X
- Stator core high energy test	B9			X
- Stator Core Through-Bolt Insulation Resistance Test	B10			X
- Stator Core Flux Shield Insulation Resistance Test	B11			X
- Turn insulation test for synchronous motor rotor	B12			X
- Bearing Insulation Test	B13			X

2.3 Continuous on load monitoring of motor condition

Large motors used for critical processes require the continuous monitoring of its health while in operation. Should these motors fail without prior notice, it could lead to production losses that far exceed the cost of the motor or the cost of the most expensive on-line monitoring equipment presently available on the market. The use of permanently fitted on-load condition monitoring is still very limited in use across the world but newer plant seems to focus on gathering more knowledge on a continuous basis form motors while in service. For continuous on-load condition monitoring to be possible, field instrumentation needs to be permanently fitted to the monitored equipment, which requires a capital expense on each motor. Factors that affect the installation of field equipment and monitoring of it includes the cost of the instrumentation for each motor, the cost of modifications to the motor to accommodate the instrumentation, the cost and complexity of routing instrumentation cables over long distances as well as the cost of the measured information processing equipment.

A number of techniques exist that can be used continuously on-line to determine the health of a motor while in service. These techniques can be very effective in determining the motor health if used correctly and if the analysis of the measured information is done correctly. Techniques presently available for continuous on-load condition monitoring of large motors are those having a tick in Column 3 of Table I.

2.4 Periodic on-load condition monitoring of motor condition

Due to the cost of installing and maintaining on-load measuring equipment and analysing on-line measured data, users still rely heavily on periodic measurement of motor operational data while on-load. The cost of equipment required for the continuous monitoring of a large number of motors can far exceed the cost of technicians and engineers to measure, trend and analyse the operational data obtained periodically on a large number of motors. The frequency of condition monitoring using portable equipment is normally done once per month but can be different due to the criticality of certain motors, known defects, quantity of motors to be monitored on the plant, cost of monitoring, etc. Techniques used for periodic monitoring is very similar as for on-load continuous monitoring, the difference being the fact that field instrumentation are not normally permanently installed and the measurement and processing equipment is portable and need to be handled by a skilled operator. Data measured also needs to be manually downloaded onto a data base where software can do certain basic analysis and diagnosis. Although software for basic fault diagnosis is available on the market, most users still perform analysis using experts in the field of motor fault diagnostics. Although many users still perform periodic monitoring of motor condition, an increase in the use of continuous monitoring equipment is evident in North America, Europe and Asia. This is mostly driven by the scarcity of skilled labour to manage large quantities of motors in large production plants.

The risk with periodic monitoring of motor health is that motor problems can occur between periods of data capturing. In some cases these undetected problems can result in catastrophic failure of the motor. The occurrence of such undetected problems is fortunately low and when an economic justification for on-line condition monitoring equipment is done, the low probability of failures of undetected faults leading to catastrophic failures does not justify the more costly expenditure. Techniques presently available for Periodic on-load condition monitoring of motors are those having a tick in Column 4 of Table I.

2.5 Periodic off-line tests for assessing motor condition

When motors are scheduled for testing and inspections, numerous off-line tests exists to assist the user in detecting and diagnosing problems on motors. Techniques presently available for periodic off-line condition monitoring of motors are those having a tick in the last column of Table I. For the assessment of dielectric health of in-service motors, some believe that excessive high test voltages that exceed the rated line-to-ground voltage of the motors should be avoided in order to prevent further deterioration in the insulation system. Modern motors usually have two phases in a slot. The insulation between two phases in the same slot is normally the weakest area for motor insulation. Should dielectric testing be carried out, both phase-to-phase insulation and ground insulation (if the star-point can be isolated) should be tested.

EPRI’s technical report on Evaluation techniques for Motor Testing [14] can be very useful for users planning maintenance interventions. This report contains logic diagrams that guide users through the process of doing fault finding on motors to detect specific problems and failure modes.

2.6 Effectiveness and general acceptance of monitoring and assessment techniques

Various monitoring techniques exist but most of it only supplies very basic information to the user, and as standalone techniques not enough to do a full assessment of the condition of the motor. IR and PI tests are the most common tests performed but will only supply the user with basic insulation condition information, not enough to do a full life assessment on a motor. To get a better understanding of the present condition of a motor, almost all of the mentioned parameter measurements and tests need to be performed. It also needs to be effectively analysed. Supply current and voltage measurement in the time domain with Fourier transform analysis of the measured spectrum can supply more information with regards to the motor condition, but need more expensive and advanced equipment and specialist expertise to evaluate and analyse. Performing Partial Discharge (PD) and Polarisation Depolarisation Current (PDC) measurements will supply advanced information about insulation condition, but as with voltage and current measurements, it needs advanced equipment and specialist interpretation. Not one system can be used alone to perform a complete motor remaining life assessment. A combination of tests and monitoring is required to perform effective and complete assessment of motors. Sufficient monitoring and testing techniques exist to perform such a complete assessment although not all of the techniques are always used in combination.

Numerous papers and experience indicate the more complicated monitoring methods to be very effective and reliable, but due to cost and scarcity of experience, as well as users not understanding and feeling comfortable with these methods, they are not utilised optimally. Only by proper education of all available testing methods and techniques and users of large motors accepting the value of these techniques, will complete and successful assessments of motors be possible. To perform effective predictive maintenance, accurate and correct information of all aspects of an electrical motor is required. Only by integrating all the techniques, will effective condition monitoring be possible. From surveys performed, only certain known techniques are used by most users of large motors. These known techniques do not give a global and effective condition assessment of insulation life and therefore insufficient in determining a motors remaining life. Not only testing and condition monitoring is necessary for remaining life assessments of motors but also history of maintenance and repairs as well as knowledge of known defects on similar fleet is required.

2.7 Section conclusion

Various motor condition monitoring techniques exist in power generation and the manufacturing industry which is used in different combinations to monitor the operational condition of motors. These techniques can give effective feedback to operators of the operational behaviour of an electrical motor but is sometimes costly to implement as a combination for ensuring complete Continuous on-load monitoring of all motors. Users will mostly only fit continuous on-load monitoring to the most process critical and/or most expensive motors. Less critical motors often have only periodic on load monitoring in a limited quantity as the periodic on load monitoring of motors are very labour intensive. It requires skilled maintenance personnel to measure data from each motor manually. Less critical motors, which make up the majority of the motor base in the world, will only be exposed to periodic on load/off load testing.

Only by having all data populated in a central database where all accurately measured data is captured and analysed by well trained, well experienced and skilled staff, can effective diagnostics of motor problems be performed. Presently only some of the most common monitoring and testing techniques are used in industry, thus still leaves significant room for implementation and expansion in future. By educating users of large motors and proving to them the effectiveness of these techniques, will more exotic techniques find its way into power stations and the manufacturing industry.

EPRI created a Technical report [9] discussing the modelling of integrated systems to perform a complete condition assessment of Nuclear Plant. For integrated modelling systems to work effectively, automated and intelligent systems are required to capture reliable plant data.

The next section focuses on techniques that presently exist which can make problem diagnostics more effective and motor ‘mean time to failure’ (MTTF) more predictive.

3. Section 2: Guideline for diagnosing problems in Large Motors

3.1 Introduction

We have seen in table I of the previous section that numerous condition monitoring techniques exist in power stations and the manufacturing industry to gather data from motors while in service as well as when off-line. The data accumulated with these processes can be significant and therefore impossible to trend and analyse, especially in a factory which can have hundreds and even thousands of critical motors in service. Yet, the only effective way to diagnose problems on motors is to take all measured data into consideration, to consider the failure history of the specific machine, to evaluate its operational data and abnormalities, to know design weaknesses of similar motors and to analyse present operational data. To take all of this information into account when problems are diagnosed is virtually impossible, especially if a motor has been in service for a significant period of time and was exposed to several operational abnormalities.

Two different methods of diagnosing problems are available [1]: Numerical methods as well as knowledge based methods. These methods are discussed in detail in ISO13379 [1]. In short, numerical methods are automatic and do not need expert knowledge of fault initiation and propagation. For a numerical system to be effective, vast fault data as well as operational data must be available. Knowledge based methods rely on historical case studies, behavioural models and fault models.

To make any automated model work effectively, all data monitored and history recorded need to be fed into a central database from where the relevant data can be used to perform effective motor diagnostics. If theoretical models are used to perform motor fault diagnostics in an automated system, these models first need to be proved for accuracy and relevance with regards to practical operational data and real case studies. Empirical [9] models are developed with complex algorithms to analyse motor operational data in an attempt to give a clear indication of motor health. Only accurate modelling of a component can deliver accurate information but accurate algorithms are complicated and require significant computing time to calculate. These models also take very long to create and difficult to prove, which make them very expensive. Most empirical models used in power stations and industry are therefore not fully representative of the component but a close approximation, meaning that errors can be made with automated condition assessments and fault diagnostics.

The biggest headache for users presently is to gather all the relevant information. This can be due to the fact that failure, repair and test history has not always been well kept for specific machines, motors have moved around the plant and are not in the position as originally installed and nameplates might have gone missing leaving the motor without a serial number. Without valid information, diagnosing problems effectively is impossible.

3.2 Methods employed to do problem diagnosis

The following basic methods can be used to perform fault diagnosis:

a) Experience with similar machines, or by statistical analysis:
   Where similar plant is operational with the same type and design motor, behaviour of these motors can be compared. By performing statistical analysis of the behaviour of these motors, experience can be gained as well as statistical models can be created to assist with diagnosing faults on motors.

b) Studies of deviations from required minimum or maximum values:
   By trending and analysing operational data and by creating virtual boundaries within which the monitored parameters normally operate, early detection of operational deviations is possible. This technique might require the analysis of vast amounts of data over extended periods to ensure that correct and effective operational boundaries are set. If these minimum and maximum boundaries are not determined correctly and set too insensitive, false alarms might result in operating staff loosing trust in such a pre-warning philosophy. It can also result in warning signals be given too late if the setting of such limits are not sensitive enough. By implementing continuous monitoring of all available or at least the most effective condition monitoring techniques and studying the measured data closely, the effectiveness of this technique can be vastly improved.

c) Discussions between the manufacturer and customer:
   By having direct and trusted communication links with motor manufacturer's, fleet wide experience can be gained. This can assist operators and users in identifying problems that is prevalent on a specific type and design of motor. Certain additional condition monitoring techniques as well as off-line testing can be implemented to monitor the condition of motors at risk.

Incorporating the data gathered by the above mentioned three techniques into a single environment, expert diagnosis can be performed more effectively and accurately.

ISO13380 gives a clear guideline on what and how parameters should be monitored to ensure effective diagnoses of machine faults. In essence it is critical to have informative measurements that can be trusted and that is repeatable. Diagnosis of developing faults in its infant stages is virtually impossible, especially if the frequency of monitoring is not optimal, the accuracy of the measuring instrument is not good, the measurement sample rate for high speed varying parameters is too low and if the measured parameters are not even relevant to the developing problem.

3.3 Effectiveness and general acceptance of modern diagnostic approaches

The majority of existing large motor fault diagnostics is still done by experts using their experience on similar incidents from the past. Accurate modelling that does not require any expert input is not yet available and if available, not yet trusted enough to be used on its own. There is still much to be done to create the general acceptance of such complete stand-alone total intelligent expert systems and using it comfortably without any doubt.

3.4 Section conclusion

We have relied for decades on expert opinion for motor fault diagnostics, with variable success, the success of the diagnosis purely relying on the past experience of the expert. As power stations and industry become more focussed on cost and productivity, the margin for error becomes smaller. This is also applicable to large motors which form the base of all industrial processes in the world. Reliability of processes becomes more important as economies become more competitive. Therefore diagnostic approaches also need to be adapted to ensure more reliable and repeatedly accurate fault diagnostics. Creating systems that can perform such diagnostic approaches effectively needs to be created using expert knowledge combined with theoretical models and must be proven in practice. With the decline in expert knowledge and a growth in economies requiring larger power stations and expansion in the manufacturing industry, the only way that effective fault diagnosis can be ensured for future generations is to create expert systems that will automatically perform these diagnostic functions.

4. Section 3: Guideline for fault prognosis of Large Motors

4.1 Introduction

Prognosis is the estimation of time to failure and risk for one or more failure modes to develop. Failure modes can be existing known failure modes but might also be new future failure modes. Fault prognosis is an art on its own and requires in-depth knowledge of fault initiation and fault propagation. In most cases only vast component experience of similar failure modes can assist in successful prognosis but mostly expert intuition is effective. Experience from past exposure to various repair techniques, knowledge of improved designs and materials and a full understanding of the electrical and mechanical stresses in a large machine is required to perform successful fault prognosis. Without the required experience as well as adequate and accurate information, prognosis of failures can be very inaccurate. Repairs in an attempt to increase time to failure as well as to eliminate failure modes to develop in future can be unsuccessful and result into a devastating high failure rate of motors with similar prognoses, and extremely costly to recover from.

There is only one opportunity to ensure that the repair will be effective and all possible remedial actions must be taken to ensure the money spend for the repair will ensure that reliability is regained. New software and computerised algorithms makes it possible to capture data and effectively analyse it, allowing decision makers, both repairers and users, to make the best possible decision for any repair required.

4.2 Methods employed to determine failure prognosis

To allow failure prognosis to be effective, essential pre-requisite data are required. These data are gathered by performing effective and accurate condition monitoring on equipment while in service. Also performing detailed inspections and periodic testing on motors during maintenance periods adds to the data required for effective fault prognoses. Prognosis requires collection of documented data covering the following [3]:

- Data must cover the total population of plant, machinery and components under observation
- Data of all monitored parameters and descriptors must be available
- Historical operational, maintenance and failure data
- Future operating and maintenance environments, requirements and schedules must be determined.
- Initial diagnosis, including identification of all existing failure modes

- Failure modelling processes that can include statistics, existing and future failure mode influence factors, initiation criteria, and failure definition set points for all parameters, and descriptors
- Using of curve fitting, projection and superimposition techniques
- Knowledge of alarm limits
- Knowledge of trip (shut-down) limits
- Results of past failure investigations
- Reliability, availability, maintainability and safety data
- Damage initiation data
- Damage progression data.

Only by having all relevant data available wrt the present machine condition and comparing it with past failures and operational data of similar fleet, can future more accurate failure predictions be made. Reliability data is also necessary to improve on existing reliability prediction models and to create new more reliable failure prediction models.

Keeping detailed record of complete repair processes by noting failure modes, repair methods used to recover, recording final test data, noting problems during commissioning, monitoring the operational performance after repairs and recording failure modes after repairs are concluded, can a proper data base be compiled which can be used to do more accurate failure prognosis. Unfortunately this type of detailed data capturing does not take place in practice. It is necessary to have reliability data of repaired machines to establish prediction models for accurate failure prognosis. If this data is not available, failure prognosis is extremely difficult and very inaccurate.

With the availability of data related to the present operational duties of various types of motors in different applications, can an evaluation of the repaired motors achieved reliability versus the industrial application of the repaired motor be done. This will assist in understanding the initiation and progression of different types of failures on large motors in service. It will be possible to create accurate damage estimation models which can in future be successfully used in industry for renewal and replacement capital expenditure projects, to improve the total reliability of production and to reduce maintenance budgets significantly.

It is therefore essential to monitor and record as much data as possible from running plant. This requires the implementation of advanced monitoring equipment, which is integrated with various systems (Maintenance management systems, investigation report systems, plant monitoring systems, on-line and off-line condition monitoring systems, etc.) which will record, store and analyse captured data, making it available in a manageable format.

Only by having all data relevant to the current condition and current field performance, which include current and future field duties as well as accurate and total cost data, can effective prognosis for motors be made. Any inaccuracy of data and or missing data will result in flaws of an otherwise accurate model. To ensure accuracy of any accurate prediction models, an integrated system which will capture and process plant data, which is necessary for creating such a model, is necessary on a large fleet of motors distributed globally and used on different applications. Presently such systems are only used on very a small scale.

4.3 Effectiveness and general acceptance of prognostic processes

Due to the large number of motors on each plant and probably also a lag of understanding what impact a motor can have on production, data kept on motors are limited. Therefore, implementing effective prognostic processes on large motors is presently not very popular due to its inaccuracy as a result of low data density. From surveys conducted on users of large motors, it is comforting to see that certain basic but critical data are being kept and managed by users. Data such as nameplate and manufacturing data, failure and repair history, operational data, test data and on-line condition monitoring data are kept by most users who participated in the survey. Each user has its own system of capturing, trending and analysing such data. The important fact for effective prognosis is to have data, and to make sure it is effective and accurate. The fact that extensive data are kept by so many users of large motors make the implementation of effective prognosis for large motors possible. Not many users accumulate such data on an intelligent integrated system from which analysis of all data is possible. This complicate the processing of vast amounts of data and therefore requires extensive manipulation of existing data and gathering of missing data before proper models can be derived for effective mean time to failure (MTTF) predictive models.

Models that will do effective and accurate prognosis of large motors will be welcomed by all users, but to ensure all users of large motors will accept such models, it still requires extensive work. A predictive model is only deemed reliable if its reliability and accuracy is proven. For large motors this is not available yet and most users rely on expert opinion based on the limited hand monitored data available that can be processed by the human mind. EPRI [9] has compiled a report on empirical models that can compute vast quantities of data and use it in algorithmic models to perform effective calculation for the use of fault diagnostics and prognostics of large systems. Once such models are working effectively for large motors, and proven accurate and reliable in its function, users will definitely accept prognostic processes as part of effective daily predictive maintenance.

4.4 Section conclusion

It is desirable for a cost effective industry that strive towards optimal reliability to be predicting the future. This will assist in proper cost control, ensuring effective cash flow and proper refurbishment strategies that will ensure profitability as well as reliability. Predicting the future is an art that many have attempted to accomplish with very little success. Engineers sometimes use the term 'educated guesses' or 'gut feel' to try and support a prognosis. Yet power stations and industry cannot be both profitable and reliable by relying on a 'feeling'. Industry needs Engineers to make accurate and correct decisions about the future. Many large industries rely on 5 year or longer advance project planning and cash flow predictions.

Monitoring plant performance and accumulating operational and historical data is part of a good predictive maintenance strategy. Utilising this data effectively to allow proper prognosis is not done very effectively in the present time. Developments on integrated systems that monitor all conditions of plant and that can also access data in systems like SAP makes the central availability of all technical as well as operational data a possibility. Developments on on-line condition monitoring systems that can capture and evaluate accurately any deviations from the norm is a reality and is rolled out across industry as more confidence is gained on the effectiveness of these systems. As technology develops, computing power increases, software algorithms become more powerful and users of such systems get confidence in technology, accurately predicting the future can become a reality in the next decade.

5. Conclusion

Condition monitoring of large motors is a common practice globally. Most users of large motors that use motors in critical industrial processes perform various forms of condition monitoring, ranging from on-line continuous monitoring, to periodic on-line monitoring to periodic off-line monitoring. Depending on the criticality, size and cost of the motor, different condition monitoring and testing techniques are implemented. There is still room for great improvement in the field of implementing continuous on-line condition monitoring and exotic test techniques on large motors. There is also much to be done to create global integrated systems that will capture history, test data and operational data for the use of fault diagnostic testing as well as prognostic models for large motors.

Sufficient literature presently exist to prove that such integrated modelling will definitely be cost effective and to the benefit of power stations and industry. The technology is also available to implement such systems. Significant research topics on theoretical level as well as practical level are done to prove such systems to be effective. All of this indicating the complete integrated systems for condition monitoring, fault diagnostics and prognostics to be a reality on a global scale. Once these systems have proven its effectiveness, will users of large motors be in a position to motivate and implement such systems with confidence.

6. Summary of International experience (from questionnaire)

A questionnaire containing the basic methods used in power stations and industry to determine the health of large motors was distributed to users internationally. The survey covered users in Industry ranging from factories, utilities (coal and nuclear) to refineries as well as manufacturers of large motors.

The questionnaire consists of four sections, each section focussing a different aspect of motor life management. The first section contains questions about the general logistical management of motors. The second section focuses on the on-line and on-load monitoring of motors in service. The third section contains questions about the periodic monitoring of motors that is on-line but using mostly portable equipment. The last section looks into the use of condition assessment when motors are off-line.

The answers received back from users give a good indication of techniques that are used frequently by owners of large motors. It indicates that newer technologies are not used extensively as older well know technologies. It is also clear that basic motor data are kept on record for future reference and that certain operational parameters as running hours, starts and stops, etc. are also kept on record by most users.

What is surprising from the answers is the fact that destructive testing are used by only approximately half of the users, indicating possible that an increase in on-line monitoring of motor health is leading to a decrease in the use of destructive testing.

Although modern technology makes available intelligent condition assessment equipment, these intelligent systems are not used by any of the users that submitted answers. This can be an indication that these systems are not yet perceived as reliable enough to do complete motor condition assessments or is perhaps too expensive presently to be used on large scale in industry.

Further analysis of the answers received can be found in the appendices that deals with each topic contained in the questionnaire.

Table II SUMMARY OF INTERNATIONAL EXPERIENCE

CIGRE WGA1-26 - QUESTIONNAIRE: Monitoring, Diagnosis and Prognosis of Large Motors

SCOPE: Large motors higher than 1000V and 800kW that is critical and essential to a production/process

Country Name	AU, TH, ZA, KR, PL, IT, BR, RS
State the industry name and/or type of industry	Nuclear, Water, Thermal, Refinery, Factory, Water
Quantity of motors used for this survey?	822

		Yes	No
1	Are motor nameplate and manufacturing data for these motors recorded and maintained in a database?	100%	
2	Is machine failure history kept on record	100%	
3	Is motor repair history kept on record	100%	
4	Is operational data kept on record (running hours, excessive starts, abnormal incidents, etc.)	80%	20%
5	Are records kept of failure history and repairs performed?	100%	
6	Is continuous on-line monitoring performed on these motors?	80%	20%
7	Is periodic on-line monitoring performed on these motors?	60%	40%
8	Is routine off-line monitoring performed on these motors?	100%	
9	Is monitored data analysed periodically?	80%	20%
10	Are software algorithms used to do automatic fault diagnostics? Please supply information if Yes.	10%	90%
11	Are software algorithms used to determine repair diagnostics? Please supply information if Yes	10%	90%

Comments:
Bearing Vibration, Partial Discharge analysis, Polarization Depolarization Current analysis.

A) Are the following CONTINUOUS ON-LINE monitoring performed on process critical motors larger than 800kW, 1000V:

Type of monitoring	Yes	No	Not Applicable	Nr of motors monitored
Supply voltage monitoring and analysis	70%	30%		195
Supply Current monitoring and analysis	70%	30%		195
Bearing Temperature	90%	10%		607
Winding Temperature	90%	10%		475
Core Temperature	40%	60%		90
Cooling air temperature	40%	50%	10%	72
Cooling water temperature	50%	30%	20%	42
Cooling water flow through coolers	60%	30%	10%	35
Bearing and shaft vibrations	50%	50%		17
On-line continuous Partial Discharge		100%		0
Shaft volt and current measurement and analysis		100%		0
Flux coil		100%		0

	Yes	No
Is the above data captured in a database?	50%	50%
Is the above data trended and analysed?	30%	70%

	Jnr	Snr	Expert	Automated
What skill level is used for capturing data?	50%	10%	20%	20%
What skill level is used for trending data?	20%	50%	30%	0%
What skill level is used for analyses?	0%	60%	40%	0%
What skill level is used for repair scope?	0%	30%	70%	0%

B) Are the following PERIODIC ON-LINE monitoring performed on process critical motors larger than 800kW, 1000V:

Type of Monitoring	Yes	No	Not Applicable	Nr of motors monitored	Frequency
Supply voltage monitoring and analysis	40%	60%		54	1W/3M
Current monitoring and analysis	40%	60%		54	1M/3M
Bearing Temperature	40%	60%		72	3M
Winding Temperature	40%	60%		72	3M
Core Temperature	40%	60%		72	3M
Cooling air temperature	20%	80%		30	1M
Cooling water temperature	30%	70%		30	1M
Cooling water flow through coolers	20%	80%		66	1M/Req
Bearing and shaft vibrations	90%	10%		350	1M/6M
On-load Periodic Partial Discharge	40%	60%		52	1Y/3Y
Periodic Stator Current analysis	0%	100%			
Flux coil	10%	90%		30	1Y
IR Thermography	20%	90%		90	3M/6M
Ultrasonic sound measurement	0%	100%			
Shaft volt and current measurement and analysis	0%	100%			
Oil tribology	40%	60%		186	1M/3M/1Y

	Yes	No
Is the above data captured in a database?	70%	30%
Is the above data trended and analysed?	70%	30%

	Jnr	Snr	Expert	Automated	N/A
What skill level is used for capturing data?	40%	10%	20%	0%	30%
What skill level is used for trending data?	20%	30%	20%	0%	30%
What skill level is used for analyses?	0%	40%	30%	0%	30%
What skill level is used for repair scope?	0%	20%	50%	0%	30%

What other off-line monitoring techniques are used?
- Current Spectrum Analysis

C) Are the following OFF-LINE monitoring performed on process critical motors larger than 800kW, 1000V:

Type of Monitoring	Yes	No	Not Applicable	Nr of motors monitored	Frequency
Insulation Resistance	100%	0%		822	1Y/2Y/3Y
Polarisation Index	100%	0%		822	1Y/2Y/3Y
HV Tests	60%	40%		552	1Y/6Y/ Rep
Tan delta	80%	20%		650	1Y/6Y/Rep
Winding Capacitance	70%	30%		592	1Y/3Y/4Y/6Y
Ultrasonic sound measurement	0%	100%			
Cooling water flow through coolers	20%	80%		92	6M
Bearing Vibrations	70%	30%		490	1Y/6Y/Rep
Off-line Partial Discharge	70%	30%		166	1Y/Rep
Polarisation Depolarisation Current (PDC)	40%	60%		46	Once
Dielectric Dissipation Factor (DDF)	40%	60%		116	1Y/Rep
Intelligent digital combination diagnostic tests	10%	90%		5	Occasional

	Yes	No
Is the above data captured in a database?	90%	10%
Is the above data trended and analysed?	90%	10%

	Jnr	Snr	Expert	Automated	N/A
What skill level is used for capturing data?	40%	40%	20%		
What skill level is used for trending data?	10%	60%	30%		
What skill level is used for analyses?	0%	60%	40%		
What skill level is used for repair scope?	0%	30%	70%		

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Appendixes

Appendix A
Condition monitoring systems to assess General Health

A1. External visual inspection

It is a good habit for operation or maintenance people to notice and record any abnormalities of:
- External appearance of the motor (looseness, vibration, smoke, arc, etc), sound, heat, etc.
- Unusual environment of the location where motors are installed, e.g. flood, damp, heat, particles & contaminants from production line, etc.

External visual inspection can be applied as on-line condition monitoring while the motor is in service, during other periodic off-line, on-load monitoring and during periodic off-line tests.

A2. Internal visual inspection

Introduction: Visual inspections of the motor winding, stator core, motor frame, electrical leads, etc. is and will remain the most important tool to assess the condition of an electrical motor. Performing a thorough inspection by an expert eye will reveal most problems that can be found in electrical motors. Having the right expert performing a visual inspection, problems on critical components can be quickly identified. Online condition monitoring techniques can identify problems with the motor while in service but it will require a trained and expert eye to identify the exact problem. It is therefore imperative that all motor engineers and maintainers acquire this expertise and ability. Important evidence, which can be used in assessing the condition of an electric motor, can be gathered by performing a visual inspection on motor windings and cores. Visual inspections can be performed as frequently as possible and is not destructive in nature. Equipment like boro-scopes, endo-scopes and magnifying glasses can be used to assist with the effectiveness of visual inspections.

Applicable on: All motors

Purpose: To visually determine the condition of a motor to assist in identifying scope that will require more advanced testing

Test Instrumentation:
- Endoscopes
- Borosonic scopes,
- Magnifying glasses

Procedure: Performing a careful and systematic inspection of the complete motor and all its components. Specialised equipment can be used to inspect inaccessible areas. The areas to be inspected as follows:

Visual Inspection of Stator Slots: The checks to be carried out are as follows:
- Presence of dust
- Migration of slot side filler
- Blockage of ventilating passages
- Looseness of slot wedges
- Coil insulation damage
- Overheating evidences
- Evidence of partial discharge

Visual Inspection of Stator End Winding: The checks to be carried out are as follows:
- Accumulation of dust, or evidence of oil contamination
- Evidence of erosion or cutting
- Displaced or broken lashings or banding

- Connection taping Insulation disturbance
- Loose hardware
- Coil or bracing distortion
- Overheating evidences
- Evidence of partial discharge
- Solder/braze joint overheating or broken strands
- Evidence of water leakage

Visual Inspection of wound rotors:

- Presence of copper dust in the slot areas
- Axial movement of slot components
- Overheating of any rotor components
- Balance weights looseness
- Cracked, raised or displaced wedges
- Movement of the retaining rings
- Damage to bearing journals, bearing or gland seal rings
- Retaining ring damage
- Dirt and other contamination build-up
- Damage of fans and compressors

A3. Motor current signature monitoring and analysis

Introduction: The health of an electrical motor can be determined by doing current spectral analysis of the electrical supply to the three phase motors. This technique of motor condition monitoring is referred to as motor current signature analysis (MCSA). Information such as winding insulation health as well as rotor condition can be retrieved from the motor electrical spectrum.

Continuous on-load monitoring: By utilising digital processing equipment continuously connected to the motor current instrumentation transformers and analysing the frequency spectrum of the motor supply current, it is possible to detect insulation breakdown, electrical supply problems, internal electrical problems, mechanical looseness, imbalance, misalignment and bearing problems. No other sensors or field equipment other than the existing current measurement transformers are necessary to retrieve valuable motor health data using this technique.

Using specially formulated algorithms, users of large motors can be immediately alarmed of any deviations in the motor's operating conditions occur. Some systems available in the market use intelligent self-learning algorithms that continuously compare and analyse motor operating data, identify motor problems, create condition assessment reports and recommend corrective actions. The technique is used in Thailand, Italy, Korea, Poland and Brazil. In spite of the high cost to install on every motor, it is very valuable for condition monitoring on critical and expensive motors.

Periodic on-load condition monitoring: Using portable equipment to measure data from motor current measurement equipment will give users an insight in the condition of the motor winding and rotor cage can be derived but will not be as effective as the method described in 4.2.1.1. Periodic measurements of motor supply current will give some satisfaction of the motor health but the accuracy of the data will be dependent on the measurement technique, measurement method, measurement equipment as well as accuracy of analysis. Any destructive faults developing between periodic measurements and analysis will not be detected in time to save the motor from failing. This technique is also rarely used on large motors for periodic measurement and data trending. It is used more on an ad-hoc basis as fault finding technique if other on-line and off-line monitoring systems do detect problems on motors.

A4. Temperature monitoring of bearing, winding, core and cooling water/air

General: The installation of resistance temperature detectors and or thermocouples on motor components like windings, bearings, coolers, etc. is common practice. The effective utilisation of these instruments is not so common. Due to the cost of interfacing motor field instrumentation with plant control and monitoring systems, these valuable monitoring devices are rarely effectively used. Valuable data from motor operating conditions can be retrieved by measuring and analysing motor winding temperatures, stator core temperatures, cooling water and/or air temperatures and bearing temperatures. By performing effective monitoring, trending and analysis of data measured from these devices, motor faults can be detected before failures occur.

Continuous on-load monitoring: By requesting motor manufacturers to perform proper modelling of a motor during the design phase, the most effective placement of temperature measurement instrumentation can be determined. This will make hot spot monitoring in stator windings and stator cores effective and can assist with proper control of motor cooling, repair prognosis, operating conditions, etc.

By continuous monitoring of the temperature of different components on an electrical motor, developing defects can be located before it results into destructive damage of the motor and connected systems. On-line monitoring of motor temperatures in operation is one of the most common on-line monitoring techniques used on almost all large motors. Normally bearing temperatures, winding temperatures, core temperatures and cooling air/water temperatures are monitored on large critical motors. Alarms are set at predetermined values, normally at levels prescribed by the manufacturer. These prescribed alarm levels are in most cases much higher than the maximum that the motor temperature ever reaches when in service. Once alarm levels are reached, significant damage was already caused to the motor. It is therefore essential to optimise operational alarm values to ensure that alarms will be effective in pre-warning of developing faults. By reducing alarm values to a value slightly higher than normal operation, say for argument sake at 5% above the highest temperature reached by the motor on the hottest day of the year, more effective alarming is possible because slight deviations from the normal operational component temperature will be alarmed and the reason for the deviation can be investigated by personnel. This can prevent severe failure of a motor due to the fact that small deviations from the norm can be detected in time. The downfall is that it can also cause false alarms if alarm values are not carefully selected.

A5. Shaft volt and current measurement and analysis

Introduction: Motor shaft earthing refers to the connection of the one end of the motor shaft to an earthed network using a brush riding on the rotor shaft. Carbon-silver brushes are normally used to rid eon the rotating shaft due to their good electrical characteristics ensuring a low resistance connection between the rotor shaft and the earth network.

Shaft earthing on one end of the rotor shaft, while the other end is insulated from earth, is required to prevent damage to motor bearings and journals due to circulating electrical currents from flowing between the motor rotor and the bearings. Circulating electrical current will cause frosting, pitting and spark tracking on bearing journals, sleeve bearings and roller/ball bearings.

For a shaft earthing system to function correctly, the bearings and oil baffles/wipers that is connected to the side of the motor that is not earthed must be insulated from the motor frame. It is general practice on large motors to insulate bearings and bearing housing assembly on both sides of the motors from the motor frame. Shaft earthing can therefore be done on any side of the motor rotor shaft. Voltage shaft measurement on the opposite end that (insulated end) is done to measure a rise as well as voltage harmonics present on the rotor shaft. By measuring the magnitude of the shaft current flowing from the shaft through the brush to the system network earthing as well as the voltage on the opposite end of the shaft, developing problems on the motors can be detected before it causes significant damage.

Continuous on-load monitoring: Problems that can be detected by monitoring and evaluating shaft voltages and current continuously on-line includes stator core faults, rotor problems, shaft rubs, residual magnetism on rotor shafts, bearing insulation deterioration, asymmetry between the rotor and stator air-gap, broken rotor bars on induction motor, winding faults on synchronous motor rotor, winding faults on motor windings as well as voltage harmonics due to thyristor drive problems, rectifier problems, etc. EPRI compiled an extensive report [11] on the monitoring of rotor shaft voltages and currents on generators to detect stator core problems. This document gives also valuable insight into this topic that can be applied to large motors.

To continuously monitor shaft voltages and current on-line require a shaft earthing brush system as well as a shaft voltage monitoring brush system to be installed on opposite ends of the generator. It also requires an online data acquisition unit that can convert the measured data into meaningful measured data that can be interpreted and analysed by users of large motors. These systems are normally of a digital nature with build-in frequency spectrum analysers and harmonic filters with pre-set algorithms that will filter out only meaningful data. It also has online alarm capability that will inform operators of any deviations in measured shaft voltage and current levels.

A build-up of grease, oil and dust might occur between the brush surface riding on the rotor shaft which will affect the electrical resistance between the shaft and the brush. Brushes therefore need periodic cleaning to ensure proper contact is maintained to ensure effective on-line measurement of data.

Periodic on-load condition monitoring: If an on-line system is not installed to measure shaft voltages and current on rotors shafts, periodic monitoring can also be done. This will normally be planned on a planned schedule to take place weekly or monthly, but can also be done on an ad-hoc basis when motor problems are experienced. It is normally done using portable equipment and snapshot measurements are taken and recorded. Portable equipment presently in use range from very crude basic voltage and current measurements without any analysis or filtering being done through to sophisticated digital data processing equipment.

By performing these measurements periodically while a motor is on-load can give satisfaction of the health of the motor to some extend but will not be able to give sufficient information of developing faults shortly before failure. If measured data is also accurately measured and analysed shortly after measurement, developing faults might be missed. The quality of the measured data is also essential to ensure accurate analysis.

Although this technique is frequently used on large turbo-generators to determine generator rotor and bearing insulation problems, this method to determine motor condition is not very popular. Although large motors have shaft earthing, the earthing current is not measured, trended and analysed on the surveyed motors. None of the motors have shaft voltage brushes to measure any rise in rotor shaft voltage on the opposite end of the earthing brush.

Although it is possible to find motor operational problems with this condition monitoring technique, users do not have sufficient knowledge nor trust in such a system to rely on its value for preventative maintenance purposes. Present earthing and measurement brushes need frequent cleaning and/or replacement and maintenance free brushes are presently very expensive and also needs a perfect running surface on the shaft in the case of gold bristle brushes. With the recent developments in carbon-fibre shaft earthing and voltage brushes, which require no maintenance for the life of the motor, delivering accurate and consistent data from shaft current and voltages, this method might become more popular in future.

A6. Monitoring of cooling water flow

General: The worst enemy of motor insulation is excessive heat. Most large motors require cooling water for the indirect cooling of winding and rotor cooling air. It is a common problem for operators to leave cooling water supply valves to motor coolers in the closed position after performing maintenance work.

The measurement of cooling water flow through motor heat exchangers can aid in calculating the efficiency of coolers. If water flow through coolers is not according to original design criteria, blockages in the cooler might be present. Coolers with poor flow can be identified and opening, inspection and cleaning of such coolers is then possible.

Electrical insulation life is largely dependent on cooling efficiency and where heat exchangers is dependent on cooling water it essential to be assured that coolers always operate at optimal performance. Where raw water is used for heat exchanger purposes, the measurement of cooling water flow during outages is essential as bacteria growth and sludge formation will significantly reduce cooler efficiency. After cleaning of coolers were performed during outages, measuring flow through coolers prior to returning motors to service is necessary to ensure cooler efficiency is back to the original design specification. This will also ensure that obstruction like rags and plastic bags have not entered the cooling water system during the maintenance outages and that all airlocks were effectively vented during commissioning.

By incorporating flow switches in the cooling water supply lines, electrical interlocking with motor start-up control circuits is possible to prevent motors from starting when the required minimum water flow rate is not detected in coolers. Motor trip circuits can also be activated if the water flow rate drops to below the minimum flow required for full load operation.

Few motors in power stations and industry are fitted with cooling water flow sensors and/or flow switches, yet the absence of such relatively inexpensive devices can significantly reduce the possibility of motor insulation overheating.

Continuous on-load monitoring: By performing continuous flow measurements and trending of cooling water flow data, the fouling of coolers can be detected and cleaning performed before damage is done to motor windings. By operating a motor at cooler temperatures, the life of a motor can be greatly enhanced. Users of certain critical motors in Australia, Korea and South Africa have reported the use of this technique to determine cooling performance of motors.

Periodic on-load condition monitoring: The periodic monitoring of cooling water flow through motor heat exchangers is essential for large high efficiency critical motors. The integrity of windings on these motors are jeopardised if operated without sufficient cooling water which will result in overheating and subsequent failure of costly equipment as well as the cost of production down time. By periodic measurement of cooling water flow it is possible to trend cooler efficiency and determine if cooling water flow is deteriorating due to blockages in cooler tubes. Air ingress into coolers can also result in air locks which will prevent cooling water from flowing. Coolers with poor flow can be identified and opening, inspection and cleaning of such coolers can be planned when opportunities are available.

Electrical insulation life is largely dependent on cooling efficiency and where heat exchangers is dependent on cooling water it essential to be assured that coolers always operate at optimal performance. Where raw water is used for heat exchanger purposes, the frequent periodic measurement and monitoring of cooling water flow is essential. On-line cooling water flow would be preferred on high risk motors using raw water for heat exchange purposes but frequent periodic monitoring can be an effective alternative option.

A7-A8. Vibration Monitoring of Bearing and shaft

General: Measuring motor bearing and shaft vibrations is a common condition monitoring technique in power stations and industry. Various on-line as well as off-line instruments are available on the market for the effective continuous or periodic measurement of motor vibrations. Using accelerometers for roller and ball bearings and Eddy Current Transducers (Proximity Probes) on journal type bearings is common practice on large critical motors but evidence of both can also be found on the plant of users.

Portable vibration analysers using velocity meters and accelerometers for the measurement of bearing vibrations are a common sight on plants using predictive condition monitoring techniques. Accelerometers are frequently used for periodic as well as continuous monitoring of motor bearing vibrations due to their small size as well as wide frequency response bandwidth. An accelerometer utilizes a piezo-electric crystal to convert mechanical energy from the vibrating bearing into an electrical signal. The piezo-electric crystal is placed between the accelerometer casing base and a pre-determined amount of mass. As physical movement is applied to the sensor the mass squeezes and exerts pressure on the crystal, and this action produces an electrical signal which is measured and analysed by the spectrum analyser.

The accelerometer is placed on the motor pedestal in different positions resembling the three axis of movement in three dimensional space. Using frequency transform techniques (Fourier transform), the different frequency components resembling the different harmonics created by different operational problems can be determined. Most mechanical problems as well as some electrical problems can be detected.

The use of Eddy Current Probes [19] is more limited as it is only possible if proximity probes are permanently fitted to motors. The fitment of these probes requires special brackets for secure mounting inside pedestals or on motor frames as the probe tip should not move relative to the mounting and should also not get into contact with the rotating shaft. Wiring need to be effectively screened from magnetic fields produced by motors as it will affect the measurements. The distance of the probe from the rotor is critical for acquiring meaningful data. Rotor probe tracts need to be free of indents and surface defects as well as free from any magnetism as it will influence measured data. An Eddy Current system consists of a probe, a cable and an oscillator/demodulator which must all form a perfectly matched system. The oscillator generates a high RF signal which is sent through the cable and radiated from the probe tip. Eddy Currents are generated in the surface of the shaft which is measured by the probe and demodulated by the demodulator. The measured data consists of a DC component and an AC component. DC data resembles the distance of the probe from the shaft, therefore used for shaft position indication and the AC component supply data of the rotor shaft radial vibrations. Probes are placed in two positions, 90° apart from each other, resembling an X and Y vector.

Continuous on-load monitoring: The Continuous on-load monitoring of rotor shaft vibrations and/or bearing pedestal vibrations can give the most valuable operational information while a motor is in service. Mechanical problem as well as a large number of electrical problems can be detected on a motor by analysing the frequency spectrum of vibrations measured in the time domain. By converting the time domain measured data into a frequency spectrum, various problems can be found on motors. From an international survey performed, only a very small percentage of motors are monitored by on-line vibration monitoring equipment and is mostly limited to very large and very critical motors. A Power Plant in Poland has indicated that vibrations on a total of 128 motors of rating above 800kW and 1000V are continuously monitored on-line. A power utility in Australia has shown a similar phenomenon on a total of 60 large motors. Most users perform continuous on-line shaft and bearing pedestal vibrations on less than 10% of their large motors covered in this survey.

Periodic on-load condition monitoring: Periodic monitoring of bearing vibrations is very common on almost all plants using predictive monitoring maintenance philosophies. This service can be performed using permanently employed skilled staff of can be contacted to specialising companies who has access to very skilled and experienced experts.

Using portable velocity meters and/or accelerometers with a magnetic base, the measurement probe can be easily attached to bearing pedestals and motor frames for the measurement of vertical, horizontal and axial displacement of the measured component. Modern processing equipment is a digital battery operated portable device with sufficient processing power to perform an immediate Fourier transform of the measured data. If a skilled and experienced operator is used to gather data, he can immediately determine if any obvious problems with the motor exist.

Most users of large motors utilises basic skills to accumulate data from a large number of motors, skilled Technicians to populate a database and identify motors with problems and expert engineers to perform more difficult fault diagnostics.

The frequency of bearing vibration measurements vary from twice per year to once every month. No user indicated to perform vibration monitoring more frequently than once per month, unless specific motors with known problems are more closely monitored. The majority of users indicate the use of periodic monitoring of vibrations on the largest number of large motors, although some users indicated the use of Continuous on-load monitoring on all their large motors.

Periodic off-line test to assess bearing vibration: Motor bearing vibrations are normally measured when a motor is in service and forms part of periodic condition monitoring of motors. Information gathered from monitoring is normally used to plan repairs to a motor. Although more applicable to condition monitoring while in service, bearing vibration measurements on motors after repairs to motors is regarded as very important quality acceptance criteria by clients prior to accepting a repaired motor from a repair shop or manufacturer. A significant amount of motor condition information can be retrieved for the frequency domain derived from measured bearing vibrations. Measured data after repairs on its own can be used to determine if the motor is mechanically and well as electrically sound after repairs was performed. Comparing vibration data after repairs with data while the motors was in service will also prove that the repairs were successful.

If motors are known to be problematic when in service once installed on the plant, customers of repair shops might use very strict acceptance criteria prior to accepting a motor after repairs. It is therefore a valuable tool to be used as part of factory and repair shop acceptance criteria.

Applicable on: **-** Squirrel Cage Induction Motor Frames and Rotors

- Wound Rotor Induction Motor Frames and Rotors
- Synchronous Motor Stators Frames and Rotors

A9. Measurement of Leakage flux

General: The measurement of leakage flux from a squirrel cage induction motor stator winding can also be used as a valuable condition monitoring technique. It is mostly used for the detection of broken rotor bars [21] on induction motors but research on measuring leakage flux from squirrel cage motors indicates that it can also be a tool to detect other motor problems like rotor winding degradation, stator winding turn to turn failure and asymmetry of three phase supply voltage.

Periodic on-load condition monitoring: The leakage flux measurement is done using a circular search coil [22] that is placed at the non-drive end of a motor to measure axial leakage flux from the winding. The principle of operation is the same as for current spectral analysis where a problem inside a motor results in asymmetric distribution of current and flux. This asymmetry due to faults results in characteristic fault frequencies. In the frequency domain, these fault frequencies appear as sidebands additional to the normal characteristic frequency spectrum of a healthy motor. By comparing the frequency spectrum of a healthy motor to the spectrum of an unhealthy motor, as well as to the spectrums of other unknown motors with known symptoms, motor faults diagnostics can be made.

Measurement of the motor stray fluxes can be done using portable flux coils for periodic measurements but also with permanently fixed coils that is wound around stator core teeth [23] or placed in the axial flux path inside the motor to enhance measurements accuracy. A significant amount of research is still being done on various stray flux measurement techniques although this method for condition monitoring is not often used. Due to its low usage, experience and knowledge of this technique seems to be low among users of large motors. Using this method in combination with Motor Current Signature Analysis, rotor cage problems can be very effectively identified. These tools in combination can therefore be very valuable for fault diagnosis where one method is not always very accurate of successful.

Using Flux coil analysis for motor condition monitoring is not a very popular technique and only one user in at a nuclear utility in Brazil reported the use of this technique once per year on 30 of the 50 motors surveyed at this plant. On-going research for the development of effective permanently fixed flux measurement coils is still on-going [21] [22] [23]. Handheld coils deliver variable results if moved to different positions. This technique for periodic monitoring of large motors might become more acceptable as better flux probes and placement positions are determined.

A10. Infrared Thermography

Lightweight and low cost thermal imagining cameras and associated software has made the use of it in monitoring temperatures on motors a possibility. Thermal images of motors can be recorded, analysed, stored and trended. These data can be evaluated by experts to identify motor cooling problems, bearing problems and abnormal core temperatures during core tests.

The use of infrared (IR) thermography equipment as a condition monitoring technique is widely used on power plants for measuring temperatures of large and critical systems like generator brushgear, transformer bushings, switchgear, etc. The application on motors is mostly limited to the confirmation of high temperatures once measured or detected by other systems. Instrumentation used varies form small and basic hand held scanners to very advanced high tech equipment to assist the user with analysis and trending of measured data. Infrared thermography is also widely used in power stations and industry to determine if cooling performance and flow of cooling air and/or liquid is as per design. Blocked oil lines and coolers with poor performance can easily be detected by experienced users.

The use of Infrared Thermography as a periodic condition monitoring tool on large motors is not widely used. This technique is more used as a fault finding technique once other systems have indicated a temperature problem to exist. Only 22% of users used this technique as a periodic monitoring tool on large motors and only ninety of the surveyed 500 motors were periodically monitored using this technique. Frequencies varied from between once every three months by a power utility in Australia to once every six months on motors used in a nuclear plant in Brazil.

A11. Ultrasonic acoustic measurement

By measuring and monitoring noise levels on electric motors, electrical as well as mechanical defects can be detected before resulting in failure with disastrous consequences. Mechanical rubs on fans and baffle plates can be detected before metallic particles get dislodged and end up destroying the stator winding. Abnormal vibrations also result in abnormal noise levels, especially if resonance of connected equipment is present. If motor frame resonance is not detected and rectified in time it will result in complete destruction of the motor and its connected components.

By measuring acoustically the electrical discharging of a stator winding, the condition of the stator winding can be trended as it deteriorates. The measured value is given in dB. Very sensitive ultrasonic acoustic equipment with noise filtering capability is necessary for this test. Noisy environments, like in a power station with running units, make this test sometimes very difficult. The use of this technique seems to be very low as no country indicated the use of this for motor condition monitoring.

No users in the survey conducted indicated the use of this technique to perform planned periodic condition monitoring. Due to significant noise levels in large factories, this technique can have variable success rate, pending the specific noise frequency and volume. The position of the ultrasonic measurement probe also has a significant effect on the accuracy and success of the measurement. It is not an easy tool to use for trending as numerous external factors will affect the dB value measured. It makes accurate trending therefore very difficult.

The tool is helpful in confirming problems on bearings, fans and stator noise but not very effective as a periodic condition monitoring tool. Although this technique is not officially used as a periodic condition monitoring tool using ultrasonic equipment, all maintenance personnel do use this technique when they perform plant surveys by purely listening to the noise coming from motors. It is of great help to identify problems on motors due to fan and air/oil baffle rubs as well as motors operating with high frame vibrations due to resonance. Maintenance personnel must therefore always listen carefully to any abnormal noises coming from motors when they perform periodic plant inspections, even if high tech tools are not available.

A12. Conductor resistance measurement

Introduction: Occasionally, the electrical connections between series connected stator coils or bars degrade, resulting in local overheating. In particular, the braised connections between coils/bars crack or otherwise become less conductive. These problems can sometimes be detected by a conductor resistance test.

Applicable on: - Squirrel Cage Induction Motor Frames and Rotors
- Wound Rotor Induction Motor Frames and Rotors
- Synchronous Motor Stators Frames and Rotors

Purpose: To check healthiness of the conductor

Test Instrumentation: Kelvin bridge or micro-ohmmeter

Procedure: Kelvin bridge or micro-ohmmeter can be used for conductor resistance measurement. Measured resistance R_t is to be corrected for temperature. If the temperature during test is T_t and taking standard condition as 75 °C correction for copper conductors is given as:

$$R_{75} = R_t (234.5 + 75)/ (234.5 + T_t)$$

Compare the value obtained with previously obtained values of resistance and corrected for same standard condition.

Acceptance norm: 2% variance from expected is usually an indication of an abnormal stator winding circuit.

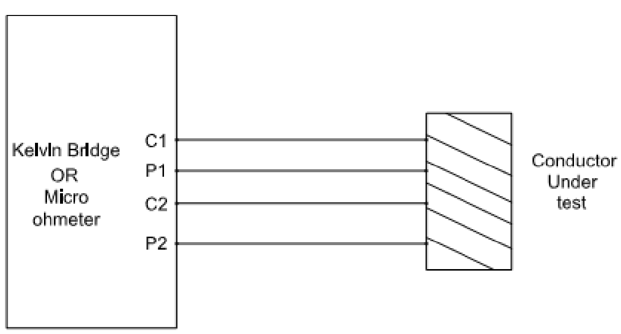


Fig A12-1: Kelvin bridge test arrangement

A13. Dye penetrant test

Introduction: Damage to high speed rotating shafts occur as a result of high cycle fatigue, although damage can be by overheating due to rubs or some other form of abnormal operation. Rotor shafts therefor need to be tested from time to time to determine if cracking is present.

Applicable to:
- Rotor Mechanical Components
- Stator frames

Purpose: To monitor the health of highly stressed mechanical components of rotors in order to avoid the catastrophic failure which might result due to fracturing or stress corrosion.

Procedures:
- Metal surface should be thoroughly cleaned with surface cleaner.
- Dye penetrant is applied to the surface and allowed to penetrate the metal surface for the time as prescribed by dye manufacturer.
- At the end of prescribed time metal surface is cleaned and developer is applied. On application of developer general shapes of cracks can be observed and pits are observed as round stains.

Acceptance norm: Depending on the imperfection observed the corrective action can be taken. Surface grinding can be done to remove the imperfections and micro-welding can be considered to re-establish original dimensions. It might also be necessary to scrap the tested component if the damage to it is significant.

A14. Lube oil analysis

Motor bearing lubrication oil sample analysis is a very common condition monitoring technique used to determine if motor bearings are in a good condition. The condition monitoring technique requires an oil sample to be taken from a bearing reservoir or forced lubrication system for analysis. The oil analysis itself is not complicated although the successful outcome of the analysis will be determined by the quality of the oil sample and also if the sample is representative of the oil that the bearing and motor journal is exposed to. EPRI is creating and valuable motor predictive maintenance guide [13] that describes in detail the best practices in performing effective motor lubricating oil sampling.

A15. Winding ground detection test

Winding ground can be detected as a periodic off-line test by combined use of two tests viz.

Split voltage test and **Forging current test**.

When ground resistance is lower than 10,000 ohms detection can be done precisely. For ground resistance ranging from 10,000 ohms to 100,000 ohms better instrumentation system is needed. While for ground resistance above 100,000 ohms it may be necessary to burn the ground to lower value by first conducting overvoltage test so that exact ground detection can be done.

Applicable to:
- Wound Rotor Induction Motor Rotors
- Synchronous Motor Stator Rotors

A15-1 Split voltage test

Purpose: To detect the ground within a copper winding.

Test Instrumentation:
1. DC Power source (5 – 20 V)
2. miliVoltmeter (1-5 milivolt, High impedance)

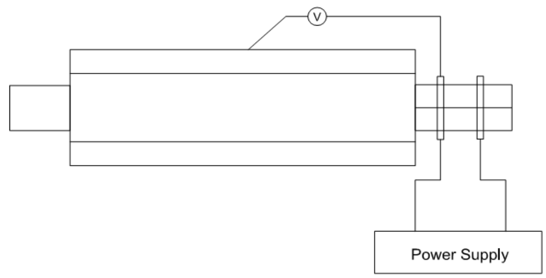


Fig A15-1: Split voltage test arrangement

Procedures:
- Ensure a low resistance connection between power source and collector ring.
- Power source (5 – 20 V) should supply the current in the range of 100 – 300 A. DC power source.
- Should be ungrounded.
- Voltage across two collector rings is measured and recorded.
- Measure the voltage from each individual ring to any point on the forging.
- The sum of the two voltages measured between the individual rings and forging should be equal to the voltage measured across the collector rings.
- If the readings produce satisfactory totals, the ratio of the voltage from a ring to ground divided by the total voltage is proportional to the distance (resistance) through the winding from that ring to the ground location.
- If there is less than 2% difference between the two readings, then the ground could possibly be at the collector rings.

A15-2 Forging current test

Purpose: To detect the axial location of the ground within the field forging.

Test Instrumentation: 1. Current source (300-1,000 A)
2. miliVoltmeter (1-5 milivolt, High impedance)

Procedure: Connect the current source to each end of the forging. Connect the voltmeter between any of collector rings and forging. Set the current flow and increase up to the point to obtain suitable sensitivity for measurement purpose. Check the forging axially and determine the point where voltage becomes first zero and then changes the sign. Fault location is identified by zero voltage location where polarity reverses.

Acceptance norm: Pass/fail test

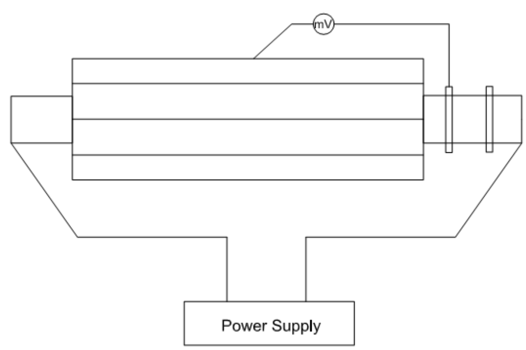


Fig 15-2: Forging current test arrangement

A16. Other health detection system

A16.1 Cooler leak test

Purpose: To determine the leakage in tubes of cooler.

Procedure: Hydrostatic pressure is applied using clean water by blanking off inlet and outlet piping. Pressure decay indicates presence of tube leak. This is called global leak test. Same test can be performed on each individual tubes called as single tube isolation test.

Acceptance norm: Pass/fail test

A16.2 Air leak test

Purpose: To determine the leakages in overall assembly of motor to avoid the loss of coolant.

Test Instrumentation: Manometer, Thermometer

Procedure: Machine is pressurized at operating pressure using instrument air and kept isolated from external air supply for the period of 24 hours. Pressure decay in 24 hours can be used to compute the quantity of coolant (hydrogen or air) that would have leaked in the same duration.

A 1 hour test can also be carried out instead of a 24 hour test. This test uses a standard test cylinder which has two ports. The one port is attached to a manometer and other port has a valve. The test cylinder is kept inside the machine and the valved port is used to obtain the test cylinder pressure to equal the machine internal pressure i.e, generally operating pressure, and other end of the manometer is open to machine internal pressure. On getting pressure equalization, the valved port is closed. Air leak if any is indicated by the calibrated manometer.

Acceptance norm: Pass/fail test.

A17. Health Diagnostic Tests

A variety of integrated systems are available on the market that can perform an all-in-one motor condition assessment. These systems consist typically of a probe connected to the motor that that can measure motor frame vibrations and temperature, even stray fluxes from the stator winding. By having external inputs into the integrated system such as motor volts and current, bearing vibration, pressure, flow, bearing and oil temperature as well as tachometer input, it can perform a detailed analysis using advanced software packages that create automated condition reports. These reports will contain information such as speed, slip, output power, output torque, efficiency and percent of rated load. It can also contain power quality indicators such as phase-to-phase voltages, phase currents, real power (W), power factor, total harmonic distortion (THD), crest factor and unbalance.

Integrated condition monitoring systems also have alarm outputs that can be configured by users. Alarms that will be announcing abnormalities to operators can for example be system voltage high or low, motor current high or low, motor loading high, performance low, rotor condition and stator condition. It can also have auxiliary alarm inputs to route alarms from external systems to operators and at the same time capture events of these alarms on its own internal log. Integrated systems can, depending on the capability of the software, also perform certain current and vibration signature analysis such as frequency domain analysis (FFT), filtering, and time domain analysis.

From an international survey conducted, no country or user indicated the use of intelligent digital equipment for the complete evaluation and automatic reporting on the health of large machines. This does not mean that the technique is not used but only that it is not popular at present for large motors. The reason might be the cost of such a complete intelligent system as well as the confidence level of users of large motors in power stations and industry.

There is definitely a place in industry for such systems on large critical motors as similar systems are used worldwide on large generators with success. As these systems become more cost effective to implement and also known to engineers, technicians and maintenance personnel, it will definitely be used more widely in industry.

Appendix B
Condition monitoring systems to assess Dielectric Health

B1. Partial discharge measurement

Introduction: Partial discharge is a phenomenon in which the insulation capability of a gaseous substance breaks down locally (internally) because of high intensity electric fields [17]. It does not break down across the total thickness of an insulation medium but occurs only internally to the insulation medium where defects are present, therefore an incomplete breakdown [18] of the insulation take place – therefore term Partial Discharge. Partial Discharge is evident on windings operating at voltages above 4000VAC.

Two basic types of Partial Discharge occur in insulation systems:

a) Internal Discharges where the partial discharge of electrical energy occurs across a void that contains air of gas. The voids are internal to the insulation material.
b) Surface discharges occur on the outside of insulation surfaces. It occurs between an electrical charged insulation system and an earthed

Partial discharge tests are performed for the following reasons:

- To determine the current state of the machine insulation based on present and previous test information.
- To localise the cause of insulation problems.
- To identify insulation problems at an early stage and trend them over time.
- To have enough information on the state of the insulation to plan outages well in advance.

Partial discharge occurs in the following locations in a machine:

- Internal voids in the insulation
- On the surface of the endwinding
- Between the end winding conductors
- Between the bar semi-conductive coating and the slot wall

With careful analysis by an expert in the field of partial discharge, it is possible to determine the condition of insulating material. It is also possible to determine which area or section of a winding is responsible for high discharges.

Different methods are used to measure PD on high voltage stator windings:

(a) Condenser Coupling Capacitors.
Coupling capacitors are used on high voltage motors to measure partial discharge signals from high voltage insulation. The capacitor separates the high frequency partial discharge signal from the high voltage 50Hz motor supply. Permanently installed coupling capacitors are the most commonly used for the measurement of PD. The high voltage end of the capacitor is directly connected to the motor high voltage terminals.

(b) RTD's used as PD sensors.
The majority, if not all critical motors are fitted with resistive temperature detectors (RTD's). As PD is a high frequency broadcast signal, RTD's can act as antennas inside the motor casing. By connecting PD measurement equipment directly to RTD's, it is possible to measure the occurrence of partial discharge in on a motor winding.

Although other techniques exist in industry to measure partial discharge on transformers, motors and cables, these techniques are not commonly used on motors.

EPRI published an extensive research report on the use of PD and EMI [5] to detect various problems on motors. Physical problems were created on motors to determine if PD and EMI can find these manually introduced faults. The outcome of this report is very positive and shows that PD and EMI has a definite place in day to day monitoring of large electrical motors.

Due to the fact that PD only occurs on high voltage systems and also the expert knowledge required for fault diagnosis, the use of PD in motor condition monitoring is presently in limited use.
(c) Radio Frequency Current Transformers (RFCT)
Radio Frequency Current Transformers (RFCTs) are also used to measure partial discharges on stator windings. This is normally referred to as inductive sensors as opposed to the capacitive coupler type. The convenience of using clamp-on CTs is that the normal line of power supply to the motors does not have to be interrupted for measuring partial discharges when on-line couplers are not available. RFCTs can be mounted around a neutral terminal, motor earth connection or supply terminals.

Continuous on-load Partial Discharge measurement: By performing on-line continuous monitoring of Partial Discharge on large motors it will be possible to monitor and detect the development of motor problems on a continuous base. If powerful effective analytical software is combined with on-line PD monitoring, pre-warning of developing faults is possible. Problems such as arcing due to broken rotor bars, loose connectors, broken conductors (including within the stator) can be found with PD. Corona due to dirty, contaminated or wet windings as well as the development of internal insulation voids can be found and rectified before insulation failure occurs.

From a survey conducted on users using large motors in critical processes, it is clear that this technique for continuous on-line condition monitoring is not yet very popular on large motors. Reasons might be cost, complexity and poor knowledge of the capabilities of such a system.

On-load periodic partial discharge measurement: To allow on-load periodic partial discharge to be performed, capacitive couplers need to be permanently connected to the motor load terminals. High voltage capacitors (also referred to as bus couplers) are physically connected to the motor high voltage terminals. The data measurement and processing equipment are portable and connects to the low voltage output of the capacitive couplers. An operator has to manually connect to the low voltage connectors and measure operational data. The motor needs to be warm and settled to get reliable data.

Only approximately 10% of large motors and 44% of users that were surveyed were performing periodic on-load partial discharge monitoring. As Partial Discharge monitoring is only affective on motors operating at a supply voltage higher than 4kV, this condition monitoring tool is only valuable for the largest of the large motors in industry.

Off-line Partial Discharge measurement: 78% of large motor users indicate the use of off-line partial discharge testing during motor outages as a condition assessment tool. Because of the cost associated with installing permanently fitted capacitive couplers, it is more cost effective to perform this test off-line when other tests such as HV testing and Tan Delta testing is performed. Performing it off-line requires and external voltage source which is also required for HV testing and Tan delta testing. The fact that such a large percentage of users perform this test indicates a great acceptance of this technology as a motor condition assessment tool.

Applicable on:
- Squirrel Cage Induction Motor Frames and Rotors
- Wound Rotor Induction Motor Frames and Rotors
- Synchronous Motor Stators Frames and Rotors

Purpose: To identify presence of voids in insulation system at an early stage and trend them over time.

Test Instrumentation:
- PD detector
- Discharge coupling capacitor
- High voltage source

Procedure:

- Test voltage is raised until partial discharge pulses are observed on the display device. This voltage is called discharge inception voltage (DIV).
- Test voltage is raised to the prescribed maximum voltage for the test. At this voltage the peak magnitudes of the positive and negative partial discharge pulses are recorded. For the purposes of these measurements the power frequency voltage cycle should be superimposed on the display.
- The voltage is then decreased until the partial discharge pulses extinguish; this is known as the discharge extinction voltage (DEV). Normally the DEV is lower than the DIV. The voltage is then decreased to zero. The test is repeated on the other phases of the winding as required.

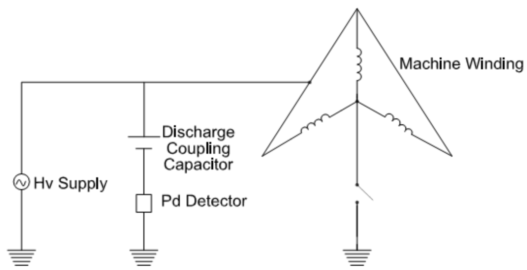


Fig B1-1: Partial Discharge test set-up

Information on the nature of the deterioration mechanisms can be obtained from distribution of positive and negative partial discharges with respect to the power frequency cycle.

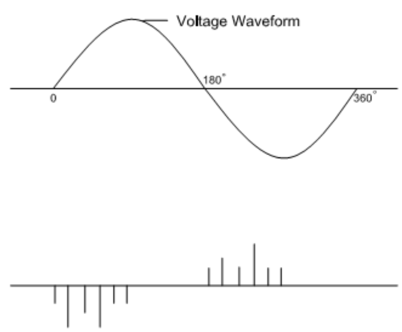


Fig B1-2: PD pulses – Oscilloscope display

Acceptance norm: For interpreting the result of the test highest PD magnitude recorded is important. IEEE 1434 has defined highest PD magnitude associated with peak PD pulse repetition rate of 10 pulses per second (pps).

An equal distribution of partial discharge in the positive and negative half indicates voids in the groundwall insulation.

Predominant positive partial discharge activity is indicative of partial discharge occurring on the surface of the stator bar or coil.

Predominant negative partial discharge activity is indicative of partial discharge occurring at or very close to the copper conductors of the winding.

Refer to IEC 60034-27 for off-line PD testing and IEC60034-27-2 for on-line PD testing.

B2. Corona Probe test (TVA probe)

Introduction: The Corona Probe Test (TVA Probe) is a proximity detector which is sensitive to the RF signals produced by partial discharge (pd) within the winding. The corona probe test is done with the machine off-line, and with at least part of the winding exposed. The corona probe test locates the sites in the stator winding which might be most deteriorated, thus permitting the user to concentrate inspection activities to a relatively smaller area. The ultrasonic probe can often confirm results from a corona probe test.

Applicable on: **-** Squirrel Cage Induction Motor Frames and Rotors

- Wound Rotor Induction Motor Frames and Rotors
- Synchronous Motor Stators Frames and Rotors

Purpose: To detects the exact location partial discharge internal to the coil ground-wall and between the ground-wall and the core.

Description: Partial discharge tests only tells that partial discharge phenomena is happening in stator winding somewhere so winding insulation might be deteriorated but it does not give any indication about where the deterioration has occurred. Location of partial discharge activity can be assured by the use of corona probe test. This test electromagnetically probes each individual stator slot.

Test Instrumentation: Corona probe

Procedure:

- Energize winding or one phase to the test voltage from an external voltage source when machine is stationary. Energize the winding for about one hour so as to stabilize the instrument readings.
- Tune probe detector circuit to suitable frequency (partial discharge frequencies) so as to get optimum selectivity, usually frequency is 5MHz.
- Insert the corona probe into the air gap to bridge a slot about eight centimeters from the end of the slot and record the peak meter reading. Corona probe can be inserted at either end of the winding.

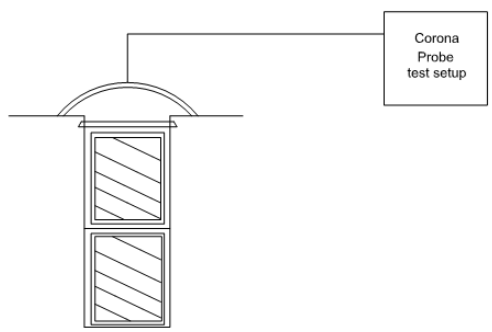


Fig B2-1: Corona probe test

Acceptance norm: Indication in any slot is above 20mA for modern epoxy–mica insulation, suggests significant PD is occurring in that area. Major change in reading from that of previous reading or any abnormal high reading demands further investigation of insulation system. IEEE std 1434-2000 can be used as reference to get idea about the magnitudes of reading.

Fig B2-2: Power Corona probe

Corona probe supplements online PD measurements by more precisely locating the PD to the particular slot and position with winding energized phase by phase using high voltage AC source.

B3. Insulation Resistance, Polarisation Index (P.I.) and Time constant, RC

Introduction [6]
Problems in any electrical insulation are produced by the mechanisms of *conduction* or *polarization* or both. *Conduction* refers to Conductive contaminants which are present at the surface and does not cause chemically change to the insulating materials. *Polarisation* refers to by-products which are the results of chemical reaction. The insulating material itself is changed chemically. Table B3.1 shows classification of problems in machine insulation based on its basic properties.

For decades, problems caused by *conduction* and *polarization* have been detected in combination through the measurement of insulation resistance [7]. Since this is the measurement during the charging of insulation by a constant direct voltage, the current consists of the steady-state *conduction current* (caused by conduction) and time-dependent *absorption current* (due to polarization) which decays exponentially to zero at longer time. At initial time when the *absorption current* is high and dominant, the conduction current is hardly noticed. At longer time when *absorption current* decays to minimum, the steady-state conduction current then becomes obvious. The constant applied voltage divided by the time-dependent *charging current* gives the result of the time-dependent *Insulation Resistance*.

In spite of the name, *Insulation Resistance*, which should have constant value and refer to problem caused by conduction only, it includes the time-dependent Insulation *Polarization* or Dielectric Absorption which refers to problem caused by polarization.

Since many years people are familiar with the test instrument which provides readings in term of *Insulation Resistance* rather than *charging current*. But in order to understand the actual meaning of the results, it is better explained in the term of *current*. Fig. B3-1 shows current during Insulation Resistance measurement. There were many efforts in the past for the calculation of absorption current from the values of *Insulation Resistance* in order to identify problems caused by *conduction* and *polarization* but none has been an easy task before the arrival of PDC Analyzer in 2000 [8]. By the Polarisation Depolarisation Current (PDC) technique, the *absorption current* is the measurement result of the *depolarisation current* (or discharging current). See more details in B4.

Table B3-1:
Classification of problems in motor insulation based on its dielectric nature.

Polarisation	Conduction
By-products of Partial Discharges	Surface humidity
Aging molecules at interfaces	Free water or droplet
Arcing by-products	Surface contaminants
Thermal aging by-products	Tracking
Products of spilled lubricating oil & dust	Carbon dust
Chemical dust including salts	Metal dust
Corrosive products	Debris from fault
By-products from heat & mechanical force	Leakage path
Moisture in adsorbed or molecular state	

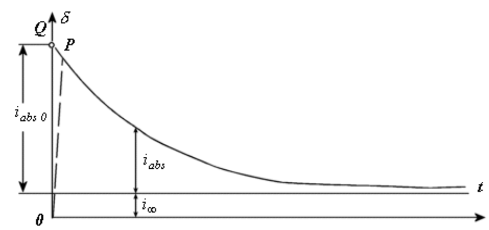


Fig B3-1 Current during Insulation Resistance measurement
The steady-state *Conduction Current* is caused by Conduction phenomena.
The time-dependent *Absorption Current* is caused by Polarization phenomena.
So Insulation Resistance measurement detects both *Conduction* and *Polarization* in combination

One-minute reading of Insulation Resistance and Polarization Index (P.I.): Conductive contaminants (such as free water, surface humidity, droplets on insulation surface, carbon dust, metal dust, debris from a fault, etc.) can cause the *charging current* to be steady as early as one minute. So the one-minute reading of Insulation Resistance has been successfully used by maintenance people since the old days in the detection of *conduction* problems. To make it handier, **Polarization Index (P.I.), a ratio of the reading at ten minutes to the reading at one minute, was introduced as an indicator of conduction level.** When P.I. =1.0 which means the *conduction current* appears as early as 1 minute, the problem caused by *conduction* is severe and needs action. Cleaning and drying decrease *conduction current,* thus cause charging current to be steady at longer than one minute, which means P.I. is higher. But when P.I. is too high e.g. $\geq$ 7, the insulation is overheated. In summary, P.I. is not another measurement but it is the same as insulation resistance with a longer measurement time.

Test instrument for Insulation Resistance: A portable DC voltage supply (insulation resistance tester or Meg-Ohmmeter) is normally used to measure ground insulation of motors.

Test connection for Insulation resistance: All terminals of the stator should be isolated from any connected means. If the star-point of a motor cannot be disconnected, then the ground insulation of all three phases are measured together. When the star-point of a motor can be isolated (which is the preferred way of measuring insulation resistance of motor windings), the insulation-to-ground of each phase can be measured. The two non-tested phases are earthed for safety reason. When the non-tested phases are earthed, the capacitance-to-ground of the tested phase is in parallel to the capacitance between the tested phases and the other non-tested phases. This means two pairs of phase-to-phase insulation are included in the measurement of the ground insulation of the phase under test. However, the current of the ground insulation of the phase under test is dominant since the capacitance of ground insulation of any motor is much larger than the phase-to-phase insulation.

Test voltage: Although the dc test voltage for insulation resistance is suggested as guildlines in IEEE Std. 43 which is presented here in Table B3-2, the test voltage with diagnostic purpose for an in-service or a service-aged machine should be lower than the rated line-to-ground of the stator or rotor under test in order to prevent any deterioration to the insulation. Many manufacturers in the past usually specified a test voltage of 500V in their maintenance manual. 500V is usually enough to detect *conduction* problems in motor insulation. The insulation of other accessories is also tested at 500V. Before the test, the insulation should be discharged long enough to ensure that the results are not influenced by the remaining charges which may be stored in the insulation.

Table B3-2:
Guidelines for dc voltages to be applied during insulation resistance test
(From IEEE Std. 43)

Winding rated voltage (V) *	DC test voltage (V) during Insulation Resistance test
< 1,000	500
1,000 – 2,500	500 – 1,000
2,501 – 5,000	1,000 – 2,500
5,001 – 12,000	2,500 – 5,000
> 12,000	5,000 – 10,000

* Rated line-to-line for 3-phase ac machines, line-to-ground for 1-phase machines and rated direct voltage for dc machines or field windings

Temperature correction: To perform effective monitoring and trending of periodically measured IR values, it is necessary to perform a temperature correction to the measured insulation resistance value. To accomplish this, the tested winding temperature must be measured the same time at which the IR test is carried out. The formula explained in 'Appendix C' can then be used to perform a temperature correction of the measured IR value to a standard temperature for trending and evaluation purposes.

Acceptance norm: Recommended minimum insulation resistance values and P.I. given by IEEE Std. 43 are presented in Table B3-3 and B3-4. While the value lower than the recommendation means the insulation has big problem and unacceptable to be in service, the value higher than recommendation does not always mean the insulation has no problem. Insulation resistance is sensitive to conductive contaminants. Insulation may have other problems and requires other diagnostic tool.

The polarization index (PI) cannot be used **alone** for the judgement of insulation condition. It should be interpreted in conjunction with the insulation resistance since it is also influenced by the characteristics and the design of the insulation. The insulation resistance itself describes the quality, though it also depends on the capacitance value. The comparison of insulation resistance can only be made among similar part of insulation having similar design. The resistance of phase-to-phase insulation shall not be compared with the resistance of ground insulation due to their much differ in capacitance.

Table B3-3:
Recommended minimum insulation resistance values at 40 °C (all values in MΩ)
(From IEEE Std. 43)

Minimum insulation resistance (megohms)	Test specimen
$IR_{1\,min}$ = kV + 1	For most windings made before about 1970, all field windings, and others not described below
$IR_{1\,min}$ = 100	For most ac windings built after about 1970 (form wound coils)

Notes:
1. $IR_{1\,min}$ is the recommended minimum insulation resistance, in megohms, at 40 °C of the entire machine winding
2. kV is the rated machine terminal to terminal voltage, in rms kV
3. It may not be possible to obtain the above minimum IR1 min values for stator windings having extremely large end arm surface areas, those in large or slow-speed machines, or for dc armature windings with commutators. For such windings trending of historical IR1 min values can be used to help evaluate the condition of their insulation
4. The values in the Table may not be applicable, in some cases, specifically when the complete winding overhang is treated with some grading material

Table B3-4:
Recommended minimum value of P.I.
(From IEEE Std. 43)

Thermal class rating	Minimum P.I.
Class A	1.5
Class B	2.0
Class F	2.0
Class H	2.0

Time constant, RC: In order to compare insulation condition among different types of materials and different design, the time constant, RC is introduced. It is the product of time-dependent insulation resistance and capacitance at 50 Hz. The larger this time constant, the better the insulation quality

For interpretation of the insulation resistance results and P.I. it is more understanding to look or explain in term of polarisation current (or charging current) in conjunction with depolarisation current (or discharging current). Details are in B4.

B4. Polarisation Depolarisation Current (PDC) measurement with its evaluation of tan delta & Capacitance

This motor insulation condition monitoring tool measures the polarisation (charging) current in conjunction with the depolarisation (discharging) current of motor insulation with the purpose of identification between *Conduction* and *Polarisation* in the insulation system, as described in the introduction of B3.

How PDC technique identifies *conduction* and *polarisation* in motor insulation

Figure B4-1 presents the principle of test arrangement for PDC measurement on phase-to-phase and ground insulation of motors. Under a constant direct voltage, the polarisation current (or charging current) consists of conduction current caused by *conduction* plus absorption current caused by *polarisation* while the discharging current consists of only absorption current due to *polarisation* (since conduction current does not exist when there is no power supply during discharging). Absorption current during charging and discharging has the same magnitude but opposite polarity. Capacitive current, though it is high, is not usually mentioned since it appears very short time only during switching. When the motor insulation has very low *conduction*, the polarisation current and the depolarization current will be nearly equal for about one-tenth of the charging time. This is how PDC identifies *conduction* and *polarisation* in motor insulation (or problems which are classified in table B3-1I).

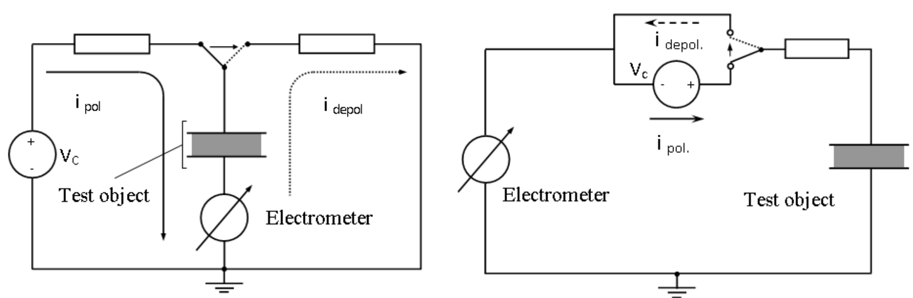


Fig B4-1: Principle of test arrangement for PDC measurement of phase-to-phase insulation (left) and ground insulation (right)

PDC measurement and evaluation results

With a commercial Swiss-made PDC-Analyser based on [8], the PDC software evaluates the *frequency-domain Capacitance (C) and Dielectric Dissipation Factor (DDF) or tan* δ from its PDC measurement results. Other results from the PDC-Analyser include Insulation resistance and Polarisation Index. For interpretation of PDC results presented later, both the time-domain PDC measurement results and the frequency-domain PDC evaluation results of C & DDF are obtained from this PDC-Analyser. Due to the ability of PDC in measuring current as low as 1 pA (10^{-12} A) with high precision, the test voltage can be very low e.g. the ground insulation of the stator is tested at the voltage of 50 V - 200V. This ensures the insulation is not deteriorated by the test stress.

Test Connection for PDC measurement

For large motors which star-point of the stator can be isolated and disconnected from earth, the measurement of both phase-to-phase insulation and ground insulation can be performed. Unlike the AC test, there is no need to bond the line and neutral of each phase together during PDC measurement. The test can be made on either line or neutral terminal. All connected devices shall be disconnected from the motor terminals.

For PDC test on phase-to-phase insulation, the voltage is applied to one phase while the current is sensed from another phase. The non-tested phase is earthed. The ground reference of the PDC shall be connected to the same point where the stator frame is earthed, in order to prevent any potential difference which may cause unhealthy measurement. For PDC test on ground insulation, the non-tested phases are not earthed during the measurement due to the very low voltage used by the PDC-Analyser. This is an advantage because ground insulation of each phase can be assessed individually without having phase-to-phase insulation in parallel like those high voltage tests (which require non-tested phases to be earthed).

In case the star-point of motors cannot be isolated, only one test of three phases to ground can be performed.

Factors which influence the PDC measurement results

It is important that the winding temperature is stabilized during the measurement. For large motors, the time required for the temperature to be cooled and stabilized is longer than the discharge time. For the PDC-Analyser, the remaining charges stored in the insulation can be assessed by measuring the depolarization current without any voltage application. When the depolarization current is stable, the insulation cannot be further discharged. This stabilized remaining current (or background current) can be applied to the actual measurement results later in the correction process, in order to obtain the accurate PDC measurement results for evaluation.

Surface contaminants can influence the PDC measurement results so it is a good practice to clean all motor terminals before test. Outdoor motors are also influenced by air humidity and a sunny day will ensure internal insulation is assessed.

Interpretation of PDC Results and Acceptance criteria

Interpretation of PDC results

Supatra Bhumiwat proposed in [26], [27] three diagnostic parameters to be used together in the interpretation of PDC results of motor stators and rotors, which are *PDC shape*, *C ratio* and *DDF*.

PDC shape: It has been mentioned above how *conduction* and *polarisation* can be identified by the PDC. The difference in shape of polarisation current and depolarisation current at the same time scale means conductive contaminants which can be easily refurbished by cleaning and drying. The similarity in shape of both currents at the same time scale refers to *polarisation* and it means problem has caused chemical change (or by-products) or deterioration in the insulating material which is irreversible process in some cases e.g. thermal aging, discharge by-products, etc. But in some cases such as chemical dust or corrosive by-products, special solvent can successfully stop the degradation process. PDC shapes for different types of aging are shown in case studies.

C ratio: C ratio is used in the interpretation instead of C, which varies from one machine to another. C ratio is the ratio of capacitance at corresponding frequency to capacitance at 50 Hz. When the insulation system contains negligible amount of deterioration products (has no *polarisation* problem), the capacitance value is constant from 50 Hz towards low and very low frequencies. In another words, C ratio =1.00. While *polarisation* increases C ratio, *conduction* does not. So the C ratio is the key parameter in telling whether the insulating material has been deteriorated.

DDF: Both *conduction* and *polarisation* increase DDF. So this is not the parameter to indicate deterioration of insulating material. But it is the important key to indicate the insulation condition such as good or bad, no matter what the cause of problem is.

The details for interpretation are presented through case studies of motors having different aging types.

Acceptance criteria

While the type of insulation aging is identified by the PDC shape, the acceptability of motor insulation is decided by C ratio and DDF. Fig B4-2 presents the suggested in-service criteria of C ratio and DDF proposed by Supatra Bhumiwat in [27], for both phase-to-phase insulation and ground insulation of the stator of rotating machines at winding temperature 20-35^{o}C. Voltage rating of a rotor is usually much lower than a stator. Although the criteria are not applicable to rotor, they can be used as a guideline of how bad the insulation is.

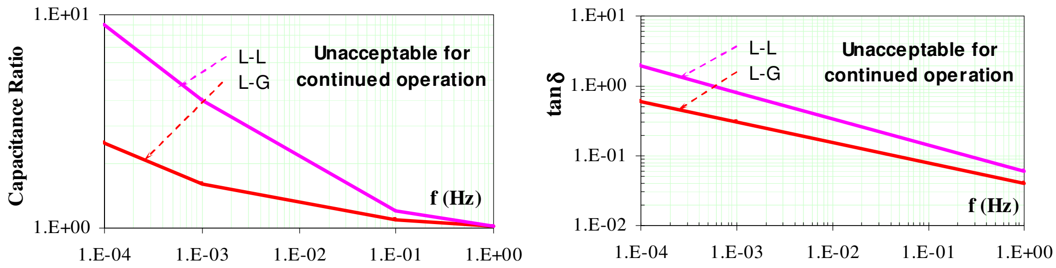


Fig B4-2: Suggested in-service criteria for PDC evaluation of C ratio & tan delta for phase-to-phase (L-L) and phase-to-ground (L-G) insulation of motor stator

Identification of insulation problems through Case studies (Fig B4-3):

The three diagnostic parameters of dielectric responses, PDC shape, C ratio and DDF, from the measurement and evaluation results of the Swiss PDC Analyser [8] are presented in each case study of Fig B4-3. The suggested criteria are included in each C ratio chart as well as DDF chart.

<u>Case 1</u>: A motor stator having good insulation

PDC shape: Polarisation current and depolarization current are straight in log-log scale and quite similar for about one-tenth of the charging time. This means *conduction* in this motor stator is low.

C ratio: C ratio slightly deviates from 1.00 at very low frequencies e.g. at 1 mHz. C ratio at 0.1 Hz is also closer to 1. This means the motor insulation has only slight deterioration.

DDF: DDF at 1 Hz is far lower than 0.01 and slightly increase towards low frequencies. The whole DDF is much lower than the suggested in-service safe limit for continued operation.

<u>Case 2</u>: Problem of Moisture in the insulation but the surface was cleaned and dried

PDC shape: PDC shape is just like good insulation of case 1, with polarisation and depolarization currents straight in log-log scale and quite similar for about one-tenth of the charging time. This means *conduction* in this motor stator is low (since surface humidity and conductive contaminants were removed by drying & cleaning). But if there is a good sister unit to compare or a previous good finger-print, it will be obviously seen that the magnitude of both currents are still very high after drying.

C ratio: C ratio is much deviated from 1.00 and exceeds suggested limit for in-service motor. Moisture in the adsorbed state or molecular state is the case that C ratio can be the highest among all other aging problems due to very high permittivity of water. This case of moisture is different from free water or surface humidity which is classified as conductive contaminants (*conduction*) because conductive contaminants without moisture in the adsorbed state or without other problems do not increase C ratio.

DDF: DDF reveals the insulation system has problem. The values exceed suggested limit line.
This case of moisture in the internal insulation without free water or conductive contaminants is the case that Insulation Resistance and P.I. are not sensitive to. Without comparing with its sister units, the Insulation resistance in fig B4-4 looks acceptable because capacitance of this motor is not high. The P.I. (between 1 and 10 min.) is also high since the problem is caused by *polarisation*, not *conduction*. Nevertheless, time constant RC, C ratio and tan δ reveal the insulation is in bad condition.

<u>Case 3</u>: Problem conductive contaminants

Conduction or problem with conductive contaminants is the problem which Insulation Resistance and P.I. are sensitive to. In this case study, the rotor having problem belongs to the same motor in case 1 which has good stator insulation.

PDC shape: The steady-state conduction current is obviously seen from the polarisation current. The earlier the polarisation current separated from the depolarization current, the worse the condition of the insulation is caused by *conduction*. Although *conduction* is the major problem of this rotor, it is not the only problem (otherwise C ratio will be close to 1.00). If the past results are available to compare the current magnitude of the depolarisation current (or absorption current), it may reveal moisture as mentioned in case study 2 is another problem. Nevertheless there is also some other problem caused by *polarisation* because the depolarisation current is deformed from a straight line. (As mentioned in case study 2 that moisture in the adsorbed state increases magnitude but does not change the PDC shape.)

C ratio: C ratio starts to deviate from 1.00 at 1 Hz and higher towards very low frequencies. The results are about the suggested limit. This confirms the problem with conductive contaminants is not the only problem; otherwise the C ratio should be about 1.00.

DDF: DDF at 1 Hz is less than suggested limit then the values increase at lower frequency and exceed suggested limit at about 0.1 Hz. The steadily increase of DDF from 0.01 Hz towards very low frequencies is caused by conductive contaminants.

Since a rotor has much lower voltage rating than a stator, the criteria may be used as reference only.

Case 4: Problem of thermal aging or overheating

PDC shape: Polarisation current and depolarisation current are very similar and have one prominent crook. At initial time both currents are straight in log-log scale up to e.g. about 60 s or one minute for this motor. After that the currents have bending shape towards lower magnitude (or higher insulation resistance). Because of this bending shape, P.I. is very high (> 7).

C ratio: C ratio increases from 1.00, higher towards very low frequencies. C ratio in this case is not so high as the case of moisture in case study 2. If there is no other problem, C ratio is within suggested limit in most cases.

DDF: DDF increases from 1 Hz towards lower frequencies but the increase rate is lower at about frequency lower than 0.01 Hz and becomes quite constant at frequency closer to 1 mHz. This motor still has acceptable condition but improvement of cooling system would be a good idea.

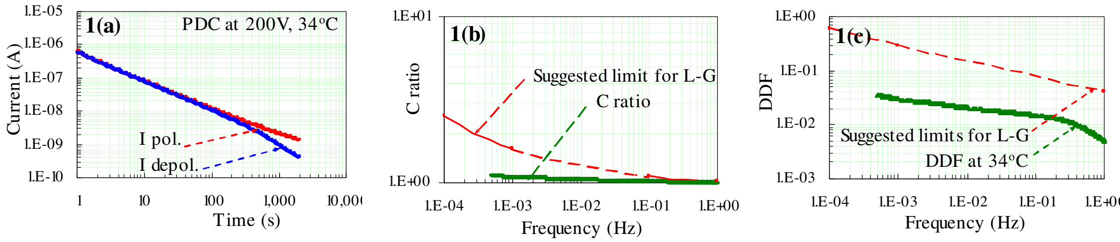
Case 5: Abraded insulation due to combination of partial discharges, thermal and mechanical stresses

These are the results about 3 months before the ground fault of this motor stator due to abraded insulation.

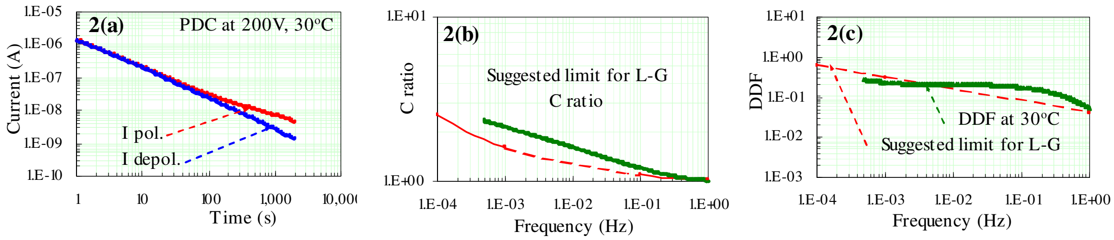
PDC shape: Both polarisation current and depolarisation current are very high and very similar at the initial time of about 20 seconds, which refer to absorption current due to *polarisation*. Erosion of stator coils (mostly due to vibration) and some by-products of slot discharge increased the absorption current. There is a change of slope (or bending) at this short initial time which means an interface.

C ratio: C ratio shows deterioration of insulating materials.

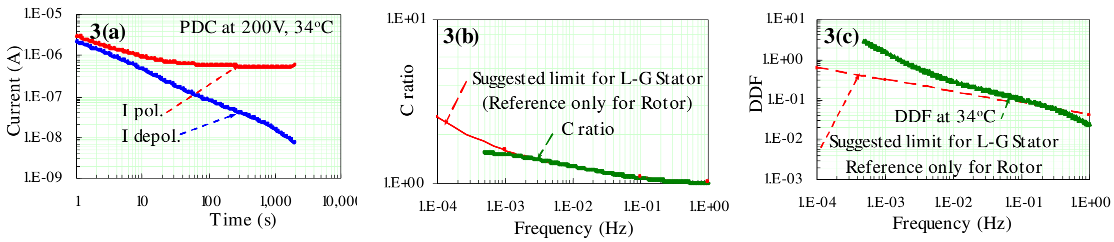
DDF: DDF is approaching the suggested limit for safe operation.



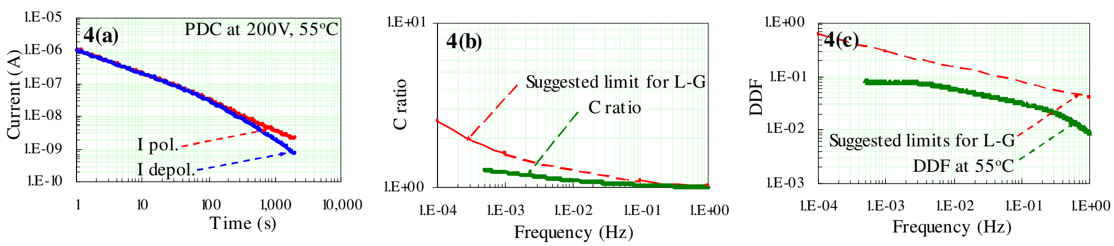
Case 1. Ground insulation of an in-service motor stator in good condition



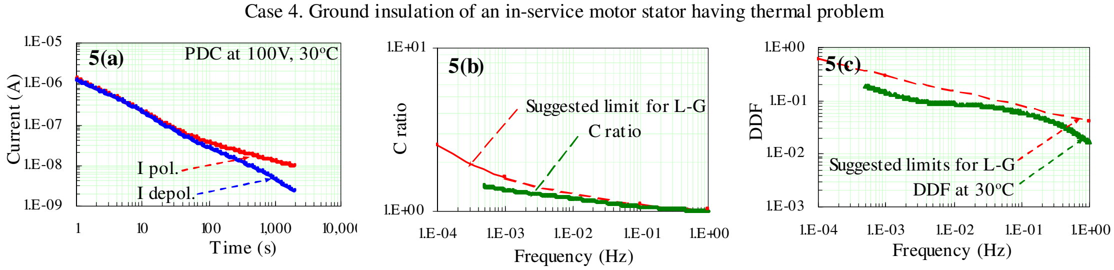
Case 2. Ground insulation of an in-service motor stator having problem of moisture (without surface humidity)



Case 3. Ground insulation of an in-service motor rotor having problem with conductive contaminants



Case 4. Ground insulation of an in-service motor stator having thermal problem



Case 5. Ground insulation of a motor stator 3 months before ground fault due to abraded insulation

Fig B4-3: Dielectric response results of motors in various insulation aging types & conditions (5 case studies):
(a) PDC (b) C ratio (c) DDF

Fig B4-4: PDC-Analyzer during PDC measurement
on ground insulation of 11 kV, 1,550 kW Motor

From international survey: Only 33% percent of the surveyed users performing condition monitoring on large motors used PDC as a method to determine the condition of motor windings. The technique is very effective and can be used to accurately determine the condition of motor windings as well as perform effective fault diagnostics as different problems is identified by different characteristic PDC curves in combination with capacitance ratio and Dielectric Dissipation Factor (DDF) [6] [7] [8] [24].

The fact that the usage of such a technique is relatively low to other methods can be contributed to the fact that specialised equipment is required to perform the test and also the fact that the test is not well known to all users across the world, therefore experts for the successful evaluation of test results from PDC testing are not many. This testing technique proves from research and applications to be a very effective tool and can be used as a successful technique in determining motor insulation condition.

B5. Capacitance & Dielectric Dissipation Factor (DDF) in term of tan delta or power factor including power factor tip-up (Conventional measurement)

Introduction: The condition of the insulation in a motor winding may be estimated by treating it like the dielectric in a capacitor. The capacitance and power factor of all or part of a winding is measured by applying an adequate voltage ac power supply and using a capacitance bridge.

The conventional measurement of capacitance and tan delta or power factor at 50 Hz (or 60 Hz) can be done on entire windings, phases, or individual bars/coils. An increase in the capacitance over time, or higher capacitance in one coil/bar as compared to others, may indicate that there is water within the insulation. A decrease in the capacitance can indicate abrasion of insulation (especially the phase-to-phase insulation), thermal aging i.e. the groundwall has been delaminated. The increase of tan delta or power factor at power frequency can be caused by *conduction* or *polarisation* or both.

The capacitance of thermally deteriorated insulation decreases over time, whereas the dissipation factor increases. In contrast, if the winding has been contaminated with partly conductive oil or water, both the capacitance and dissipation factor increase. Windings in good condition will have a stable capacitance and dissipation factor over time. High dissipation factor means higher dielectric losses.

The test instrument which is used to test tan delta or power factor is always able to measure Capacitance.

The power factor test can be performed on any high voltage stator winding of any size or rating. The test requires an outage for at least one half day. By itself, a single power factor (or tan delta or dissipation) measurement on a complete winding is of limited use. The power factor test is most useful when done at both low and high voltage.

Usually the power factor (pf) will increase as applied voltage is increase, i.e. tip-up. The greater the increase, greater the partial discharge activity within the insulation. Thus the tip up test can be sensitive to delamination discharge and endwinding discharge.

Description of Power-factor tip-up: The dissipation factor (or power-factor) tip-up test determines the void content in the insulation. The dissipation factor increases with an increase in the void content of insulation. The test is performed by measuring power factor (or tan delta) at different voltages. A set of readings is obtained, which forms an ascending curve. A fast change of insulation power factor with increasing voltage tends to indicate a coil with high void content.

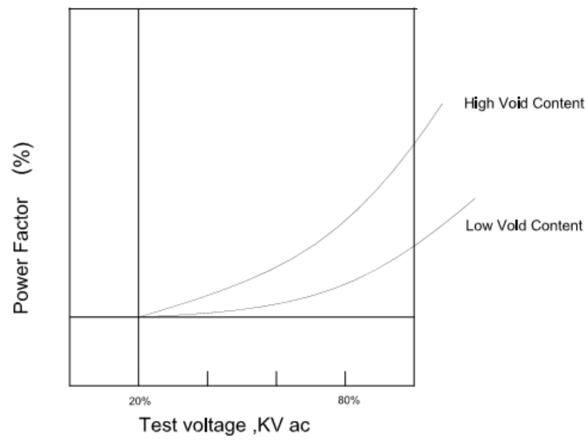


Fig B5-1: Power factor tip-up

Test Instrumentation: - AC high voltage power supply and

- A means of measuring the dielectric loss in the stator winding.

Procedure: Test voltage equal to 20% of the nominal line-to-ground voltage of the winding is applied to phase under test while other two phases are grounded. Power factor is measured.

Test voltage is increased to full nominal line-to- ground voltage of the winding and power factor is measured again. The power factor tip-up is defined as the ratio of the difference between power factor at high voltage (100% or 80% of rated voltage line to ground) and power factor at low voltage (20% rated line to ground voltage) to power factor at low voltage (20% rated line to ground voltage) . Upon completion of this measurement, the voltage should be reduced to zero and the winding shall be grounded.

Acceptance norm: As a general guide, the tip-up on an epoxy (or polyester) mica winding may be of the order of 1%. Older asphalt type windings can have tip-up values up to 5%.

B6. High Potential (Hi-pot) testing

Introduction: The general notion is to move away from periodic High Voltage (HV) testing on motors due to its destructive nature and to only perform it after major repairs and/or services. Users prefer to use other more modern techniques to evaluate winding insulation condition although users are still not completely confident that these alternative techniques can give sufficient information on winding insulation condition. From a global survey it is therefore clear that high voltage testing is still an important test to assist with proper prognosis on remaining motor life. 56% of users indicated the use of high voltage testing as a way to determine motor insulation condition.

HV testing is mostly performed on new motor windings, be it a new motor or refurbished motor. Routine testing on motors with used windings is not common practice but is used by some users. It is important to know the history of a motor winding before high voltage is applied. The value of the voltage must also be carefully selected as overstressing of old insulation will result in insulation breakdown, resulting in a costly repair. The risk of applying high voltage to a motor winding must always be carefully evaluated. Information such as the availability of a replacement spare motor, duration to repair should it fail and impact on production must always be evaluated prior to applying high voltage.

A selection between line frequency test voltage, low frequency test voltage (typically 0.1Hz) and DC test voltages is also necessary. AC test voltages are more favourable towards the testing of AC motor windings as the stress grading on the motor insulation is also exposed to the stresses it will be exposed to when in operation. DC test voltages might be a substitute but the test voltage needs to be increased to resemble the voltage amplitude that AC equipment stresses a motor winding to. A typical factor of 1.7Un is used to increase the DC test voltage above AC test voltage.

DC is also very dangerous if not discharged properly and can lead to the loss of life if a charged winding is not discharged completely prior to touching motor terminals. International standards such as IEC60034, BSEN50209, IEEE Std 95 must be considered prior to testing motors with high voltage, especially when DC is used. Internal procedures guiding test personnel on safety requirements as well as allowable voltage levels and risk assessment requirements must be in place prior to the performing high voltage testing on motors.

The two different streams of high voltage testing is explained in the following two sections:

B6-1 Controlled direct overvoltage tests (DC Hi-pot test)

Purpose: To ensure adequacy of insulation system electrical (dielectric) strength. A substantial higher D.C. Voltage is applied on the winding conductor to ground. The DC leakage current, gives quantitative information about condition of coil insulation deterioration and localized incipient failures.

Description: Test is performed to determine whether the winding is capable of sustaining the rated voltage level without insulation breakdown.

The recommend test voltage level is (2 X $V_{L\text{-}L}$ + 1) X 1.7 kV dc for new windings. The recommended test voltage level for maintenance purpose is 125 to 150% of (1.7 X $V_{L\text{-}L}$) kV dc.

The leakage current is plotted against dc voltage applied to give early warning of any impending insulation breakdown. When dc voltage is applied to the winding, a time-dependent flow of current is established. This current has a constant component, called the conduction or leakage current, and an initial component, called the charging or absorption current. Therefore it is advisable to raise the voltage to the first level of the kV/min rate, hold for 10 minutes to get beyond the charging phase of the voltage application, and test while dealing primarily with the leakage current. This way the charging current influence on the leakage current rate of rise will be minimized.

Test Instrumentation: **-** High voltage DC generator set up

- Portable DC equipment using inverter/converter technology

Procedure: The testing is done after isolating the test machine from power cables, isophase bus, transformer etc. which are not intended to be tested. Ensure that all RTD'S and CT's are shorted and grounded. Before carrying out test ensure that PI value for test machine is greater than 2.

Test voltage is applied to one of the phases with its ends shorted while other two phases are grounded with their ends shorted together.

Three types of voltages can be used for test:-

- Step voltage
- Time graded voltage
- Ramp voltage

For Stepped overvoltage test voltage level used to determine PI is considered first step and then further increased in steps of 1kV. Each level is held for period of 1 min before moving to next step.

For Graded-time overvoltage test time schedule of applied voltage is determined as per IEEE std 95-2002. Usual voltage steps are 20% of the level used for PI determination.

For Ramp overvoltage test rate of rise of test voltage is 1 kV/min. Ramp in voltage starts at the voltage level where the ten minute PI test is performed and is actually a continuation of that test.

Precaution to be undertaken: The energy stored within the test specimen may be lethal and shall be dissipated safely.

Acceptance norm: A plot of current vs. voltage should be recorded on a log scale and should be nearly linear. Faster rise of current compared to voltage indicates possibility of insulation breakdown and test should be stopped. While contrary observations i.e. rate of current rise lower than Voltage increase rate suggests problem with test setup.

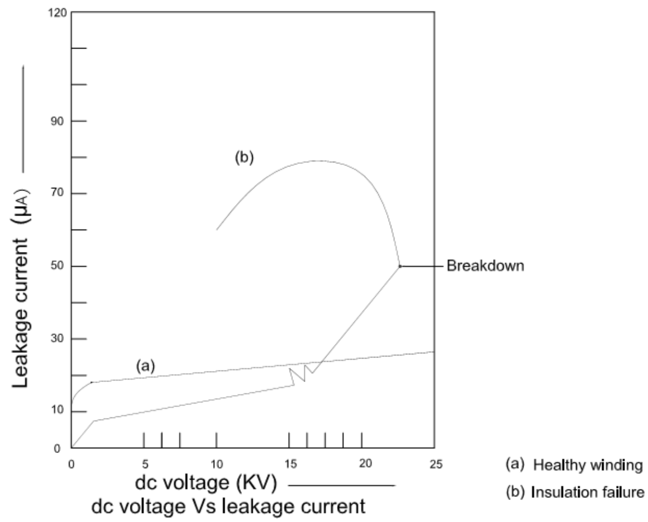


Fig B6-1: A plot of current vs voltage from the test results of DC Hi-pot

B6-2 Overvoltage proof tests (AC Hi-pot test)

Purpose: Determine condition of conductor insulation

Description: The ac hi-pot test is performed to determine whether the winding is capable of sustaining the rated voltage level without insulation breakdown. The test consists of applying high voltage to the winding (the three phases together, or one at a time, with the other two grounded) for one minute.

The recommend test voltage level is (2 X V_{L-L} + 1) kV ac for new windings. The recommended test voltage level for maintenance purpose is 125 to 150% of V_{L-L} kV ac although this test voltage must be carefully selected based on the age of the motor, spares availability, criticality of motor, etc.

DC proof testing of the machine requires small, relatively inexpensive test set. But DC test stresses the end winding insulation to relatively higher value compared to the ac voltage stress it experiences during service. AC power frequency proof testing requires relatively bigger test set-up. So the intent behind the 0.1 Hz test was to overcome the limitation of both DC and Power frequency AC proof testing.

Test instrumentation: **-** Test voltage generator setup

- Test transformer with variable output voltage control
- Portable low frequency AC equipment using inverter technology

Procedure:

1. Isolate the test winding specimen from all other windings and equipment's not intended for test. Ensure grounding of test set frame, ducts, shield or any nearby hardware.
2. The magnitude of the test voltage is determined using IEEE Std 95-2002 and ANSI C50.10-1990 as guides.
3. Test voltages (AC or DC or 0.1 HZ AC) are gradually increased starting at less than 5% of final test value to selected test value.
4. When selected test voltage level is reached it is held at that point for 1 minute and then gradually reduced to zero.
5. Precaution to be undertaken: The energy stored within the test specimen may be lethal and shall be dissipated safely.

Acceptance norm: The DC, 0.1 Hz, 50 Hz and 60 Hz overvoltage proof tests are pass/fail tests.

B7. Turn-to-turn insulation test (surge test)

Introduction: Surge tests function as hipot tests to check the integrity of the stator winding interturn insulation, as well as to test the capability of the groundwall insulation to withstand steep-fronted transients likely to be encountered in normal service. Guidelines for the magnitudes and the front time of the surges for the test have been given in IEEE Working Group reports or guides [IEEE Std. 522-1992] and other specifications. The surge tests are normally used to test new windings in the factory or to detect if a fault exists in a machine before repair.

The surge test applies a voltage to the turn insulation for a very short time, causing weak insulation to fail. Thus the surge test is a hipot test for the turn insulation, rather than a diagnostic test to determine the relative condition of the turn insulation.

Applicable on: **-** Squirrel Cage Induction Motor stators

- Wound Rotor Induction Motor Stators and Rotors
- Synchronous Motor Stators and Rotors

Purpose: To avoid damage to motor windings and cores due to presence of turn to turn short.

Test Instrumentation: Surge coil setup

Description: If a rapidly increasing current is applied to a coil, a voltage will be generated across the coil by the principle of induction. The voltage across the coil is given by

$$V=L*di/dt$$

Where

'V' is the terminal voltage across the coil,

'L' is the coil's inductance, and

The time rate of change of current pulse is 'di/dt'.

The terminal voltage V at the leads of the coil is actually a summation of the induced voltage created between individual loops in the coil. If the insulation separating adjacent coils is weak and if the induced voltage is higher than the dielectric strength of the weak insulation, an arc will form between the coils. Surge testing equipment is designed to create the induced voltage between adjacent coils and detect the arcing indicative of weak or failing insulation.

Some factors causing the insulation to age include: thermal cycling, vibration, mechanical movement of coils abrading insulation, chemical attack, partial discharge, exposure to damaging transients, exposure to radiation, VFD operation, etc.

The turn-turn voltage distribution of a surge pulse is not linear across the windings of a coil being tested. A fast rise time pulse will induce a higher turn-turn voltage at the tested end of the coil than at the grounded end of the coil. The greater turn-turn voltage at the tested end of the coil is due to the wave propagation effects of the high frequency components in the surge impulse as the pulse moves through the winding.

Due to this phenomenon, IEEE 522 recommends different test voltages for different rise time pulses. For pulse rise times of 0 to 100ns, the recommended test voltage is 1pu. For pulse rise times between 100ns and 1.2µs, the recommended test voltage is 3.5pu. For pulse rise times of 1.2 µs or longer, the recommended test voltage is 5 pu.

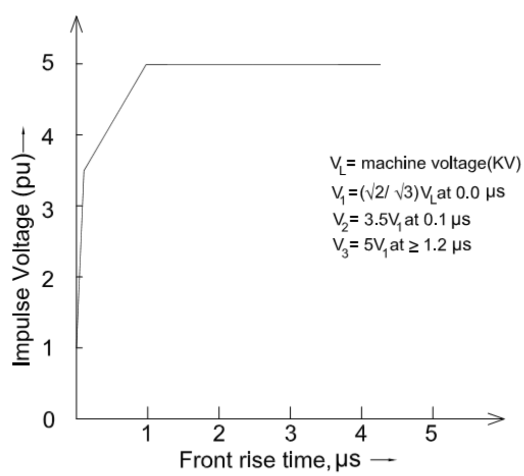


Fig B7-1: Recommended Surge test voltage vs Pulse rise time

Switching on a motor causes a fast rise time voltage surge to hit the stator winding terminals. Similar voltage surges occur from IFDs and faults in the power system. These fast rise time surges result in a non-uniform voltage distribution across the turns in the stator winding.

As an acceptance test, the surge is recommended to have a rise time of 100 ns and a maximum magnitude of 3.5 per unit, where 1 per unit is the peak line to ground rated voltage. For a maintenance test performed after the winding has seen service, the surge should have the same rise time, but reach only 2.6 per unit.

Table B7-1 below shows the recommended test voltages from the different organizations.

Table B7-1: Recommendation test voltage for Surge test

		IEEE 522		EASA	IEC34-15	
		New Coils	In Service	In Service	1.2 x 50µs	0.2µs
V_{Line}	Per Unit	3.5pu	75% New	$2*V_{line}+1000$	$4*V_{line}+5000$	65%
480	392	1372	1029	1960	6920	4498
575	469	1643	1232	2150	7300	4745
600	490	1715	1286	2200	7400	4810
2300	1878	6573	4930	5600	14200	9230
4160	3397	11888	8916	9320	21640	14066
6900	5634	19718	14789	14800	32600	21190
13800	11268	39437	29578	28600	60200	39130

Procedure:

Figure B7-2 below shows the test arrangement for surge test. Capacitor is charged to known voltage level using high voltage power supply. Charge from the capacitor is transferred to the windings of the coil by the closure of HV switch (IGBT type) at a specific time instant.

If the resistances and loss of the entire circuit are such that the system is under damped, charge will be able to flow through the inductor and on to the other side of the capacitor resulting in an oscillation This process of ringing will repeat until the resistances and losses in the circuit completely absorb all of the energy that was originally on the capacitor.

The measurement of the terminal voltage of the coil vs time gives the surge waveform, which shows the damped oscillation.

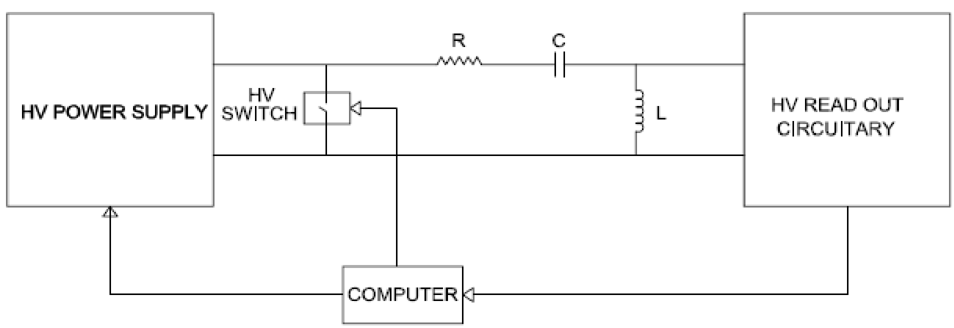


Fig B7-2: Surge Test set-up

The ringing frequency of the dampened sinusoidal waveform will be according to the following formula:

$$f = \frac{1}{2\pi}\sqrt{\left(\frac{1}{LC} - \frac{R^2}{4L^2}\right)}$$

If the turn-turn insulation fails with an arcing short between two turns in the coil, a fraction of the inductance will be shorted out of the circuit. From the equation above, the ringing frequency f will increase as the inductance decreases due to the short. An increase in the ringing frequency will show itself to be a jump to the left of the ringing pattern.

This increase in ringing frequency is the indication of the arcing turn-turn fault. Test instrumentation slowly increases the test voltage and looks for the increase in ringing frequency.

Acceptance norm: Pass/fail test

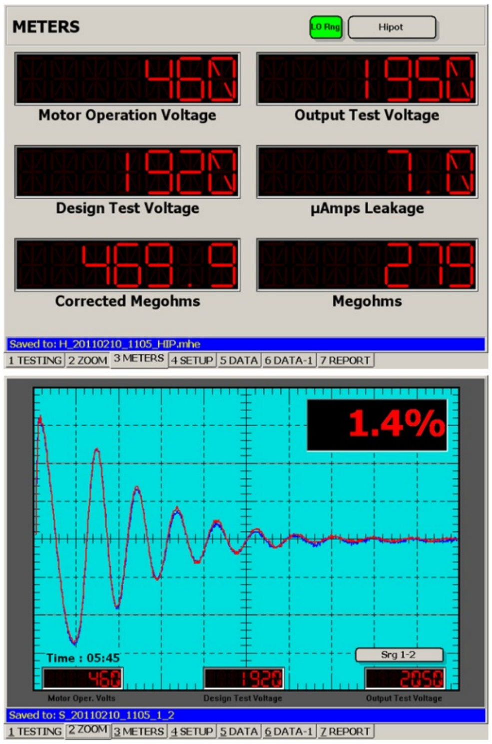


Fig B7-3: During Surge Test of stator coil

B8. Stator core low energy test (EL CID)

Introduction: Traditionally, motor core insulation has been tested for imperfections by means of a rated flux test. This conventional test requires an adequate supply to provide the relatively high power levels required by the excitation winding which has to induce rated flux in the area of core behind the winding slots. The alternative is the low flux or EL CID test devised by the former Central Electricity Research Laboratories in the UK. The main advantage is that it requires only a small capacity power supply for the excitation winding, since only approximately 4% of rated flux needs to be induced in the core (i.e. about 0.1% of VA required for a rated flux test). In fact, for most tests the power supply can be obtained from a 120/240 V ac wall socket source. At this level safety constraints are also much reduced. A further advantage is the ability to readily detect faults behind windings. The test normally takes much less time than the rated flux test and may be the only test practicable in a short outage.

Applicable on: - Squirrel Cage Induction Motor stator Cores

- Wound Rotor Induction Motor Stator Cores
- Synchronous Motor Stator Cores

Purpose: To check the condition of interlaminar resistance between stator core punchings.

Description: Since only 3 to 4 % rated flux is induced in the core during low energy core test, it requires much lower capacity power supply when compared to High energy core test (discussed later). 120 or 220 V power supply can be used with this test. Also In comparison to high energy core test time required to perform this test is significantly lower. Condition of inter-laminar insulation is judged in this test by measuring the magnitude of axial fault current in the core set up by use of excitation coil. But use of excitation coil also results into generation of circumferential magnetic field. There is a phase shift between the excitation winding flux and that produced by axial fault currents since these currents are at 90° to one another. With use of signal processing circuit it is possible to detect the output voltage proportional to axial fault current only.

Test Instrumentation: - Suitable power source

- Exciting loop with instrumentation
- Search coil loop with metering

Procedure: In this test the motor core is excited with low energy magnetic field obtained by using an excitation loop. The resultant induced currents in interlaminar stator core insulation are measured.

- Excite the core with weak magnetic flux using excitation loop.
- Scan each slot one by one with the help of search coil (Rogowski type coil) and current readings are taken.

Acceptance norm: Current response greater than 100mA suggest core insulation damage and further investigation is needed.

With the advancement in technology now the digital equipment has taken the place of analogue set up used earlier to perform the low energy core test but the basic principle remains the same.

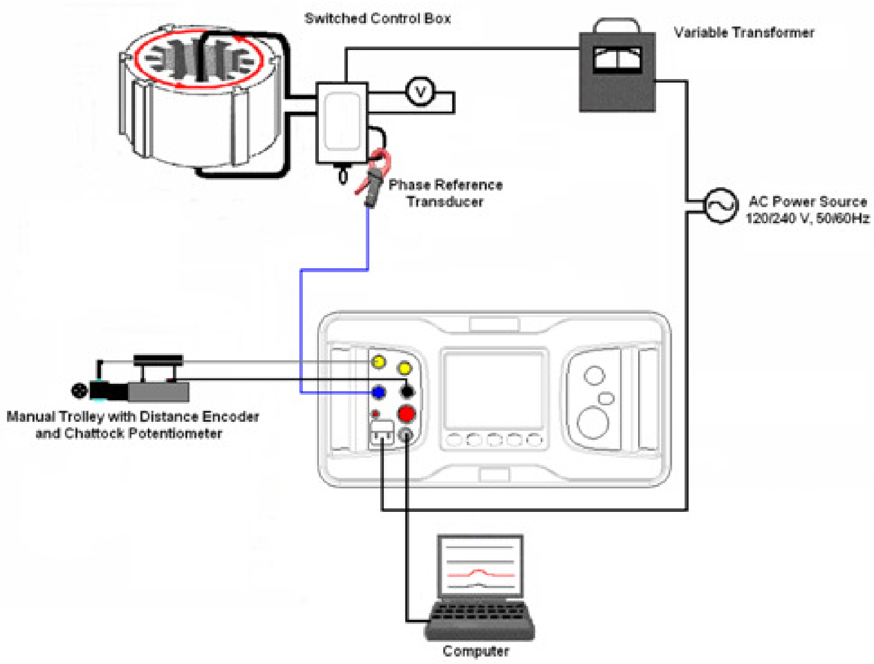


Fig B8-1: Digital Instrumentation for stator core low energy test

Fig B8-2: EL-CID test instrumentation.

Fig B8-3: During Stator core low energy test

B9. Stator core high energy test

Introduction: The rated core flux test (also called the "ring flux" test) is the traditional method of determining the insulation integrity of any type of laminated core in an ac motor. The test can detect hidden damage, assess the severity of damage, and indicate whether repair is required. The major drawback of this test is that it requires machine disassembly and removal of the rotor before it can be performed. As the test is normally carried out at or near the rated flux for the core, this test may aggravate an existing problem.

Applicable on: **-** Squirrel Cage Induction Motor stator Cores

- Wound Rotor Induction Motor Stator Cores
- Synchronous Motor Stator Cores

Purpose: To check the condition of interlaminar resistance between stator punchings.

Test Instrumentation:

- Suitable power source
- Exciting loop with instrumentation
- Search coil loop with metering
- Thermocouples and instrumentation
- Infrared scanning equipment

Procedure: In this test core is tested near the designed flux density range. Usual design range for flux density is 1 to 1.5 tesla.

Excitation cable is wound around the core (as shown in figure). Excitation voltage is adjusted and Search coil voltage is read which is used to determine the core flux density. Test is carried out for the period of two hours and during the test temperature of different parts of core is monitored using thermocouples and infrared scanning equipment. Localized hot spots are detected with infrared scanner.

Acceptance norm: Core temperature rise of 100 °C or more indicates damaged interlaminar insulation.

Temperature difference of more than 10 °C for bore surface hot spot and surrounding ambient background indicates associate iron damage.

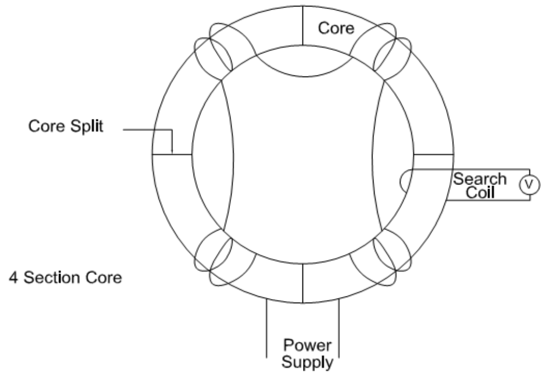


Fig B9-1 Stator core high energy loop test

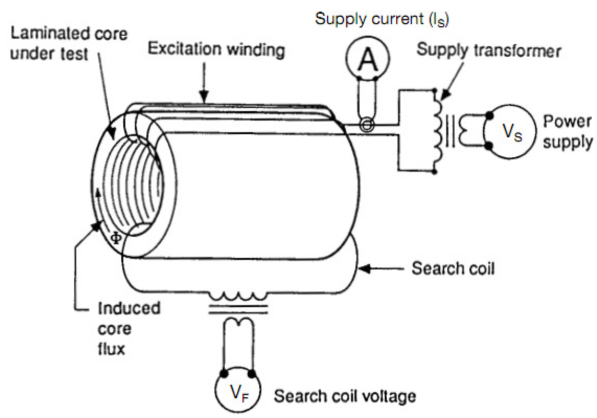


Fig B9-2 Stator core high energy loop test set-up

B10. Stator Core Through-Bolt Insulation Resistance Test

Introduction: Some stator cores have insulated bolts which penetrate through the motor stator core to clamp the core laminations together. If the through-bolt insulation loses its insulating properties, circulating currents between the core laminations and the through-bolts will cause heating to the core which can eventually lead to failure of the core.

Applicable: on: Stator cores fitted with through-bolts

Purpose: To check the healthiness of through-bolt insulation

Test instrumentation: DC mega-ohmmeter

Procedure: Using DC mega-ohmmeter stator frame (ground) to through bolt resistance is determined.

Acceptance norm: Core through bolt insulation resistance should be greater than 1 mega-ohm.

B11. Stator Core Flux Shield Insulation Resistance Test

Introduction: Flux shields are insulated from the stator frame as well as stator core. This insulation prevent circulating currents to flow between the flux shield and adjacent components. Circulating currents can cause heat to develop in adjacent components which can lead to component failure.

Applicable on: Large motors with flux shields.

Purpose: To check the healthiness of stator core flux shield insulation.

Test Instrumentation: DC mega-ohmmeter

Procedure: Using DC mega-ohmmeter determine the resistance between adjacent core support plates, between the laminated flux shield and each core support plate, and between the laminated flux shield and the grounded frame.

Acceptance norm: Insulation resistance should be more than 1 mega-ohm.

B12. Turn insulation test for synchronous motor rotor

Introduction: Two tests are used to validate synchronous motor rotor winding i.e. Impedance test and pole drop test.

Applicable to: Synchronous motor rotor windings

B12-1 Impedance test

Purpose: To detect shorted turns in rotor winding.

Test Instrumentation: AC voltmeter (250V), AC ammeter (50A) and Auto transformer

Procedure: Usually 10 incremental steps of voltage are applied to the winding (magnitude of the voltage step is determined by the capacity of the available test source). At each step current is measured to determine the impedance and plot of impedance Vs voltage is obtained. Presence of lowered impedance on the plot with increased voltage suggests shorted turns. Change in magnitude of impedance can be used to get the number of shorted turns.

Sometimes it may so happen that shorts are present during running condition only so in this case above test can be carried under running condition of motor.(called as running impedance test)

B12-2 Pole drop test

This test follows the impedance test and uses the same instrumentation. Voltage drop is measured from start and finish end of each coil for each pole. Turn short is indicated by lower voltage drop across the coil from that of the value obtained for the similar coil.

Acceptance norm: Pass/fail test

B13. Bearing Insulation Test

Introduction: Large motor bearings are insulated to prevent circulating currents from flowing through the shaft bearings and the frame. When this insulation fails, large circulating currents can develop causing significant damage to the bearing white metal surfaces, which will ultimately lead to the failure of bearings and subsequently the complete motor.

Applicable on: All large motors with insulated bearings

Purpose: To check the healthiness of bearing insulation. In case of bearing insulation failure induced circulating current might damage the bearing.

Test Instrumentation: Insulation resistance tester or 500 V megger

Procedure: Using 500 V dc applied from shaft to ground, the insulation resistance is determined.

Acceptance norm: Bearing insulation should be greater than or equal to 5 mega-ohm.

Appendix C

Temperature Correction for Insulation Resistance measurement

It is necessary to do temperature correction to insulation resistance measurements. Insulation resistance of insulation material changes significantly with temperature changes. The insulation resistance of insulation decreases as temperature increases. It is therefore necessary to set a standard for insulation resistance at a certain temperature. Insulation resistance should always be corrected to a standard temperature to compare the measured insulation resistance with the minimum acceptable criteria. Ambient humidity at the time of test can also significantly affect the insulation resistance value measured.

Temperature and humidity for all measured insulation resistance values should be recorded. Temperature at the direct area of test should be determined as accurately as possible. Temperature correction for each test result should be done using the following formula:

$$R_C = K_T R_T \qquad [1]$$

R_C is the insulation resistance (in megohms) corrected to 40℃

K_T is the insulation resistance temperature coefficient at temperature T℃

R_T is the measured insulation resistance (in megohms) at temperature T℃

Determining the Temperature Coefficient (K_T)

Recommended method:

The recommended method for determining a value for K_T is to measure insulation resistance at different winding temperatures and plotting the insulation resistance change versus temperature change. If a logarithmic scale is used for insulation resistance and a linear scale for temperature, the test points should approximate a straight line that can be extrapolated to obtain the corrected value at 40℃

Alternative method for approximating K_T:

The general rule is that the insulation resistance will halve for every 10℃ rise in winding temperature. To determine K_T using this rule:

$$K_T = (0{,}5)^{(40-T)/10} \qquad [2]$$

Where

'T' is the temperature at which the insulation was measured

K_T is the temperature coefficient to be used in formula [1] to correct the temperature to 40℃.