

RECOMMENDATION OF MAINTENANCE SCHEDULE BY ANALYSING CONDITION MONITORING TEST DATA OF GENERATORS

Kelum Niroshan Senarathne

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Department of Electrical Engineering

University of Moratuwa
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.....
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.....
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.....
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.....
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Abstract

Condition monitoring is a modern engineering tool developed to assess the status of valuable properties. The thesis describes generator stator winding condition by analyzing three main test procedures, called DC ramp test, Partial discharge test and vibration test. Above mentioned tests were conducted on three main power station attached to Thermal complex of Ceylon Electricity Board in Sri Lanka.

Off line DC ramp test is conducted on the generator stator winding by applying ramped DC voltage. Accordingly total leakage current is plotted against the applied voltage. After obtaining final leakage profile, analyzing is done according to the winding insulation type. Partial Discharge test equipment is installed to monitor electrical discharges due to voids of the stator winding. Those discharges will degrade the insulation and, if not corrected, repeated discharges will eventually erode a hole through the stator winding insulation, leading to failure. Therefore detection and analyzing methodologies discuss throughout the thesis. Finally discuss the importance of introducing PD detection system for identified generators which are more severe effect to generator and the power system.

Some rotating machinery problems show themselves as excessive vibration. It can be identified using online vibration measurement, because vibration signatures show machine's mechanical and electrical conditions. Also it can be identified possible effect to the stator winding.

During the case study, 19 generators were considered in plant wise to assess the condition using above mentioned tools. Tests were carried out to identify the status of generator stator winding and it helps to categorize the degree of acceptability of present condition and planned their preventive maintenance to improve the reliability and availability. Finally preventive maintenance schedule is introducing parallel to the present maintenance plan.

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1 Table of Contents

1	CONDITION MONITORING.....	1
1.1	Introduction	1
1.1.1	Trend monitoring.....	2
1.1.2	Condition checking.....	2
1.2	Condition Monitoring test procedures.....	2
1.2.1	DC Ramp test	3
1.2.2	Partial discharge testing	4
1.2.3	Vibration monitoring testing	6
1.3	Construction of Stator Winding.....	6
1.3.1	Thermal Stress.....	8
1.3.2	Electric Stress.....	9
1.3.3	Ambient Stress (Factors).....	9
1.3.4	Mechanical Stress	10
1.4	Case study	11
1.4.1	Kelanithissa Power Station.....	11
1.4.2	Sapugaskanda Power Station.....	12
1.4.3	Kelanitissa Combined Cycle Power Station	12
2	DC RAMP TEST.....	13
2.1	Instrumentation and Preparation.....	13
2.2	Test Voltage.....	14
2.3	Test Procedure.....	14
2.4	Test Analyzing Methodology	15
2.4.1	Capacitive Current (I_C).....	16
2.4.2	Conduction Current (I_R)	16
2.4.3	Surface leakage Current (I_L).....	16
2.4.4	Polarization Current (I_P).....	17
2.5	Classification of leakage current profile.....	17
3	PARTIAL DISCHARGE TEST	19
3.1	Instrumentation and Preparation	19
3.1.1	Coupling Capacitor	19
3.1.2	Resistive Thermal Detectors (RTDs) Module for PD Detection.....	20
3.2	PD Analyzing Methodology.....	22
3.2.1	Negative polarity	23
3.2.2	Positive polarity.....	23
3.3	Advantages of PD Continuous Monitoring.....	25
4	VIBRATION MONITORING TEST.....	27
4.1	Instrument and Preparation.....	27
4.1.1	Vibration Sampling Points	28
4.1.2	SKF GX Series MX 70 Microlog Data Analyzer.....	28

4.1.3	SKF CMSS2200- Data acquisition equipment	29
4.2	Vibration Analyzing Methodology	30
4.2.1	Identifying of the Machine's Running speed.....	33
4.2.2	Misalignment.....	33
4.2.3	Imbalance.....	34
4.2.4	Mechanical looseness.....	36
4.2.5	Bearing defects	37
5	PREVENTIVE MAINTENANCE SCHEDULING.....	38
5.1	Sapugaskanda power station.....	38
5.1.1	PIELSTICK plant	38
5.1.2	Case study of PIELSTICK plant.....	39
5.1.3	MAN plant	46
5.1.4	Case study of MAN plant.....	47
5.2	Kelanithissa Power Station.....	54
5.2.1	Kelanitissa Small Gas Turbine	54
5.2.2	Case study of small gas turbine	55
5.2.3	Kelanitissa Gas Turbine No7.....	61
5.2.4	Case study of Gas Turbine No7.....	62
5.3	Kelanithissa Combined Cycle Power Station.....	68
5.3.1	Gas turbine of Kelanitissa Combined Cycle Plant.....	68
5.3.2	Case study of Gas turbine.....	70
5.3.3	Steam turbine of Kelanitissa Combined Cycle Plant.....	73
5.3.4	Case study of Steam Turbine.....	74
6	CONCLUSION.....	77
6.1	Review of Sapugaskanda Power Station	77
6.1.1	Review of maintenance schedule of Pielstick plant	77
6.1.2	Review of maintenance schedule of MAN plant.....	78
6.2	Review of Kelanitissa Power Station	78
6.2.1	Review of maintenance schedule of Small Gas Turbine	79
6.2.2	Review of maintenance schedule of Fiat Genarator.....	79
6.3	Review of Kelanitissa Combined Cycle Power Station.....	80
6.3.1	Review of maintenance schedule of Gas Turbine Generator	80
6.3.2	Review of maintenance schedule of Steam Turbine Generator	81
7	REFERENCE	i
8	APPENDIX - A	iii
.	APPENDIX - B.....	v
.	APPENDIX - C.....	vii

LIST OF FIGURE

Figure 1:1 Cross section of a coil winding with an air pocket.....	5
Figure 1:2 Cross section of the coil in a stator slot	7
Figure 1:3 Physical cross section of winding	7
Figure 1:4 Generator life span with operating temperature	8
Figure 2:1 Instrumentation layout of DC ramp test	13
Figure 2:2 DC ramp test result of DG04 of Sapugaskanda Power Station	15
Figure 2:3 Classification of leakage current profiles	15
Figure 2:4 Classification of total leakage with insulation condition	17
Figure 3:1 Layout of PD monitoring sensors.....	19
Figure 3:2 Coupling Capacitor	20
Figure 3:3 RTD or RC temperature sensor mounting	20
Figure 3:4 Interface terminal board for Temperature and PD monitoring.....	21
Figure 3:5 PD test sample	22
Figure 3:6 Classification positive & negative polarity	23
Figure 3:7 Relationship of electrons flow in positive and negative polarity cycle.....	24
Figure 4:1 Vibration monitoring process	27
Figure 4:2 Vibration sampling position.....	28
Figure 4:3 SKF GX Series Microlog Data Analyzer	29
Figure 4:4 SKF CMSS2200- Data acquisition equipment and structural layout.....	29
Figure 4:5 Vibration profile of Generator 05, Sapugaskanda plant	30
Figure 4:6 Angular misalignment.....	33
Figure 4:7 Parallel Misalignment	34
Figure 4:8 One side heavy Spot of the rotor.....	35
Figure 4:9 Either side heavy Spots of the rotor	35
Figure 5:1 DC ramp test before maintenance of G4, Sapugaskanda plant	40
Figure 5:2 DC ramp profile of B Phase of G4, Sapugaskanda plant.....	41
Figure 5:3 Dry ice cleaning of G4, Sapugaskanda Power Station	42
Figure 5:4 DC ramp test after maintenance of G4, Sapugaskanda plant	42
Figure 5:5 DC ramp B phase result after maintenance of G4, Sapugaskanda	43
Figure 5:6 Pielstick plant generator with Diesel engine	44
Figure 5:7 Vibration test of G 3, Sapugaskanda Power Station.....	45
Figure 5:8 DC ramp test result before maintenance of G7, Sapugaskanda plant	48
Figure 5:9 Before maintenance of DC ramp, Phase Y of G7, in Sapugaskanda plant.....	49
Figure 5:10 DC ramp test result after maintenance of G7, in Sapugaskanda plant.....	50
Figure 5:11 DC ramp test after maintenance of phase Y of G7, Sapugaskanda plant.....	50
Figure 5:12 Layout of MAN plant Genset.....	52
Figure 5:13 Vibration profile of Generator 05, Sapugaskanda plant.....	52
Figure 5:14 DC ramp test before maintenance of GT 3, Kelanitissa plant	56
Figure 5:15 DC ramp test before maintenance of R phase of GT 3, Kelanitissa plant.....	57
Figure 5:16 DC ramp test after maintenance of GT 3, in Kelanitissa plant.....	58
Figure 5:17 Layout of KPSGT02, Kelanitissa plant	59
Figure 5:18 Vibration profile of Gas turbine 05, Kelanitissa plant	60
Figure 5:19 PD Symptoms observed from GT 07 on 2014.08.13.....	63
Figure 5:20 DC ramp test before maintenance of KPSGT 7, Kelanitissa plant	64
Figure 5:21 Dry ice cleaning work of KPSGT7 during 96,000 Rhr maintenance	65
Figure 5:22 DC ramp test result after maintenance of KPSGT7, Kelanitissa plant	65
Figure 5:23 Kelanitissa Gas turbine No 07	66
Figure 5:24 Vibration test result of Gas turbine Generator No 07 of Kelanitissa plant.....	67
Figure 5:25 PD Symptoms observed from KCCPGT on 2014.08.08.....	70
Figure 5:26 Before maintenance of GT of Kelanitissa Combined cycle power station.....	72
Figure 5:27 DC ramp test before maintenance of Gas turbine generator, Kelanitissa Combined Cycle power station.	73
Figure 5:28 DC ramp test before maintenance of Steam Turbine Generator ,Kelanitissa Combined cycle power station	75
Figure 5:29 DC ramp test before cleaning of Steam turbine generator.	75

LIST OF TABLE

Table 4-1 Classification of vibration harmonics.....	31
Table 5-1 Generator maintenance Details	39
Table 5-2 DC ramp result which was obtained from Phase B.	43
Table 5-3 Classification of vibration harmonics.....	45
Table 5-4 Routine maintenance plane of MAN plant	47
Table 5-5 Comparison with DC ramp result of Phase Y, Generator 07	51
Table 5-6 Classification of harmonics	53
Table 5-7 Routine maintenance shedhule of Kelanitissa small GTs	55
Table 5-8 Classification of harmonics	60
Table 5-9 OEM Recommended Maintenance Schedule.....	62
Table 5-10 Comparison of DC ramp result	64
Table 5-11 Classification of harmonic component	67
Table 5-12 OEM Recommended Maintenance Schedule.....	69
Table 5-13 Reference vibration level of Kelanitissa combined cycle plant.....	71



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CHAPTER 1

1 CONDITION MONITORING

1.1 Introduction

Modern power stations rely on condition monitoring system for managing the maintenance and operation activities for safety and economy of the plant operations. Forced outages of generators in critical applications can cost to the relevant organization in millions of dollars for repair and outage cost. Also it will directly affect to the reliability of the power system. Maintaining of reliable operation critically depends on the stator winding insulation, which is aged by exposure to a combination of thermal, electrical, mechanical and environmental stresses. Therefore utility has a keen interest in diagnostic measurements to assess the condition of the stator insulation in the machines. Such measurements help in planning maintenance and repairs schedules. Minor repair could be done in time to prevent forced outages that need expensive major repairs, enabling the utility to use its fiscal and human resources most effectively.



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The thesis includes a survey of the utilization of condition monitoring test information for recommendation of scheduling maintenance activities of three main power stations in thermal complex of Ceylon Electricity Board in Sri Lanka, namely Kelanithissa Power Station, Sapugaskanda Power Station and Kelanithissa Combined Cycle Power Station. An important task was to understand the framework of condition monitoring strategy to indentify the problems and analising methodology of each test results and propose solutions related with machinery.

There are two main methods used in condition monitoring.

- Trend monitoring
- Condition checking

1.1.1 Trend monitoring

Trend monitoring is the continuous or regular measurement and interpretation of the data. Data is collected during machine operation, to indicate variations in the condition of the machine or its components, in the interests to ensure of safe and economical operation.

1.1.2 Condition checking

Condition checking is where check measurements are taken while the machine running, for some indicators such as Power Loss, Friction, Temperature, Noise, Vibration spectrum analysis, etc.

So, the trend monitoring is “The taking of regular measurements and their recording and analysis which gives a lead time on machine problems” and condition checking is “Comparing Numerate values with established standards or other similar machines to give knowledge of machine condition” collectively define as condition monitoring. [1]



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1.2 Condition Monitoring test procedures

There are many types of conditioning monitoring test procedures in the power sector. These consist of generators, transformers, switch gear equipment, large motors etc. This thesis covers only the generator condition monitoring test procedures. Following condition monitoring test procedures are commonly available for the generator.

- a) DC ramp test
- b) Polarize index test
- c) Vibration monitoring testing
- d) Online partial discharge testing
- e) Offline partial discharge testing
- f) Tan Delta test
- g) Acoustic emission

The generator stator winding is the most important component of the generator. There are several types of winding and insulation materials so, there should be practical and reliable diagnostic methods to identify the generator stator winding insulation to assess the condition.

Routine maintenance of the generator is governed by the guidelines of the Original Equipment Manufacturer (OEM). Due to aging of the generators and changing running conditions, there should be proper condition monitoring techniques other than to conventional maintenance pattern. This thesis is based on identification of the generators' condition using the following test procedures.

- DC ramp test
- Partial discharge testing
- Vibration monitoring testing

1.2.1 DC Ramp test

For approximately 30 years, ramped high-voltage dc testing has been used routinely by the Bureau of Reclamation, as well as several other North American utilities, to appraise the condition of generator and motor stator winding ground wall insulation. [2] The DC voltage is ramped up (usually at a low rate in the order of 1 kV/min) and the total leakage current (usually at a lower value in the order of micro ampere) is continuously recorded as a function of voltage (or time)

Diagnosis of electrical apparatus by DC ramp testing has been a much appreciated method to get to know the state of the high voltage to ground insulation of stator insulation windings. With the proper mathematical tools, data derived from DC testing reveals a wealth of information.

It has been used with a certain degree of success identifying various defects. By comparing the calculated curve according to the solution of the dielectric equations assuming linearity, the non-linearity in the experimental data can be easily identified.

Accordingly, the condition of the insulating system can be analyzed since the material dielectric properties are expected to change with the material's aging [3].

1.2.2 Partial discharge testing

When the generator stator winding voltage is greater than around 4 kV, partial discharges can occur within the stator winding insulation or between the surface of the coil or core and the stator coil. The presence of air (or hydrogen) pockets within the stator winding insulation can lead to the electric breakdown of the air pockets and that process is called partial discharge (PD). These partial discharges (PDs) are created due to high-voltage stresses. If an air pocket (also called a void or a delamination) exists in the stator winding insulation, the high electric stress will break down through the air, causing a spark. This spark will degrade the insulation and, if not corrected, repeated discharges will eventually erode a hole through the stator winding insulation, leading to failure. [4]



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The corona is appeared from partial discharge. The term corona is used for the visible partial discharges that can occur on bare metal conductors operating at high voltage, which ionize the surrounding air. However, since the PD within the stator winding insulation is not visible, it should not be termed as corona.

Electric breakdown of insulation can occur due to mechanical failure of a material too. For example, the tensile strength of a material depends on the nature of the material and the cross-sectional area of the material. Mechanical failure occurs when the chemical bonds rupture under the mechanical stress. Different materials have vastly different tensile strengths which also varies with the cross sectional area.

Electric breakdown strength is a property of an insulating material but not governed by voltage alone. Rather, it depends on the electric field. Electric stress, E , in a parallel plate geometry is given by;

$$E = V/d \quad (\text{kV/mm}) \quad \text{-----} \quad E \text{ 1.1}$$

Where,

V is the voltage across the metal plates in kV

d is the distance between the plates in mm

For air at room temperature and one atmosphere (100 kPa) pressure, and in low humidity, the electric strength is about 3 kV/mm. The intrinsic breakdown strength of most solid insulating materials such as epoxy and polyester composites is on the order of 300 kV/mm. That is, solid materials used as stator winding insulation are about 100 times stronger than air.

To understand this process, consider the stator winding insulation cross section in Figure 1.1

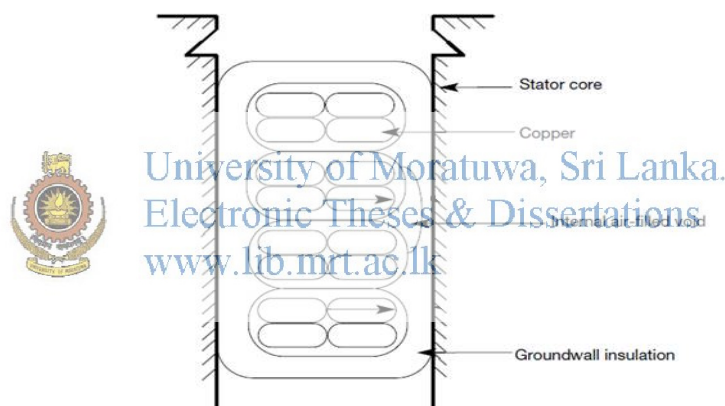


Figure 1:1 Cross section of a coil winding with an air pocket

There is practically no possibility of the stator winding insulation itself experiencing electrical breakdown. Rather, PD will occur only when there are gas-filled voids within the stator winding insulation as shown in above figure 1.1. These discharges are harmful to the stator winding insulation, because repeated PD will eventually degrade the solid insulation by breaking the chemical bonds, especially in organic materials such as asphalt, polyester, and epoxy, all common stator winding insulation materials. Gradually the constant impact from the electrons and ions will erode a hole through the stator winding insulation, which will result in failure of the entire winding.

1.2.3 Vibration monitoring testing

Vibration is a behavior of a machine's mechanical components as they react to internal or external forces. Since most rotating machinery problems show themselves as a vibration, we use vibration signals as an indication of a machine's mechanical condition. Also, each mechanical problem or defect generates vibration which may be affected to the generator stator windings and wave forms. [5]

These show that increased vibrations occur even when there is static eccentricity. Eccentricity can be split into two types,

a) Static eccentricity,

Where the rotor is rotating on its own axis but is off-center with respect to the stator bore.

b) dynamic eccentricity

Where the rotor is not rotating on its own axis but is rotating on the stator bore axis.

Static eccentricity could be caused by bearing and end-bell misalignment and dynamic eccentricity could be caused by a bent shaft. A combination of static and dynamic eccentricity is a commonly available fault and this could be due to a number of causes such as including worn bearings.

1.3 Construction of Stator Winding

Generators are expected to serve at least a 20 to 30 year life span before a rewinding. The insulation system is designed to accomplish the specified life span. If an older winding design failed prematurely, then extra insulation would be added or other corrective measures taken in a new design. Generally, to prevent premature failure, "safety margins" are added to the design; that is, the copper may have been given a greater cross section than strictly needed to make sure the operating temperature was low, the ground insulation made thicker to avoid electrical breakdown, etc. The common result in an insulation system that would greatly outperform the specified life. Within the stator slot, the restraint of the coil or bar is accomplished.

Fundamentally form-wound slots are filled as much as possible with conductors and insulation, and then the slot is closed off with a nonconductive and usually nonmagnetic wedge as shown in the Figure 1.2. The slot wedge is usually made from an insulating material and is critical to restricting movement.

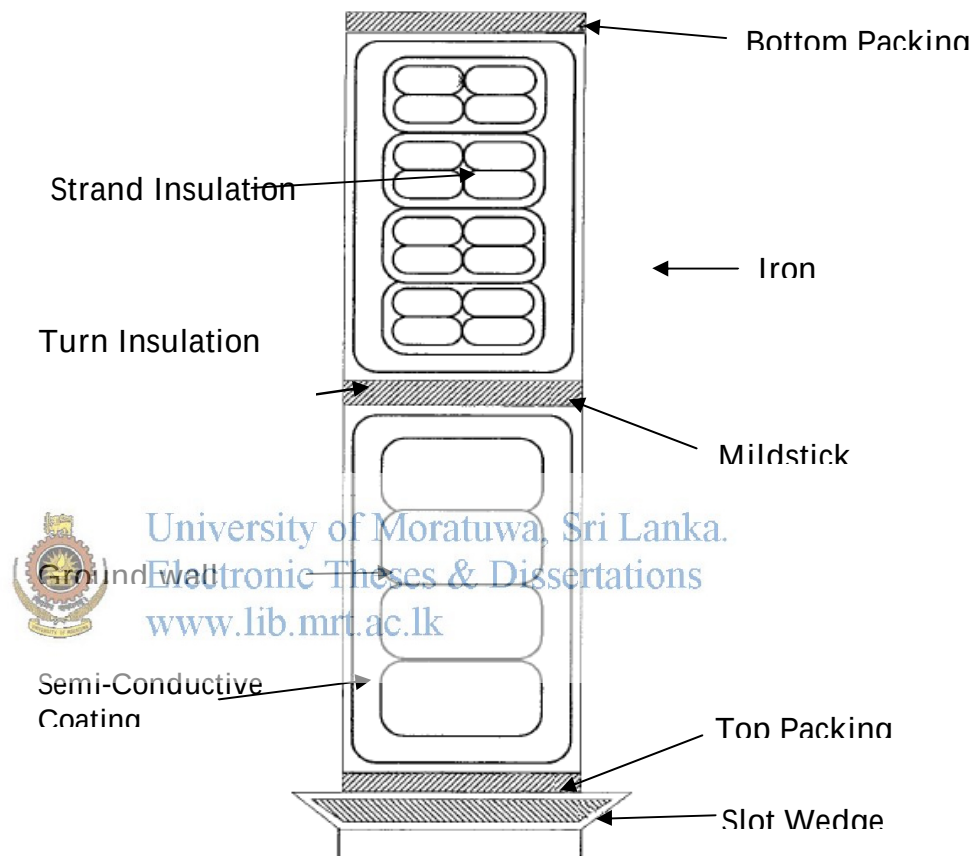


Figure 1:2 Cross section of the coil in a stator slot



Figure 1:3 Physical cross section of winding

The above figure 1.3 shows the cross section of a winding. There are many different stresses that can affect the rate of insulation degradation in stator and rotor windings. Thermal, Electrical, Ambient, and Mechanical stresses, the so-called TEAM stresses are identified for continuous deterioration of the windings. [6]

1.3.1 Thermal Stress

The operating temperature of a winding causes thermal stress. Therefore it is the most recognized cause for gradual decrease of insulation level. The operating temperature consequences from I^2R , eddy current and stray load losses in the copper conductors and additional heating due to core losses, windage etc. When generators operate above the threshold temperature, the oxidation process will be activated therefore all types of insulation may be brittle or tends to cause de-lamination in form wound coil ground walls.

The higher the temperature will cause to the shorter expected life. Following figure 1.4 shows the life time with respect to the insulation classes, e.g., A, B, F, and H

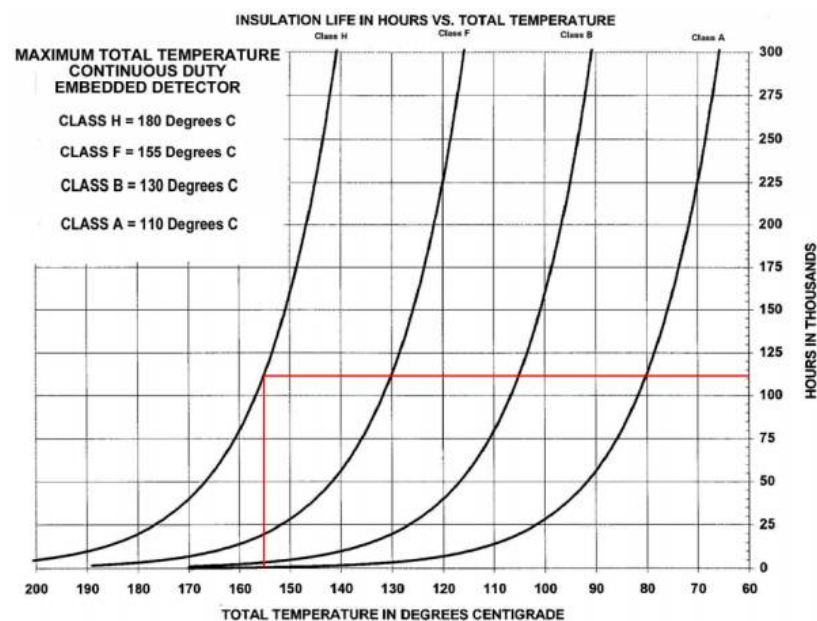


Figure 1:4 Generator life span with operating temperature

Source : <http://www.marathonelectric.com/generators/docs/manuals>

A variation of thermal stress is caused due to the thermo mechanical stress. However, high temperature of winding helps to prevent the moisture absorption into windings. Therefore it reduces the risk of electrical tracking failures.

1.3.2 Electric Stress

The insulation must be thick enough to withstand the power frequency electrical stress of coil winding. In stator windings rated at above about 1000 V, the thickness of the insulation is primarily determined by the electric stress. The breakdown strength of solid materials used as stator winding insulation is about 100 times stronger than that of air and hence small electric sparks can occur within air pockets in the insulation or on the surface of coil insulation due to electrical stress. These sparks contain electrons and ions that attack in the solid insulation. Finally chemical bond structure of insulation organic materials will change and deterioration is started.

1.3.3 Ambient Stress (Factors)

Ambient environment and physical condition changes cause to the ambient stress changes. Following factors can be identified as the directly applying ambient stress to affect the stator winding insulation.

- Moisture condensed on the windings
- Oil from the bearings or oil seal system in hydrogen-cooled machines
- High humidity
- Aggressive chemicals
- Abrasive particles in the cooling air or hydrogen
- Dirt and debris brought into the machine from the environment, such as insects, fly ash, coal dust, and powders that are by-products of associated industrial processes (cement, pulp, chemical residues, etc.)

In some cases, these “factors of influence” in themselves do not cause aging but, when combined with another stress, can lead to aging. For example, moisture and/or oil, combined with partly conductive dirt, carbon brush particles, etc. can make a

partly conductive film over the insulation, in which the electric stress then causes surface currents and electrical tracking. Oil/moisture/dirt combinations can collect in the rotor and stator ventilation passages and between coils in the end-winding to block cooling airflow, which increases the risk of thermal deterioration.

1.3.4 Mechanical Stress

There are two main sources of mechanical stress. On a rotor, the insulation system is exposed to high centrifugal force. For the most part, the insulation either has, or has not, the capability to endure such forces. As a result of the rotor insulation failure, stator winding can be damaged from foreign particle coming from the rotor. Various short-time mechanical tests can evaluate this. Also sometime rotor insulation materials slowly creep away from the high stress areas, eventually leading to a fault. [7]

The second common mechanical stress is caused by the power frequency current, which gives rise to a magnetic force oscillating at twice the power frequency. It can be shown mathematically in equation 1.2 as follows,

$$F = \frac{kI^2}{d} \text{ kN/m} \quad \text{-----} \quad \text{E 1.2}$$

Where,

The force F, acting on the top coil at 100Hz for a 50Hz (120 Hz for a 60 Hz) current in the radial direction for 1 meter length of coil is given.

I is the rms current through the Roebel bar, or $I = nI_0$, with I_0 being the rms coil current times the number of turns in the coil;

d is the width of the stator slot in meters;

k is 0.96.

The force is expressed in kN of force acting per meter length of coil/bar in the slot.

Above equation shows the relationship between the mechanical force and the current flowing in a stator coil or bar. If the coils are loose in the stator slot, the force causes

the coils to vibrate, and the ground wall insulation is abraded. A similar magnetic force occurs in the end-winding. If the coils/bars are free to vibrate relative to one another or against blocking or support rings, the insulation may again scrape.

1.4 Case study

Above mentioned stresses are highly affected on the stator winding condition. Insulation resistance level reduction, formation of voids inside of the windings, looseness of the wedges of stator windings, etc. will be developed with the age of windings. The levels of abnormality of the generator stator winding conditions monitored using three types of tests procedures as stated before.

01. DC Ramp test
02. Partial Discharge test
03. Vibration Monitoring test

 Case study was carried out on three main power stations which are highly contributing with a high plant factor to the power generation. Also these are managing as one unit called “Thermal Complex” of Ceylon Electricity Board. A brief description about the power stations is as follows,

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1.4.1 Kelanithissa Power Station.

The Kelanithissa Power Station has six open cycle diesel-fired gas turbines rated at 20 MW each, all of which were commissioned between 1980 and 1982, and a single Fiat PS-GT7 gas turbine rated at 115 MW, commissioned in August 1997.[7] Presently four 20MW small generators (KPSGT 3 & KPSGT 6 were not included for the research since these are beyond the repairable condition) and GT 7 is generated during the peak hours of power system and in less hydro generating period in Sri Lanka. Gas turbines act as prime movers and these are coupled to high speed cylindrical rotor type synchronous generators. All together plant has a total capacity of 195 MW. Since gas turbines usually rotates at a high speed of 5000 rpm (5100 rpm for GT7), generator is connected through a gear reduction unit which reduces

speed to 3000 rpm. The generator details of Kelanitissa power station is attached in Appendix A.1

1.4.2 Sapugaskanda Power Station

This plant is considered as the base load power plant due to the lower power generation unit cost throughout the year. Since heavy furnace oil (i.e. higher viscosity above 2,500 S) is using as the fuel of the plant. The 160 MW Diesel Engine power station was commissioned in three stages. Under the first stage four numbers of 20 MW PIELSTICK diesel engines with Alstom Atlantique Generator were installed in 1984. As the second stage of the power station, four numbers of 10MW MAN B&W diesel engines with SIEMENS generators were installed in 1997. Finally four numbers of similar types of 10MW MAN B&W diesel engine with SIEMENS generators were installed in 1998. The generator details of Sapugaskanda power station is attached under Appendix A.2



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1.4.3 Kelanitissa Combined Cycle Power Station

The 165 MW naphtha-fuelled combined cycle power station was commissioned in August 2002.[7] It consists of one 110 MW gas turbine, one 55 MW steam turbine, and one exhaust heat recovery boiler. Plant can be operated in two modes as open (i.e. Gas turbine only) cycle or combined cycle (i.e. Both Gas turbine and steam turbine). Open cycle operation is the same as the gas turbine generator with 110 MW capacity, while in combined cycle the flue gas is directed through Heat Recovery Steam Generator (HRSG) using diversion damper. Thereafter that steam flow drives steam turbine (High Pressure and Low Pressure) adding another 55 MW capacity all together 165 MWs. This power station uses diesel and naphtha as the fuel.

The generator details of Kelanitissa combined cycle power station is attached under Appendix A.3

CHAPTER 02

2 DC RAMP TEST

2.1 Instrumentation and Preparation

The Iris Power DCR 50TM is a simple off-line DC tester to identify problems in the stator ground wall insulation system of large AC electric machines before an unexpected in-service failure occurs

Figure 2.1 shows the simple schematic diagram to show the procedure of DC ramp testing.

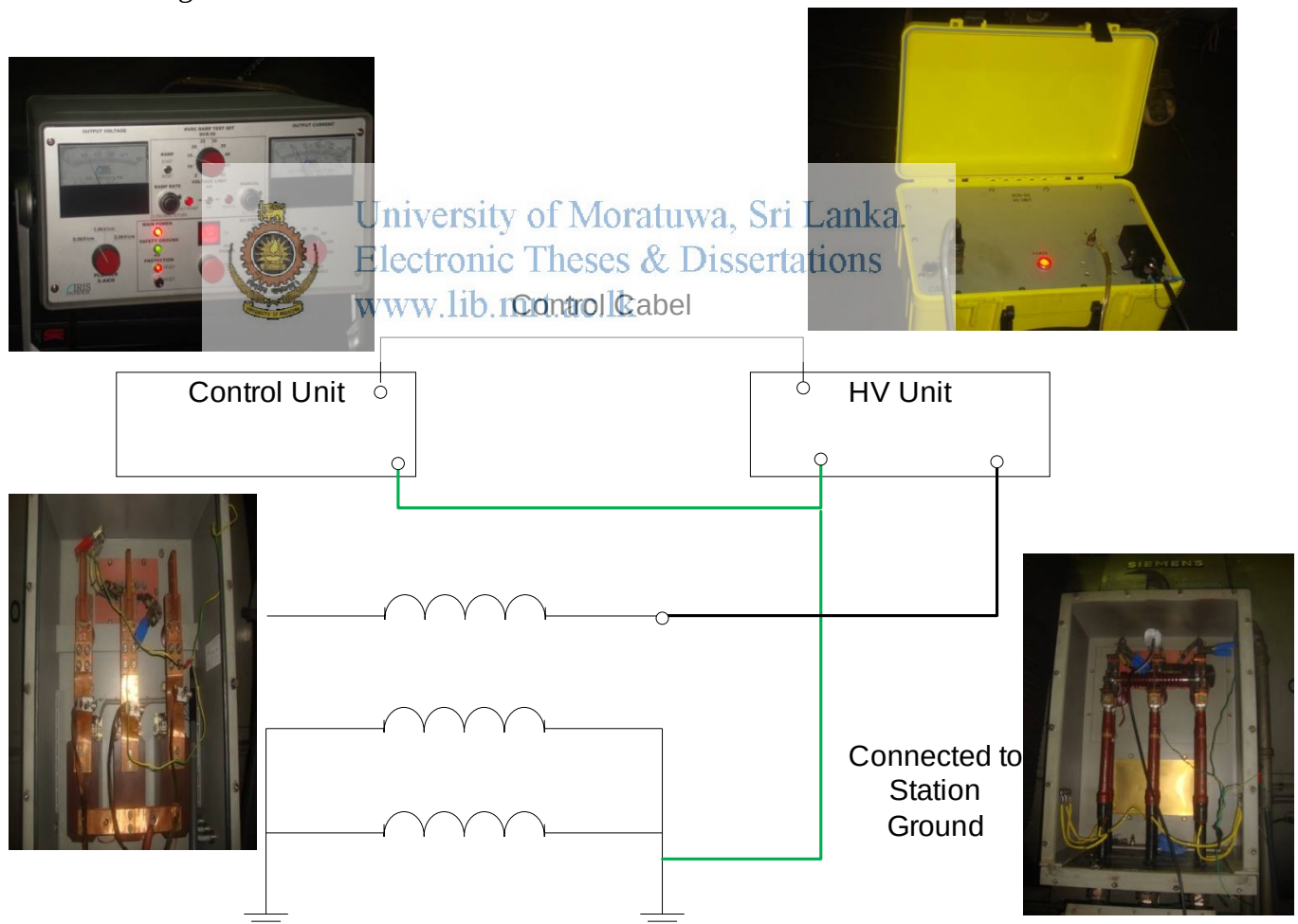


Figure 2:1 Instrumentation layout of DC ramp test.

2.2 Test Voltage

DC Ramp test is used for condition monitoring purposes, so it is necessary to avoid overstressing and breakdown of the insulation during the test. Thus for almost all the generators in CEB with rated voltage of 11 kV to 15kV, test voltage is selected as 15 kV. This test has been recommended as a diagnostic practice by IEEE95-97. In this test, a dc voltage is increased from 0 to 15kV at a rate of 1kV/min using DCR50 DC Ramp tester.

2.3 Test Procedure

The DCR 50 tests according to IEEE Standard 95-2002. If the winding temperature is below the dew point, the winding may be heated to dry off the moisture that has condensed on the winding. If the temperature is below the dew point, it is not possible to obtain correct dc ramp result due to humidity. The test procedure is as follows [8].

- a) Remove all external connections to the machine and completely discharge the windings to the grounded machine frame.
- b) Connect the two terminals of instrument to a winding and ground. When the test is carried out on one winding of three phase generator, then other windings should be grounded during the test. (Refer Figure. 2.1)
- c) Connect both Control unit and HV unit to the common ground as earlier used.
- d) Apply required DC ramp voltage between the winding and ground using the DCR 50 DC ramp tester.
- e) At the same time monitor and record the leakage current with respect to applied voltage using DCR 50 instrument.

The specimen test result which was taken from Generator No – 04 of Sapugaskanda Power Station is shown in following Figure 2.2.

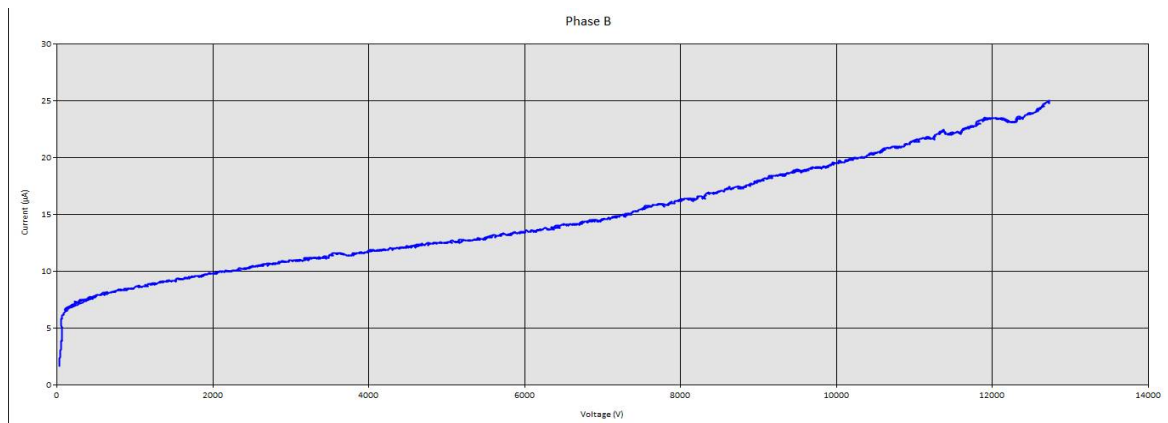


Figure 2:2 DC ramp test result of DG04 of Sapugaskanda Power Station

2.4 Test Analyzing Methodology

When using this technique, the test voltage is ramped smoothly and automatically using a programmable high-voltage dc test set. [8] Measured current versus applied voltage is recorded with an X-Y plotter, providing continuous observation and analysis of the changes in current. Classification of each current component is shown in Figure 2.3

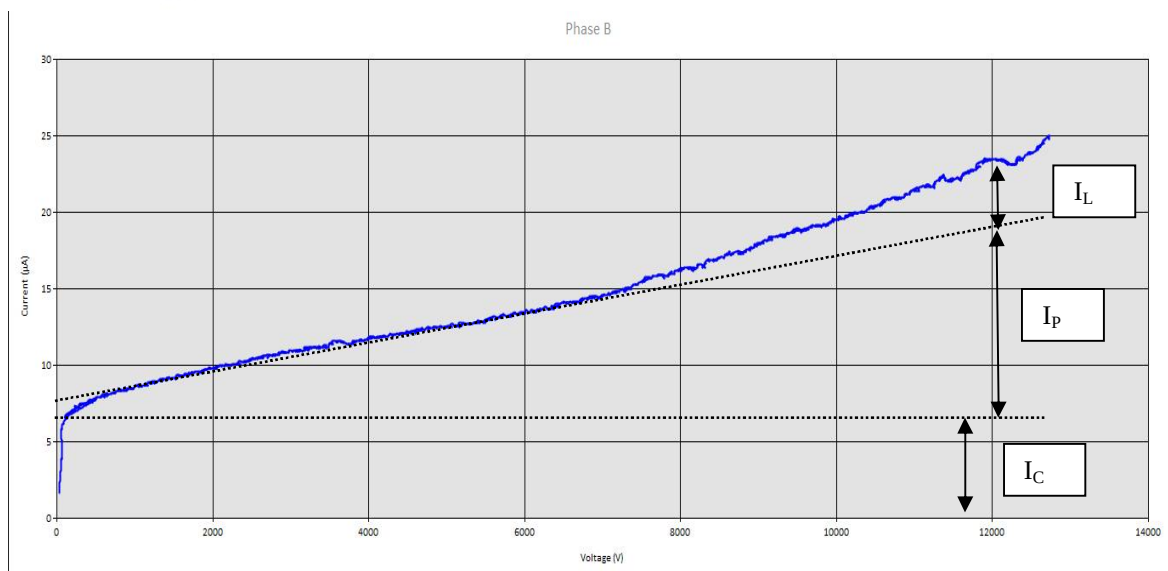


Figure 2:3 Classification of leakage current profiles

Figure 2.3 illustrates the total measured leakage current, surface leakage current, polarization current and capacitance charging current. Capacitance charging current

(I_c) is constant due to the reason that rate of change of applied voltage (dV/dt) is constant. Since the applied voltage is a ramped voltage the polarization component of the current (I_p) has a linear variation so that small variations in measured current is easily visible. The surface leakage current (I_L) volume, over its surfaces, and through defects. According to the insulation materials, the leakage profile will be changed. [9]

2.4.1 Capacitive Current (I_C)

The insulator behaves as a capacitor when a DC voltage is applied to a capacitor, a high charging current of comparatively high magnitude and short duration, which decays exponentially with time of voltage application. In case of generator or motor windings, the current effectively decays to zero in less than 10 seconds. Since the capacitive current contains little diagnostic information. Since during the polarization index measurement, initial insulation resistance (I_R) is measured once the capacitive current has decayed. Hence the first I_R measurement has been set as one minute to ensure that this current does not include for the I_R calculation.

2.4.2 Conduction Current (I_R)

This current is constant in time due to flow of electrons between the copper and the core. Such a current can flow if the ground wall has absorbed moisture, which can happen on the older thermoplastic insulation systems. The current may also flow if there are cracks, cuts or pinholes in the ground insulation, some contamination and that depends on the type of bonding material used in the insulation system is present to allow current to flow.

This current is constant with time. With modern insulation this current usually is negligible (as long as there are no cracks, cuts etc).

2.4.3 Surface leakage Current (I_L)

This is constant DC current that flows over the surface of the insulation. The magnitude of the surface leakage current is dependent upon temperature and the

amount of contamination (oil or moisture mixed with dust, dirt, insects, chemicals etc) on the surface of the windings.

2.4.4 Polarization Current (I_p)

Polarization current is resulting from molecular polarizing and electron drift, which decays with time of applied voltage. Water molecules are easily subject to polarization. When an electric field is applied across the insulation, it starts absorption of electrons from the hydrogen molecules causing ionization of hydrogen. The energy required to align the molecules comes from the current in the DC test supplied voltage. This current is called polarization current.

The water becomes completely polarized when the absorption of electron from hydrogen merging with oxygen is completed. Once the molecules are all aligned, the current stops. It will take approximately 10 minutes for complete polarization. Therefore during the Polarization Index test is carried out throughout 10 minutes.



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2.5 Classification of leakage current profile

The leakage current profile from the DCR50 DC ramp tester mainly contains following types of leakage current profiles [10],

- a) Insulation in good condition
- b) Insulation in localized weak point
- c) Very poor stator winding

The above mentioned profiles changes can be shown as figure 2.4

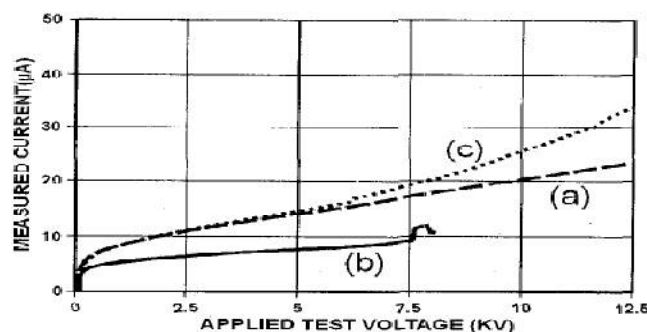


Figure 2:4 Classification of total leakage with insulation condition

Figure 2.4–(c) shows the test response of epoxy-mica insulation or any other insulation with a crack in the ground wall insulation. The current versus voltage trace appears linear almost until the point of insulation breakdown is reached. The gradually increase of the discharge current is a symptom of high moisture content or general deterioration of the insulation.

The curve of Figure 2.4–(a) is typical of new insulation. As noted, the capacitive charging current is constant and proportional to $C \times dV/dt$. This result is typical and indicated by the gradual slope of the current versus voltage curve. Also, as expected for new insulation, the leakage current is negligible up to the maximum test voltage. This test curve represents sound, high-quality insulation.

The curve of Figure 2.4–(b) displays a very nonlinear current versus voltage response. The sudden increase in leakage current, at a relatively low test voltage (i.e. well below the rated voltage level), suggests the groundwall insulation of one coil or portion of a coil may be cracked or otherwise damaged. The test was terminated early to avoid the possibility of permanently faulting the insulation.

CHAPTER 03

3 PARTIAL DISCHARGE TEST

3.1 Instrumentation and Preparation

The Capacitive Couplers and Resistive Thermal Detectors (RTDs) are used for the monitoring process and they will help to identify any abnormality of partial discharge in the stator winding location of the generator. The layout of the sensor installation is shown in Figure 3.1

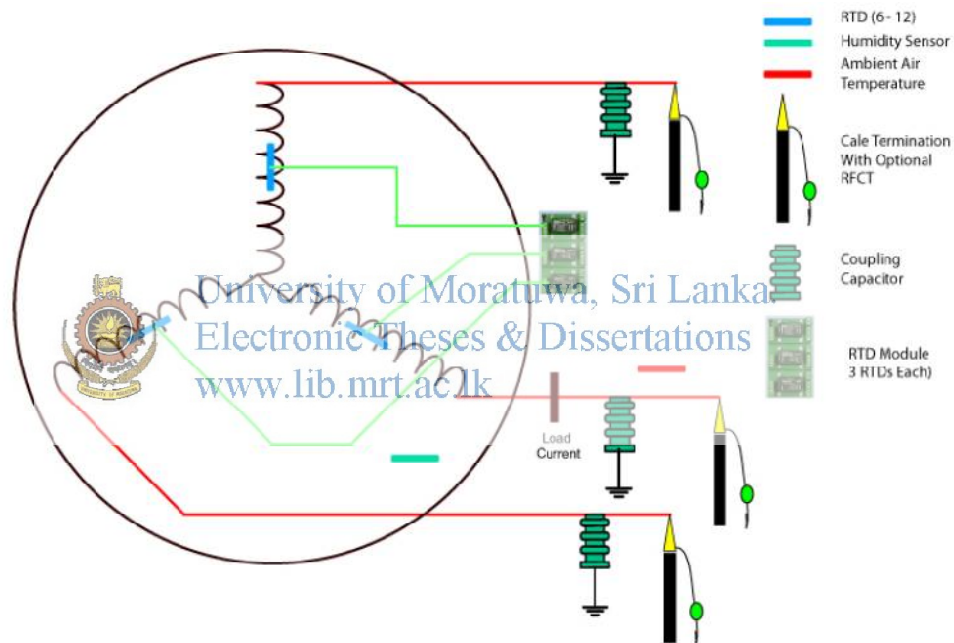


Figure 3.1 Layout of PD monitoring sensors

Capacitive couplers identify the propagation of the PD. Therefore it will help the classification of internal or external failure. RTDs identify the correct location. Flux is varying according to the PD occurring surrounding area, and this flux change is captured by RTDs and it will identify the area which was giving PD symptoms.

3.1.1 Coupling Capacitor

An epoxy-mica coupling capacitor (capacitive coupler) is a sensitive detector of the partial discharges in the electrical insulation. Figure 3.2 shows coupling capacitor.



Figure 3:2 Coupling Capacitor

Typically capacitors installed at the line terminals only cover approximately 15% of the winding closest to the terminations. Any PD occurring deeper in the winding will not be detected. Therefore the RTDs are used as additional sensing point.

3.1.2 Resistive Thermal Detectors (RTDs) Module for PD Detection

Modern stator windings in larger generators normally have at least a few temperature sensors, which can continuously monitor winding temperature. These sensors measure the temperature at specific points of stator windings. They can be at a variety of locations and they are embedded within the stator winding. In random-wound machines these are inserted between coils or coils and core. In form-wound machines, they are between the top and bottom coils in a slot. Figure 3.3 shows the RTD mounting between coils and core.

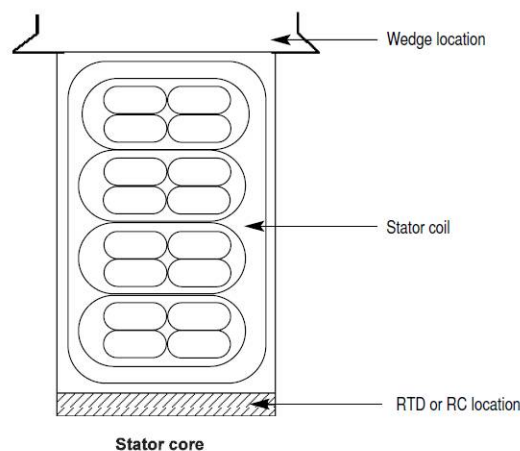


Figure 3:3 RTD or RC temperature sensor mounting

This sensor takes advantage of the fact that the electrical resistance of a conductor is directly proportional to the temperature. These contain a thin strip of metal, few centimeters long, with a nominal resistance of 10Ω or 100Ω .

The PD detection utilizes the existing RTDs embedded in a stator winding as a PD sensor. This sensor is installed in series with the existing wiring at the machine, therefore it will not affect the operation of any temperature monitoring equipment connected to the RTDs. The RTDs act as an antenna and picks up the high frequency component which are generated with a partial discharge.

In many cases the existing RTD termination board block is removed and the RTD-PD sensor is installed as close as possible to this location. Figure 3.4 shows interface board to be installed in series with the existing wiring.

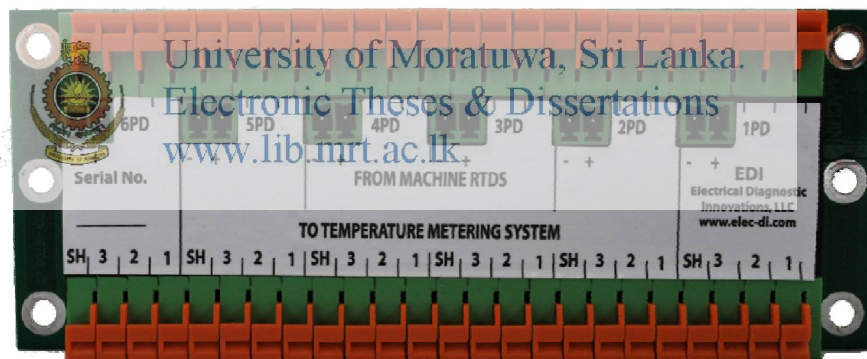


Figure 3:4 Interface terminal board for Temperature and PD monitoring

The sample of PD detection graph is shown in Figure 3.5 The differentiation of positive versus negative polarity partial discharge pulses will be related to a probable root cause and corrective actions. The two measurement illustrated on the two dimensional graph are partial discharge maximum magnitude, usually represented in millivolts, and pulse repetition rate represented by the number of partial discharge pulses during one cycle of an AC waveform.

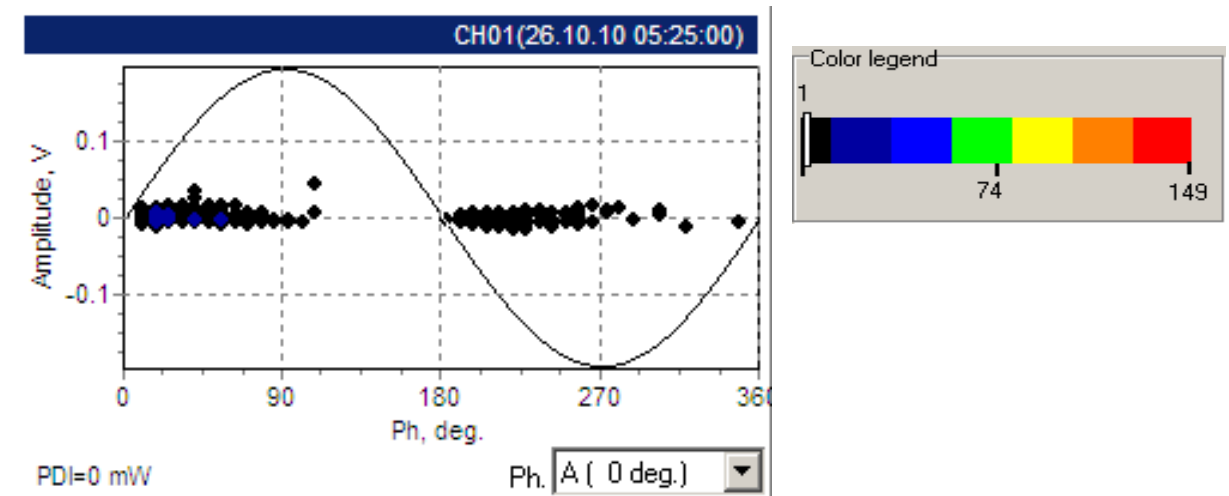


Figure 3:5 PD test sample

3.2 PD Analyzing Methodology

Partial discharge can be described as electrical pulses of discharge in a gas filled void or on a dielectric surface of a solid or liquid insulation system. These discharges might occur in any void between the copper conductor and the grounded generator frame reference. The void may be located;

- Between the copper conductor and insulation wall,
- Internally in the insulation itself
- Between outer insulation wall and grounded frame
- Along the surface of the insulation.

These pulses occur at high frequencies, and they attenuate quickly as they pass to the ground. These discharges occur only during the first and third quarter of each cycle. This is the initial rising positive signal in first quarter, and the third quarter rising the negative signal. During the initial rising positive signal, all of the capacitive components are charged until the partial discharge inception voltage is reached across each specific void, and partial discharge commence.

When the positive wave cycle begins to decrease, the positive voltage across the each void is also reduced. But some of capacitive charges remain. During the third quarter

cycle, this positive charge is effectively reversed, resulting in a positive charge in the reverse direction, and the resultant partial discharges.

3.2.1 Negative polarity

Another concept to review is that partial discharges are measured as voltage pulses. Therefore during the positive waveform cycle, a discharge results in a negative, downward oriented pulse. This is referred to as a partial discharge with a negative polarity, and occurs during the first quarter-cycle.

3.2.2 Positive polarity

A partial short-circuit results in a positive, upward oriented pulse. This is referred to as a partial discharge with a positive polarity and occurs during the third quarter-cycle of the increasing negative voltage applied. These partial discharges, which are measured as a high frequency change in the power signal in milli-volts to few volts. Therefore they are exaggerated in the following Figure 3.6 for illustration purpose,



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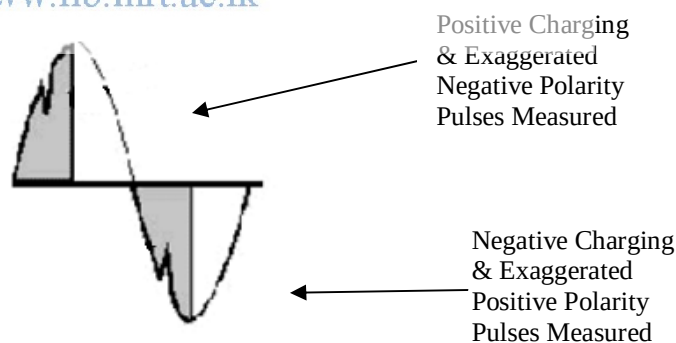


Figure 3:6 Classification positive & negative polarity

When viewing the results of partial discharge signals, the above will be illustrated, on a three dimensional graph, with two critical measurements plotted in relation to the 360 degrees of a typical cycle. Depending on the PD sensor and the recording apparatus, the magnitude can be measured in pico Coulombs, millivolts, microvolts, milliamps, or decibels. The 360 degree is usually split into four segments, therefore the level of partial discharge in the first quarter cycle (i.e. negative polarity

discharges) can be compared with the third quarter cycle (i.e. positive polarity partial discharges).

The pulse recurrence rate indicates the quantity of discharges occurring, at the variation maximum magnitude levels. This interesting phenomenon is related to the applied voltage level to the void, the void's geometric shape and the specific material that are acting as the anode and cathode. The critical material is the cathode, since the cathode supplies free electrons to allow the partial discharges to continue. Depending on the part of the power cycle, the material representing the cathode differs. Figure 3.7 shows cathode action with different locations of windings. [11]

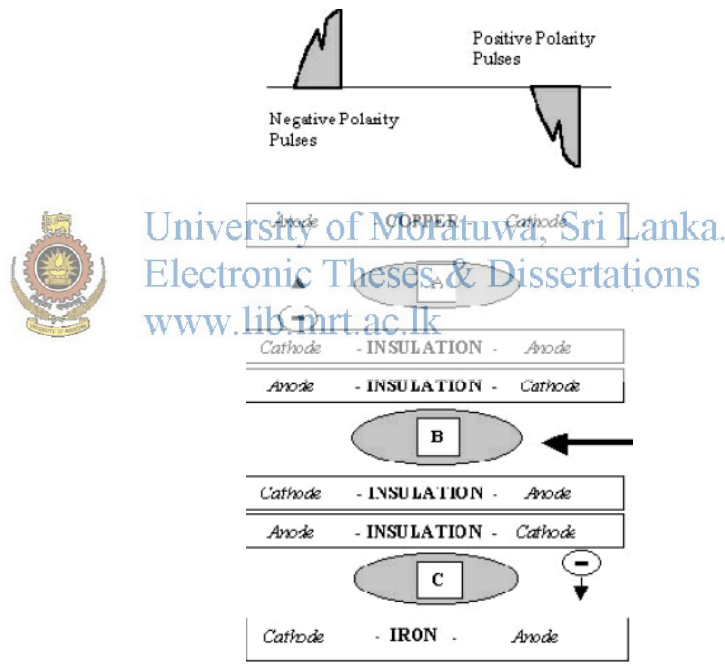


Figure 3:7 Relationship of electrons flow in positive and negative polarity cycle

For the negative polarity pulses, occurring in the first quarter cycle, the insulation acts as a cathode across voids in the copper conductor – to – insulation space Figure 3.7-A. During these negative polarity pulses, a greater tendency of the discharges will occur in this area near the copper conductor. Therefore if negative polarity pulses greatly exceed the positive polarity pulses, then the root cause is considered to be void in the copper conductor to insulation area.

For the positive polarity pulses, occurring in the third quarter cycle, the insulation acts as a cathode across voids in the insulation – to – iron space Figure 3.7 - B. During these positive polarity pulses, a greater tendency of the discharges will occur in this area near the iron. Therefore if positive polarity pulses greatly exceed the negative polarity pulses, then the root cause is considered to be void in the insulation to iron area, or in area of surface tracking since this also bridges the outer insulation wall to the iron.

Also note that when the void is prevalent internal to the insulation material itself Figure 3.7 - C then for both the positive polarity and negative polarity pulses, the cathode remains the insulation itself. In this regard, when positive and negative polarity pulses are equally prevalent, then the root cause is considered voids within the insulation material itself, and not between the insulation and either the copper conductor, or the iron.

Figure 3.5 shows higher intensity levels of positive polarity PD pulses than the negative polarity PD pulse. According to the above explanation of PD detection the insulation acts as a cathode across voids in the copper conductor – to – insulation space. Also it can find the place where PD occur by tracing sensor location relevant to recorded channel. The generator winding layout shows the place of sensor was mounted.

3.3 Advantages of PD Continuous Monitoring

The PD activity is unstable, which means it may not be active today, but tomorrow. Through continuous monitoring, variations of PD activities are observed. Many factors can affect PD activity. [12] A few of them are,

- Voltage
- Load
- Temperature
- Humidity
- Vibration
- Pressure

Most accepted PD standards avoid the setting of specific levels or quantities to determine acceptability limits. Instead, they stress trending. In order to perform proper trend analysis, one should make sure that all dynamics are nearly identical at each testing interval. This is very difficult (some time is impossible) to accomplish and time consuming. Therefore advances in technology now allow the continuous monitoring of PD in most equipment found in industrial and power generation facilities rather than rely on periodic measurements. There are many advantages available on-line as well as off-line tests. [3] These include:

- The instrument will identify a problem in its earliest stages of defect development.
- Provide information as to what phase the defect is on and generally what type of defect such as Corona, Surface Discharge, Insulation Delaminating, Ground wall deterioration (slot discharge), etc.
- It is even possible to localize even further the location of the defect.
- Unnecessary maintenance is reduced because you will be constantly testing and will have accurate data on which to base decisions.
- More accurate data as tests are conducted under real operating conditions
- No outage is required to perform the test, therefore no loss of productivity of the monitored asset.
- Other dynamics such as temperature, humidity and load current can be easily correlated to PD activity, which provides addition insight to diagnostics.
- Provides the opportunity for remote diagnostics. Therefore experts do not need to come out to the field for basic diagnostics.

CHAPTER 4

4 VIBRATION MONITORING TEST

4.1 Instrument and Preparation

Vibration data is obtained by mounting transducers on the Generator at various locations. Figure 4.1 shows typically arrangement of obtaining vibration profile using SKP GX Series MX 70 Microlog Data Analyzer.

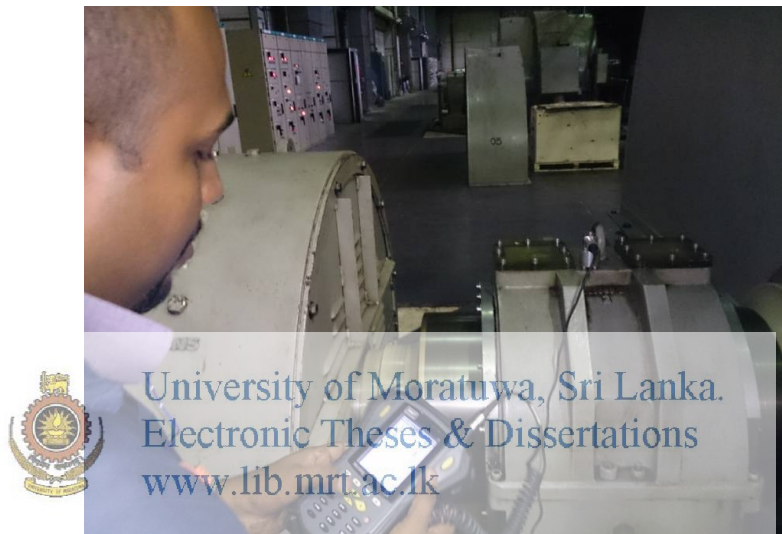
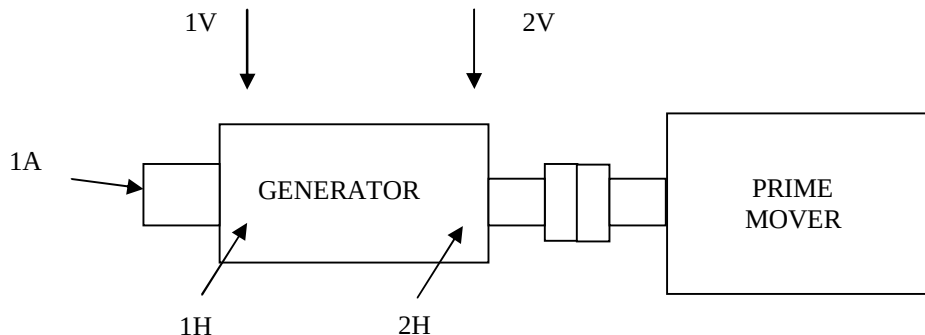


Figure 4:1 Vibration monitoring process

The portable type data acquisition device, Microlog SKF Condition Monitoring Instrument, which is capable of acquiring vibration data, convert to FFT (fast Fourier Transform). Using the software it can derive in any form of displacement, velocity or acceleration component of vibration signature.

Normally test transducer is located as close as possible to the bearing with solid metal between the bearing and the sensor. Also the position should avoid bearing caps, which are of thin metal and are thus poor conductors of vibration energy. The used accelerometer SKF CMSS2200, which responds to the acceleration of the vibration source, is shown in Figure 4.2

4.1.1 Vibration Sampling Points



1 – Generator non-driven end

2 – Generator Driven End

H – Horizontal

V - Vertical

A – Axial

Figure 4:2 Vibration sampling position

Vibration is detected by accelerometers, which produce an electrical output that is proportional to the magnitude of the acceleration that the sensor detects. By the instrument, it takes out velocity and displacement as per user requirement.

4.1.2 SKF GX Series MX 70 Microlog Data Analyzer

The SKF GX Series MX 70 Microlog Data Analyzer is used for as a data collector and analyzer of vibration signature of generators. It contains the following specification for the high performance of test data analyzing.

- Colour display and more powerful
- Modular platform.
- Full featured Route and Off-Route vibration monitoring/analysis features
- GX-M model with Two Channel and Balancing modules already installed,

The analyzer gives its output as frequency spectra as vibration spectacles. The vibration spectrum is then evaluated to determine critical frequencies.

The critical frequencies ($f_{v,k}$) ; $k=1, 2, 3 \dots$ are defined as those frequencies which lie significantly above the noise floor. The following figure 4.3 is shown below which was developed by SKF.



Figure 4:3 SKF GX Series Microlog Data Analyzer

The set of ratio constants, m_k , is then calculated for each critical frequency, as the ratio of present magnitude to the previous magnitude of the vibration.



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E (4.1)

Vibration harmonics are scaled by frequency to account for the fact that vibration is measured as a velocity. The condition monitoring of the generator then involves sampling the vibration, calculating its spectrum and then determining the ratio constants, m_k of critical frequency components of the spectrum. The values of m_k can be used as an indication for the generator health condition. The experimental results and the existing standards can then be used as a starting point in defining the limit on m_k . [12]

4.1.3 SKF CMSS2200- Data acquisition equipment

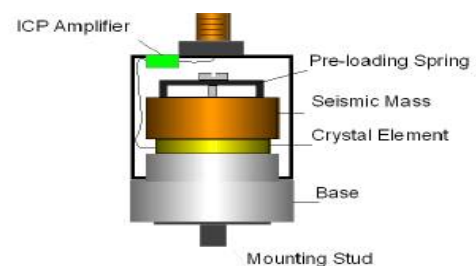


Figure 4:4 SKF CMSS2200- Data acquisition equipment and structural layout

SKF CMSS2200- Data acquisition equipment normally called as accelerometer. The piezo-electric accelerometer can be used as the standard vibration transducer for machine vibration measurement. According to the mechanism of this transducer, it can be considered as the compression-type accelerometer.

When the accelerometer is moved in the up and down direction, the force required to move the seismic mass which is clamped to the base by an axial bolt bearing down on a circular spring. According to Newton's second law, this force is proportional to the acceleration of the mass. The force on the crystal produces the output signal, which is therefore proportional to the acceleration of the transducer.

4.2 Vibration Analyzing Methodology

As describe in vibration theory when a misalignment or imbalance or mechanical looseness is present in a shaft or coupling of a generator, the frequency spectrum of the vibration will consist of specific frequency components with specified magnitudes.

During the vibration case studies of the thermal power station of Ceylon Electricity Board, test results were taken for the identification of failure symptoms and accordingly planning preventive maintenance.

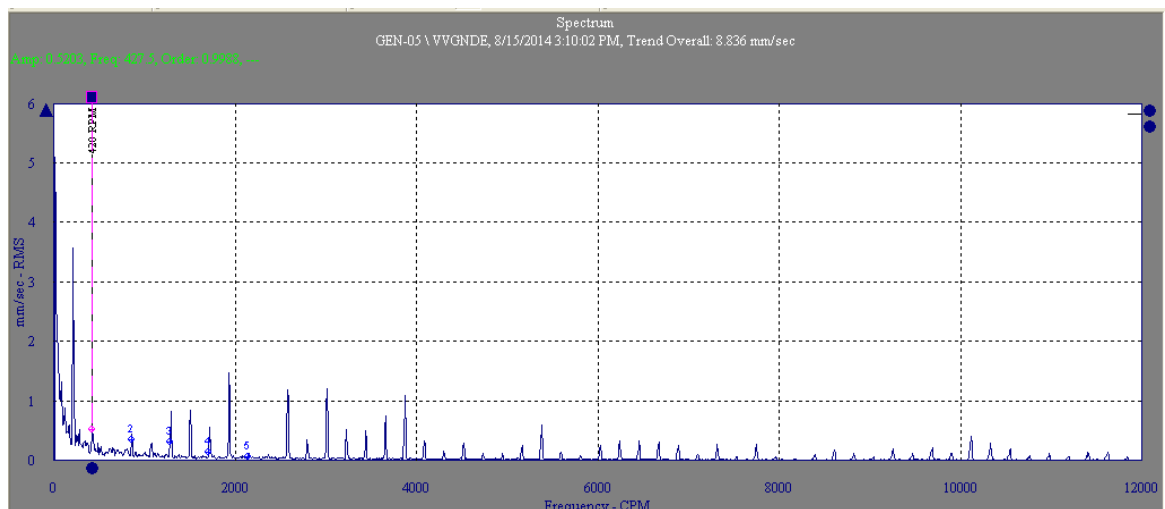


Figure 4:5 Vibration profile of Generator 05, Sapugaskanda plant

Figure 4.5 consists with list of foundation and harmonics levels given in Table 4.1

Table 4-1 Classification of vibration harmonics

	Harmonic Values		
	Amplitude (mm/S)	Frequency	% of Fund.
Fund	0.52	427	
2nd	0.334	855	64.23%
3rd	0.3018	1283	58.04%
4	0.124	1710	23.85%
4.5	1.461	1935	280.96%
5	0.0511	2138	9.83%
6	1.179	2580	226.73%
7	1.193	3015	229.42%
9	1.079	3878	207.50%

ISO 8528-9:1995, gives allowable vibration parameters for reciprocate internal combustion engines; refer Appendix B.1. It can be identified that the above generator is 10 MW larger horizontally coupled engines with 428 rpm engine speed and mounted on soft foundation. Therefore overall vibration velocity can be identified as less than 15 mm per Second at generator end for the acceptable vibration conditioned. Above generator overall vibration is 8.836 mm per second which is at acceptable level.

Above profile shows high magnitude of low frequencies and high frequencies. This will cause engine mechanical looseness due to any problems in the bearings or soft foundation mounting. Especially, when sub synchronous harmonic peak (4.5 X) is caused by oil whirling in pedestal bearing. Additionally those higher frequencies are due to engine valves operations, turbo charger speed, adjacent engines, etc.

This profile shows fundamental frequency as 427 rms. Also it can be identified as medium speed machines, since high vibration profiles cannot be firmly analyzed due to high inbuilt vibrations of those engines. Therefore the result taken in the present condition profile, can be compared with graph and will be taken later. Therefore presently took vibration profiles can be maintained as references.

Two components of the vibration signal are mainly referred, its amplitude and its frequency.

➤ **Frequency**

Frequency is the number of times an event occurs in a given time period (normally within 1 second).

➤ **Amplitude**

Amplitude is the size of the vibration signal. Therefore it can be identified the strength of the vibration through the vibration signatures.

Vibration analysis of the generators is a modern technique under condition monitoring field. Generator vibration monitoring helps to determine the condition of rotor and can study the effect on the stator winding and finally the structural stability in a system. The vibration analysis of the unique patterns created by specific components of an electro-mechanical system, gives early indications of problems such as machinery imbalance, misalignment, bearing wear, worn gears, etc. [13]



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The main phenomenon of vibration analysis is analyzing vibration signature in frequency domain. During the analysis following faults are identified,

- Rotor shaft misalignment
- Rotor Imbalance
- Looseness
- Improper fit between component parts,
- Electrical faults, etc.

There are several factors which are led to the vibration of the generator. Condition Monitoring Systems are available to assess the condition of the synchronous generators and to identify indications of generator problems and then to determine the most effective time to schedule the maintenance.

ISO 8528-9:1995, ISO 10816, the German VDI 2056 or the British BS 4675 standards are available for the analysis vibration based on frequency signature. After that several case studies were carried out to identify failures of CEB generator by

using vibration database of machine condition monitoring. In this case study the vibration analysis is based on ISO 8528-9:1995 standard for reciprocate internal combustion engines and ISO 10816 standard for gas turbine. Refer Appendix B.2

4.2.1 Identifying of the Machine's Running speed

The interpretation of vibration test data is in FFT (Fast Fourier Transform) mode. Therefore identification of each property calculates in frequency domain. Also it is important to identify rated speed through the vibration signature other than to instrumentation at the machine or from instrumentation in the control room monitoring the machine. Normally speed can be identified as first significant peak reading the spectrum from left to right. Look for this peak and check for peaks at two times, three times, four times, etc. The suspected running speed frequency (2X, 3X, 4X) is called harmonics.

4.2.2 Misalignment

Misalignment is created when generator shaft, couplings and bearings are not properly aligned along their centerlines. There are two types of misalignments:[13]

4.2.2.1 Angular misalignment

This occurs when two shafts are joined at a coupling in such a way as to induce a bending force on the shaft. Angular misalignment causes axial vibration at fundamental frequency. (1x) In the axial position, a phase shift of 180° will exist across the coupling or machine.

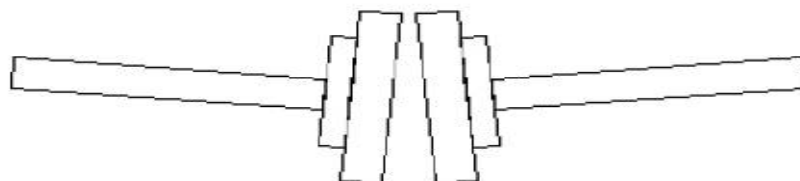


Figure 4:6 Angular misalignment

4.2.2.2 Parallel misalignment

This occurs when the shaft centerlines are parallel but displaced from one another. Parallel misalignment causes Radial vibration at double the fundamental frequency ($2x$). This was illustrated in Figure 4.6 as double revelations on radial direction per one revolution of the shaft. In the radial direction, a phase shift of 180° will exist across the coupling or machine. A 0° or 180° phase shift will occur as the sensor is moved from the horizontal to the vertical position on the same bearing. In the radial direction, a phase shift of 180° will exist across the coupling or machine. A 0° or 180° phase shift will occur as the sensor is moved from the horizontal to the vertical position on the same bearing.

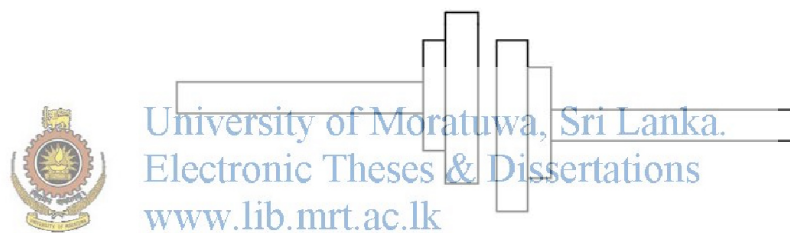


Figure 4:7 Parallel Misalignment

In parallel misalignment, double the fundamental frequency (A_{2x}) amplitude can be vary from 30% -- 200% of the $1x$ amplitude.

- Couplings with $2x$ amplitudes below 50% of $1x$ are usually acceptable and often operate for a long period of time.
- When the vibration amplitude at $2x$ is 50% to 150% that of $1x$, it is probable that coupling damage will occur.
- A machine whose vibration at $2x$ running speed is above 150% of the $1x$ has severe misalignment, the problem should be fixed as soon as possible.

4.2.3 Imbalance

Almost half of all machinery problems are caused by imbalance. The imbalance occurs when the shaft's mass centerline does not coincide with its geometric centerline. There are three types of imbalances. [13]

4.2.3.1 Static imbalance

- Only one force is involved.

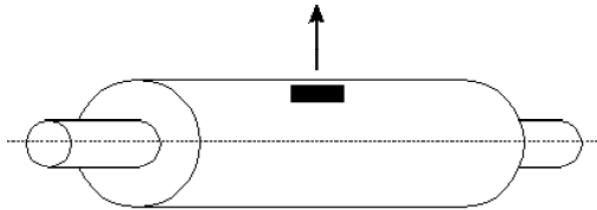


Figure 4:8 One side heavy Spot of the rotor

Only one force is involved. The term “static” implies that this type of imbalance can be observed at rest. To observe the rotor turns until the heavy spot is located in vertically.

4.2.3.2 Couple imbalance

- Two equal forces are 180° from each other

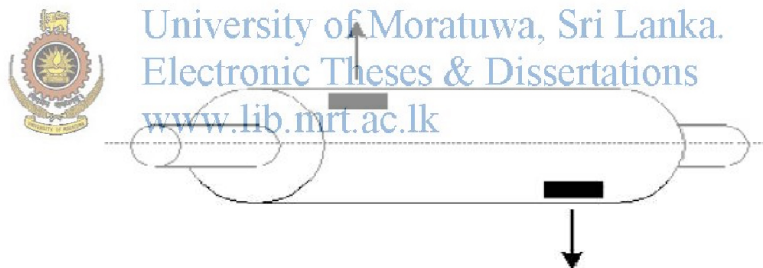


Figure 4:9 Either side heavy Spots of the rotor

Couple imbalance cannot be measured at rest. With couple imbalance, two equal forces (weights) are 180° from each other. When rotor is rotating the forces move the rotor in opposite directions at their respective ends of the shaft. This causes the rotor to wobble, which produces a 180° out-of phase reading from opposite ends of the shaft.

4.2.3.3 Dynamic imbalance

- Combination of above two

In reality, almost all imbalances are dynamic imbalance. Dynamic imbalance is the combination of static and couple imbalance.

Imbalance can be caused by a number of factors, including improper manufacture, an uneven build up of debris on the rotors, or the addition of shaft fittings without an appropriate counter balancing procedure. It is sinusoidal, occurring at a frequency of once per revolution (1X). Generally does not contain harmonics of 1X running speed as other faults. Vibration caused by pure imbalance is a once per revolution. Imbalance can be identify with following features.

- If the radial measurement's 1x amplitude is high, and harmonics are less than 15% of the 1x, then there may be imbalance.
- If the majority of vibration is in the radial plane, and the 1x amplitude is medium to high in amplitude, and the phase from the vertical and horizontal measurements differ by 90° , $\pm 30^\circ$ then there may be imbalance.
- If there is a non-synchronous peak corresponding to the 1x running speed of a coupled machine, then there may be imbalance on the other machine.
- If the primary vibration plane is both axial and radial, and the machine has an overhung mass, and the axial phase measurements across the machine are in phase, then there may be imbalance.

4.2.4 Mechanical looseness

Mechanical looseness or the improper fit between component parts. Since machine has come with loose from its mounting or bearing and generator component has developed a fault which has worn down. If looseness is generated from a component, there is a possibility the part will become detached, causing secondary damage. It can be identified by analyzing vibration FFT spectrum as follows, [13]

- If there are a series of three or more synchronous or $\frac{1}{2}$ synchronous multiples of running speed (range 2x to 10x), and their magnitudes are greater than 20% of the 1x, then there may be mechanical looseness.
- If the machine is rigidly connected (no coupling or belt), and the radial 2x is high, then there may be mechanical looseness.

4.2.5 Bearing defects

Often bearing defect is not the source of the problem. It may be due to another fault like misalignment or imbalance. Bearing defects occur at much higher frequencies with much lower amplitudes. If those frequencies align with the peak amplitudes in the vibration spectrum, there is probably a bearing defect. [13]



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CHAPTER 5

5 PREVENTIVE MAINTENANCE SCHEDULING

5.1 Sapugaskanda power station

Sapugaskanda Power Station is the plant with the lowest operating cost in the thermal power complex as at year 2010. Since heavy furnace oil (i.e. with higher viscosity above 2,500 S) is used as the fuel of the plant, 12 numbers of diesel generators are running to make a higher contribution to the power system. As described in Chapter 01, this power station is operating as two plants, PIELSTICK plant and MAN plant. Since generators and the prime movers are different in the power station, maintenance plans are also different.

5.1.1 PIELSTICK plant

Four numbers of 20 MW synchronous generators are coupled with diesel engines of Pielstick plant. Generator details are attached in appendix A.2



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5.1.1.1 OEM Recommended Maintenance Schedule

The generator Original Equipment Manufacturer (OEM) – M/S Alstom Atlantique has been instructed to carry out maintenance of the generators as follows,

- In every two years, check the air gap by disassembling one of the end shields and sliding gauge between the shoe of one pole and the internal surface of the stator lamination.
- In every three years, check the winding heads, the involutes and slot wedging. Also check the ventilation ducts in the stator body.
- The electrical resistance of rotor and stator winding should be measured every year by a specialist.
- Use clean and dry compressed air for cleaning out dust and foreign bodies with compressed air of less than 3 bars.
- Only use recommended solvent for cleaning

5.1.1.2 Present Practice of Maintenance

The Engine routine maintenance as instructed by Original Equipment Manufacturer (OEM) – M/S S.E.M.T. Pilestick has been instructed to attend maintenance for every 3,000 running hours. Accordingly diesel engines (prime movers) are taking out for instructed maintenance.

Presently it is practicing electrical maintenance along with the mechanical maintenance to reduce the outage period of the plant. Table 5.1 shows the summery of present generator maintenance practice of the PIELSTICK plant.

Table 5-1 Generator maintenance Details

Cumulative Running Hour	Routine Maintenance Type	Maintenance of Generator
3,000 Rhr	3,000 Rhr	- Take IR reading - Winding cleaning using low pressure air
6,000 Rhr	6,000 Rhr	- Take IR reading - Stator winding manual cleaning with recommended solvent
9,000 Rhr	3,000 Rhr	All task at 3,000Rhr continued.
12,000 Rhr	12,000 Rhr	All task at 6,000Rhr continued. - Check the insulation condition of the stator winding and re-varnish or other remedies appropriately.
15,000 Rhr	3,000 Rhr	All task at 3,000Rhr continued.
18,000 Rhr	6,000 Rhr	All task at 6,000Rhr continued.
21,000 Rhr	3,000 Rhr	All task at 3,000Rhr continued.
24,000 Rhr	24,000 Rhr	All task at 12,000Rhr continued. Check the winding heads, involutes and slot wedging. Check ventilation ducts in the stator body.

5.1.2 Case study of PIELSTICK plant

The review of maintenance plan was based on the DC ramp test and Vibration test of the generator since there is no installed partial discharge monitoring and it is not practical and not economical to introduce Sapugaskanda Power Station according to their retirement dates. Those four generators are serving energy for more than 30 years. And those four numbers of generators are going to be retired in the due course.

Under this case study, one generator is analysed since all four generators are identical. So the DC ramp test and vibration are conducted on Generator No 04 and its results are used for the scheduling of preventive maintenance.

5.1.2.1 DC ramp test conclusion

During the 24,000 Rhr routine maintenance work of the Generator No 04, the stator and rotor windings were closely monitored. Therefore DC ramp test was carried out on 19th September 2012. Results are shown in the curves of Figure 5.1

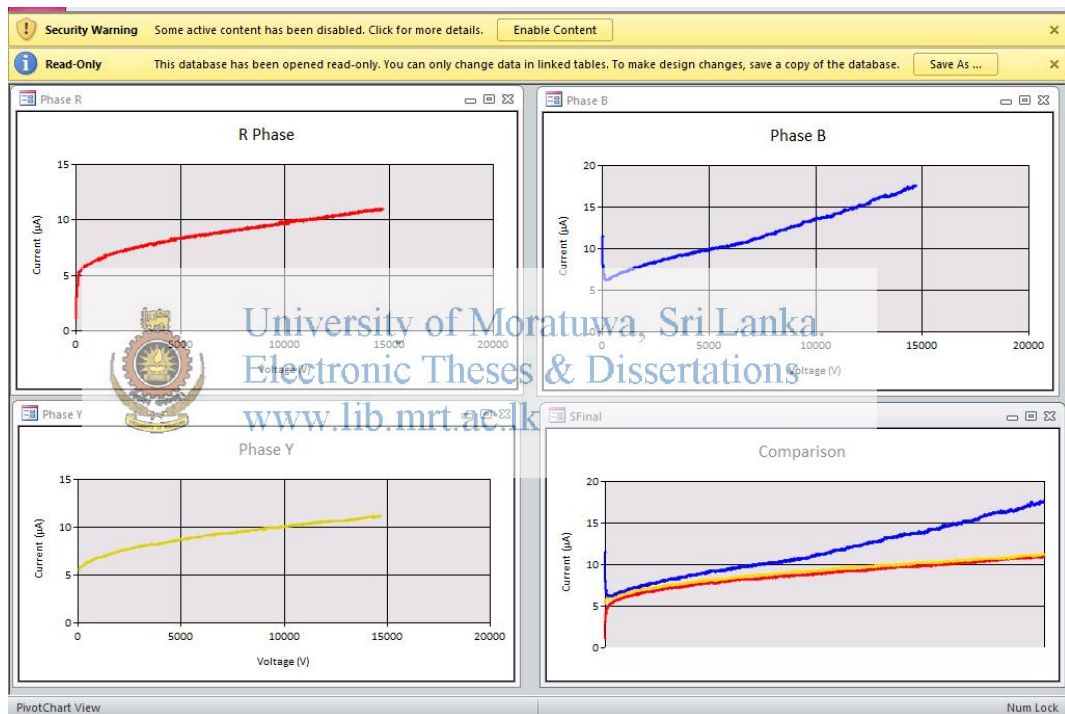


Figure 5.1 DC ramp test before maintenance of G4, Sapugaskanda plant

Observation from the DC ramp test (Figure 5.1)

- Insulation materials: Silicon wrapping impregnated with epoxy resin/glass cloth & mica paper tape.
- Although R & Y phases are behaving in normal profile, Phase B is deviated from other two phases.
- High contamination of dust is observed.

Phase B was considered for further observation, since it had a higher leakage current compared to other phases. Figure 5.2 reproduced the test result phase B given in Figure 5.1

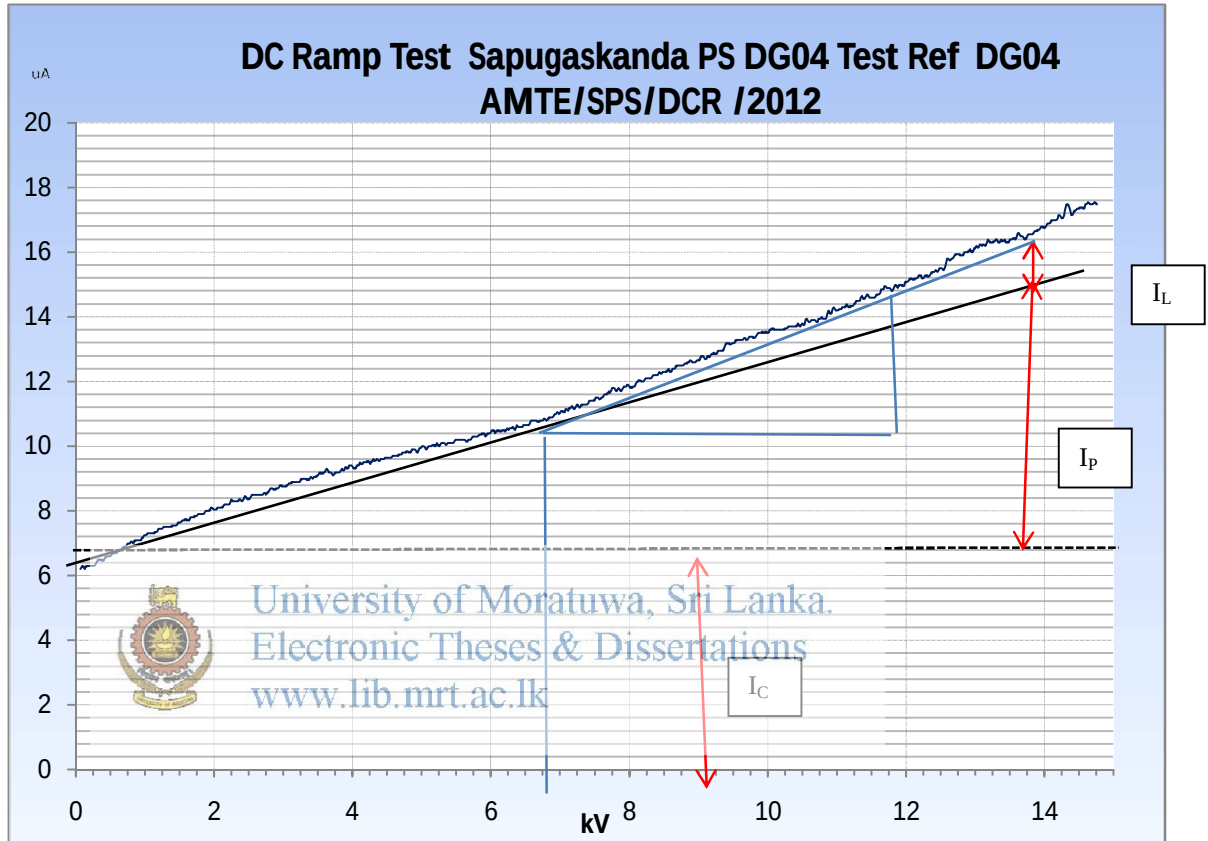


Figure 5.2 DC ramp profile of B Phase of G4, Sapugaskanda plant

The insulation materials were silicon wrapping impregnated with epoxy resin/glass cloth & mica paper tape. According to the above profile following parameters can be calculated [14]. High quality epoxy-mica insulation when tested with DC ramp, is attached in Appendix C.1

Capacitive current	$I_C = 7.4 \text{ uA}$		
Polarization current	$I_P \text{ at } 14 \text{ kV}$	$= (15.4 - 7.4) \mu\text{A} =$	$8.0 \mu\text{A}$
Surface leakage current	$I_L \text{ at } 14 \text{ kV}$	$= (16.8 - 15.4) \mu\text{A} =$	$1.4 \mu\text{A}$

$$\begin{aligned}
 &\text{Leakage current increment w.r.t} \\
 &\text{voltage increment at } 7\text{kV} \quad = \frac{(15.2 - 10.8)}{(12 - 7)} \\
 &\quad = 8.8 \mu\text{A/kV}
 \end{aligned}$$

Especially the phase B and other phases should have where a complete stator winding cleaning. After attending the manual cleaning with recommended solvent and dry ice cleaning for the further improvement of the winding, the DC ramp test was redone.



Figure 5:3 Dry Ice cleaning of G4, Sapugaskanda Power Station

After the complete cleaning process of generator No 04, DC ramp test was carried out. During this test, the following graphs were taken to identify the status of generator stator winding.

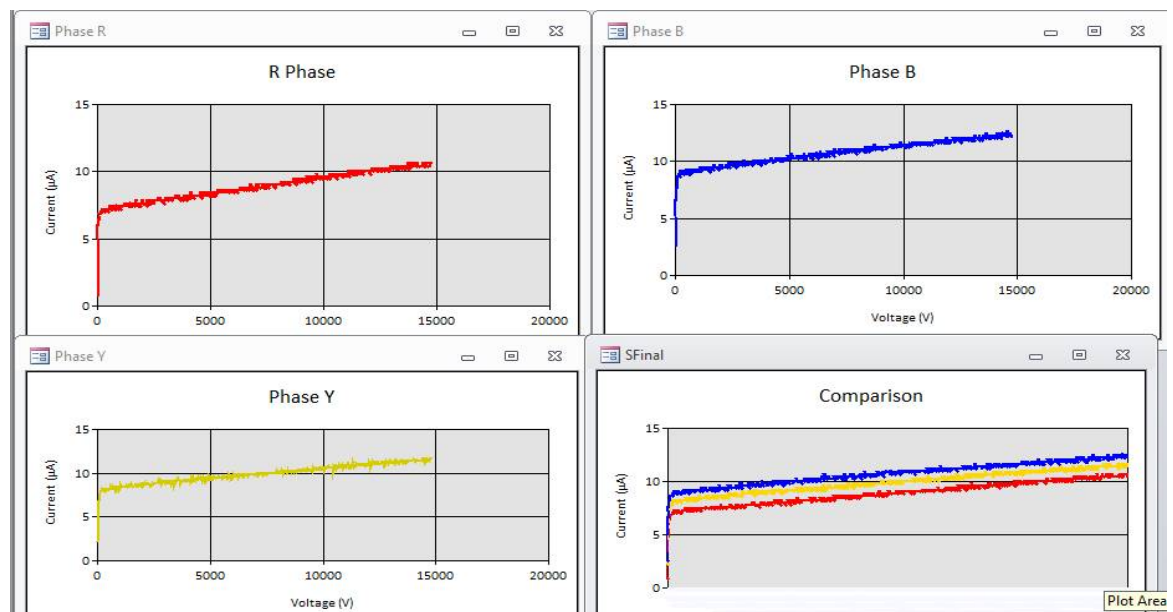


Figure 5:4 DC ramp test after maintenance of G4, Sapugaskanda plant

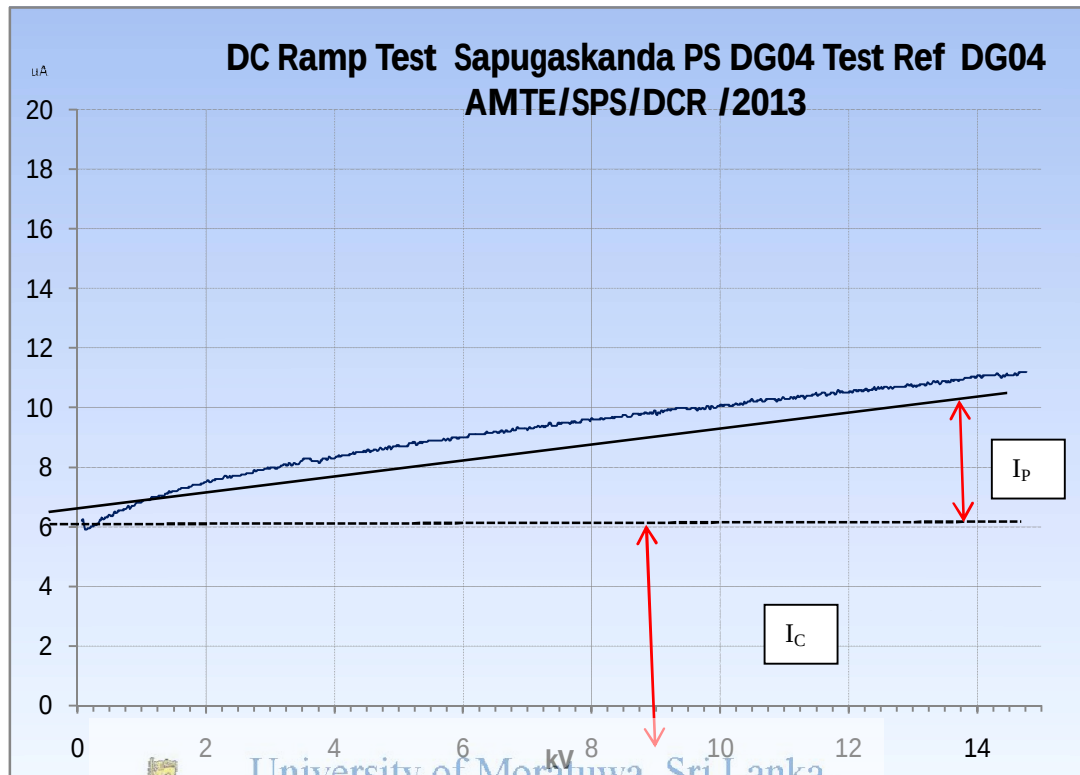


Figure 5.5: DC ramp B phase result after maintenance of G4, Sapugaskanda

$$I_C = 7.0 \mu A$$

$$I_P \text{ at } 14 \text{ kV} = (11.0 - 7.0) \mu A = 4.0 \mu A$$

$$I_L \text{ at } 14 \text{ kV} = \text{negligible}$$

According to the above figures 5.1 & 5.2 show the poor conditions of stator winding insulations. After winding cleaning process, the figures 5.4 & 5.5 show the improvement of the insulation levels. Therefore DC ramp test method is the ideal tool to evaluate stator insulation condition. Below table 5.2 shows DC ramp result which was obtained from Phase B.

Table 5-2 DC ramp result which was obtained from Phase B.

	Before Maintenance	After Maintenance
Total leakage Current at 14kV	16.8 μA	11.0 μA
Capacitive current (I_C)	7.4 μA	7.0 μA
Polarization current (I_P) at 14 kV	8.0 μA	4.0 μA
Surface leakage current (I_L) at 14 kV	1.4 μA	Negligible
Leakage current increment w.r.t voltage increment at 7kV	8.8 $\mu A/kV$	No increment

According to the above comparison, it can be identified that a considerable improvement is achieved after the maintenance.

Pielstick plant of Sapugaskanda power station operates in a highly polluted environment with oil and dust for more than 30 years. Therefore it directly affects to the stator winding condition. Also those four generators are having 2.1 – 2.4 range of PI index. (PI index table is attached in Appendix C.2.) Therefore it should add periodical DC ramp measurement for every 6,000 Rhr running hours and carry out special winding cleaning such as Dry ice cleaning during each and every 24,000 Rhr routine maintenance due to the high pollutant level of winding as observed from above testing and maintenance procedure.

5.1.2.2 Vibration test conclusion

All four engines are reciprocating engines which are fixed on a concrete base with dampening springs. Therefore those PC4-2 18V type engines are reciprocating horizontally to connect the generator as shown in following Figure 5.6

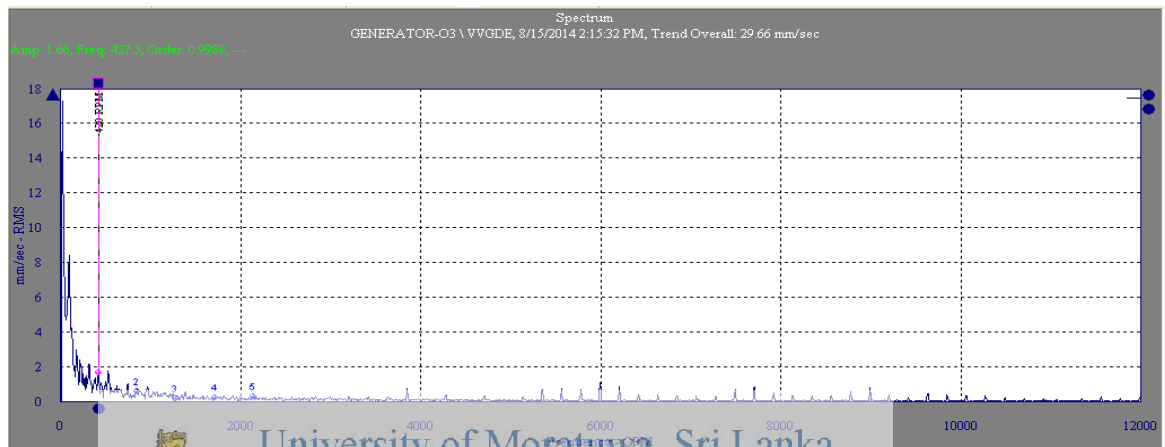


Figure 5:6 Pielstick plant generator with Diesel engine

Vibration test was not carried out from the beginning in this power station. During the continuous running of the generators, pedestal bearings were also changed during

the forced outage. Since there are no previous test data, faulty identification and trend analysis are difficult.

As described in Chapter 4, vibration results were taken for all four numbers of generators. Figure 5.7 shows the vibration profile of generator number 03 while running the Genset before taken for the 6,000 Rhr routine maintenance.



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Figure 5.7 Vibration test of G-3, Sapugaskanda Power Station

Above Figure 5.7 consists with following list of foundation and harmonics levels,

Table 5-3 Classification of vibration harmonics

	Harmonic Values		
	Amplitude (mm/S)	Frequency	% of Fund.
Fund	1.66	427.5	
2nd	0.5585	855	33.64%
3rd	0.1572	1283	9.47%
4	0.2396	1710	14.43%
5	0.2625	2138	15.81%

ISO 8528-9:1995, gives allowable vibration parameters for reciprocate internal combustion engines; refer Appendix B.1. It can be identified that the above generator is 20 MW larger horizontally coupled engines with 428 rpm engine speed and mounted on soft foundation. Therefore overall vibration velocity can be identified as less than 15 mm per Second at generator end for the acceptable vibration conditioned. However this generator shows overall vibration as 29.66 mm

per second which is not at the acceptable level. It cause high magnitude of low frequencies due to engine is mounted on soft foundations engine valves operations, turbo charger speed, adjacent engines, etc. Therefore it is required to taken for the engine maintenance immediately. Also it is require to inspect the generator stator winding parallel with engine outage.

This profile shows fundamental frequency as 427.5 rms. Also it can be identified as medium speed machines, since high vibration profiles cannot be firmly analyzed due to high inbuilt vibrations of those engines. Therefore the result taken in the present condition profile, can be compared with graph and will be taken later. Therefore presently took vibration profiles can be maintained as references. Since vibration profiles are more complex, it is recommended to do the vibration testing in every 6,000 Rhr cycle. Then can observe any deviation during 6,000 Rhr routine maintenance work.

5.1.3  **MAN plant** www.lib.mrt.ac.lk

Eight numbers of 10MW synchronous generators are coupled with diesel engines of MAN plant. Generator details are attached in Appendix A.2

5.1.3.1 OEM Recommended Maintenance Schedule

The Generator Original Equipment Manufacturer (OEM) – SIEMENS has instructed to carry out the following tasks during the maintenance,

- Cleaning the winding and ventilation duct and check insulation resistance with suitable instrument.
- Check slot wedge for tight fit
- Check end turn bracing
- Check condition of winding insulation, including ring circuit and end connection

5.1.3.2 Present Practice of the Maintenance

The Mechanical routine maintenance is carried out in every 1,500 running hours as instructed by Engine Original Equipment Manufacturer (OEM) – M/S MAN B&W Germen. Electrical maintenance is also carrying out parallel with the mechanical maintenance. Brief details of each maintenance activities are shown in table 5.4

Table 5-4 Routine maintenance plane of MAN plant

Cumulative Running Hour	Routine Maintenance Type	Maintenance of Generator
6,000 Rhr	6,000 Rhr	- Take IR reading - Stator winding manual cleaning with recommended solvent
12,000 Rhr	12,000 Rhr	All task at 6,000Rhr continued. - Check the insulation condition of the stator winding and re-varnish or other remedies appropriately.
18,000 Rhr	6,000 Rhr	All task at 6,000Rhr continued.
24,000 Rhr	24,000 Rhr	All task at 12,000Rhr continued. Cleaning the winding and ventilation duct Check slot wedge for tight fit Check end turn bracing Check condition of winding insulation, including ring circuit and end connection
30,000 Rhr	6,000 Rhr	All task at 6,000Rhr continued.
36,000 Rhr	12,000 Rhr	All task at 12,000Rhr continued.
42,000 Rhr	6,000 Rhr	All task at 6,000Rhr continued.
48,000 Rhr	24,000 Rhr	All task at 24,000Rhr continued.

5.1.4 Case study of MAN plant

The review of maintenance plan was based on the DC ramp test and Vibration test of the generators since there is no installed partial discharge monitoring system and it is not practical and not economical to introduce Sapugaskanda Power Station according to their retirement dates. Therefore a review of the maintenance plan was done based on the DC ramp test and Vibration test.

Those eight generators are serving energy for more than 15 years. Under this case study, only one generator is analysed since all generators are identical. So the DC

ramp test and vibration test results are conducted on Generator No 07 and results are used for the scheduling of preventive maintenance.

5.1.4.1 DC ramp test conclusion

During the 12,000 Rhr routine maintenance work of the Generator No 07, the stator and rotor windings were closely monitored. DC ramp test was carried out on 22nd April 2014 before taken into routine maintenance work. Results are shown in the curve of Figure 5.8

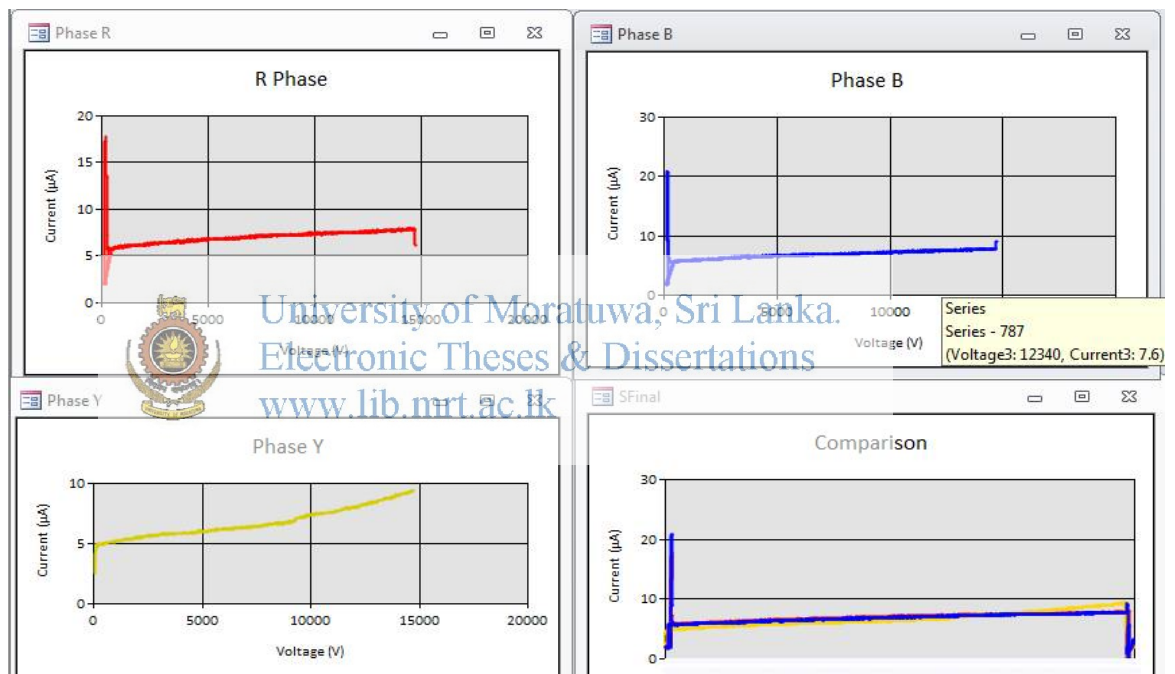


Figure 5:8 DC ramp test result before maintenance of G7, Sapugaskanda plant

Observation from the DC ramp test (Figure 5.8)

- Insulation materials: Glass polyester/mica paper tape/bonding epoxy resin.
- Phase R and phase B were initially deviated due to high moisture contamination.
- Phase Y observed a gradual increase of leakage current profile.
- High contamination of dust is observed.

Phase Y was considered for further to observe, as leakage current was higher compared to other phases. Figure 5.9 reproduce the test result phase given in Figure 5.8

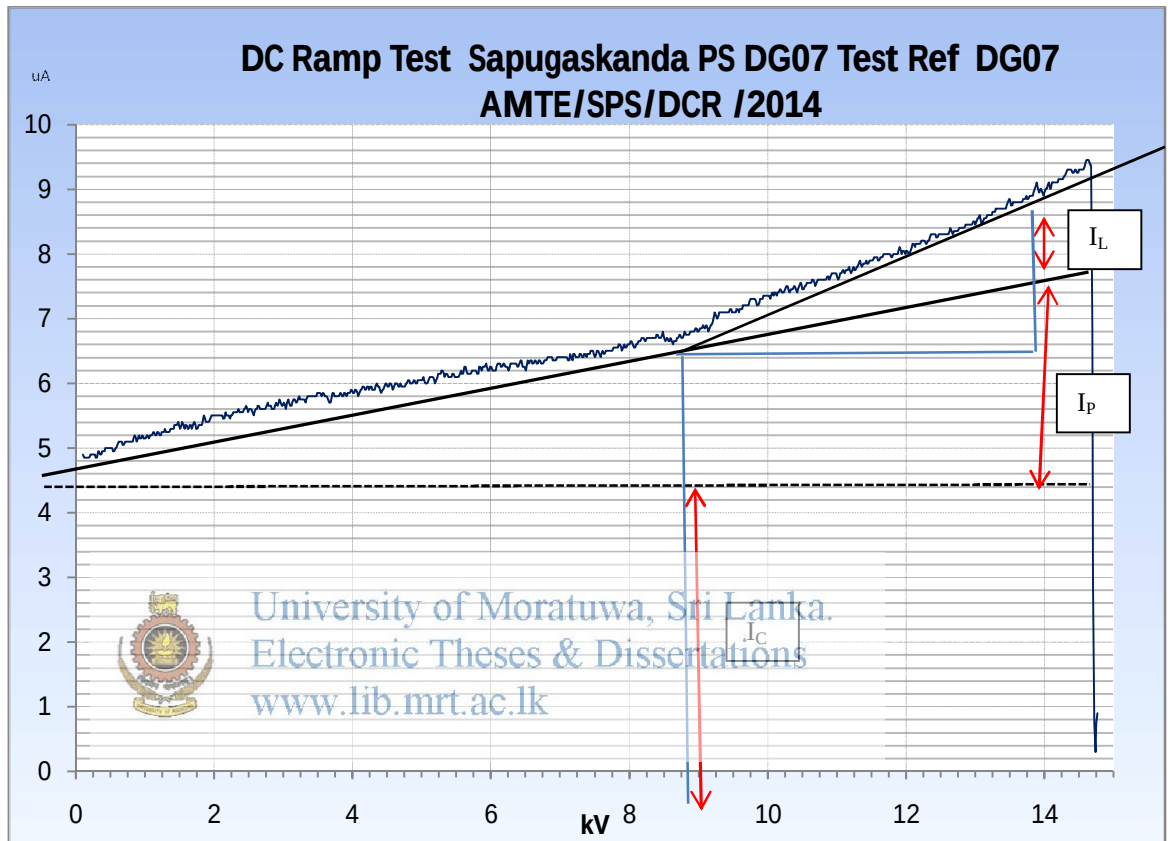


Figure 5:9 Before maintenance of DC ramp, Phase Y of G7, in Sapugaskanda plant

According to the above profile, following parameters can be calculated.

$$I_C = 4.7 \mu A$$

$$I_P \text{ at } 14 \text{ kV} = (7.9 - 4.7) \mu A = 3.2 \mu A$$

$$I_L \text{ at } 14 \text{ kV} = (9.1 - 7.9) \mu A = 1.2 \mu A$$

$$\begin{aligned} \text{Slope variation at } 9 \text{ kV} &= \frac{(9.1 - 6.8)}{(14 - 9)} \\ &= 0.46 \mu A/kV \end{aligned}$$

Therefore it was recommended to carry out a complete stator winding cleaning. After the cleaning process and necessary maintenance work, the DC ramp test was carried out. Recorded graphs are as follows;

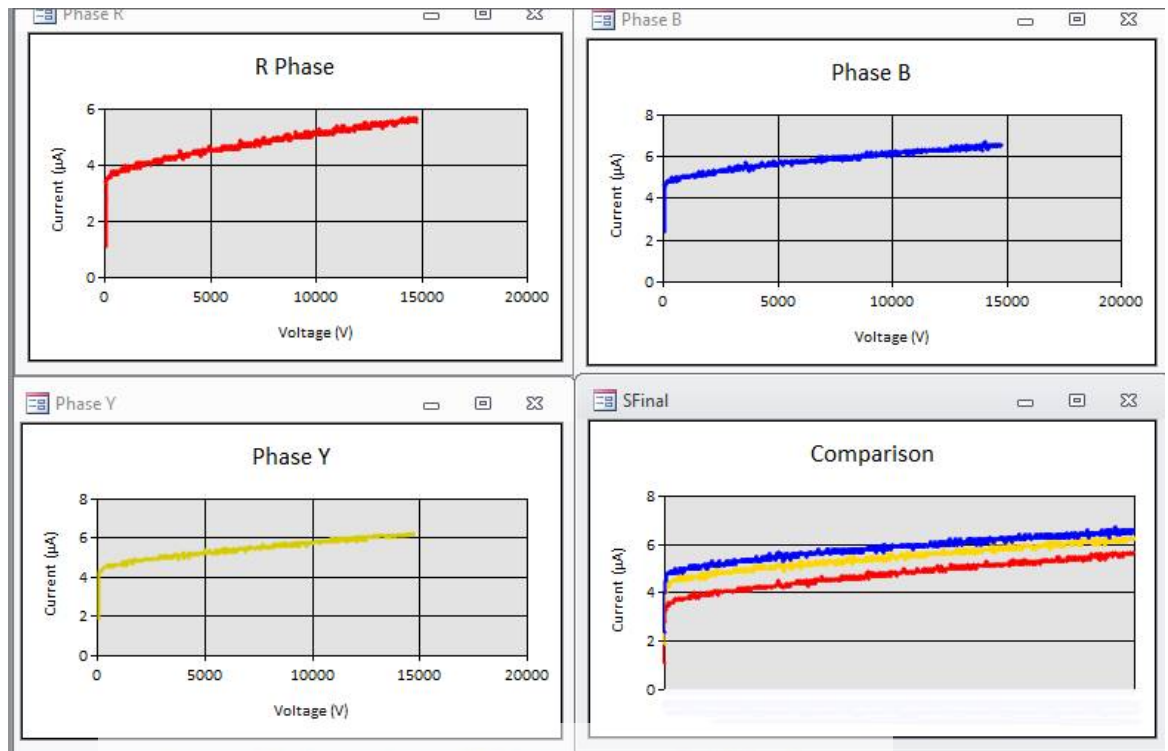


Figure 5:10 DC ramp test result after maintenance of G7, in Sapugaskanda plant

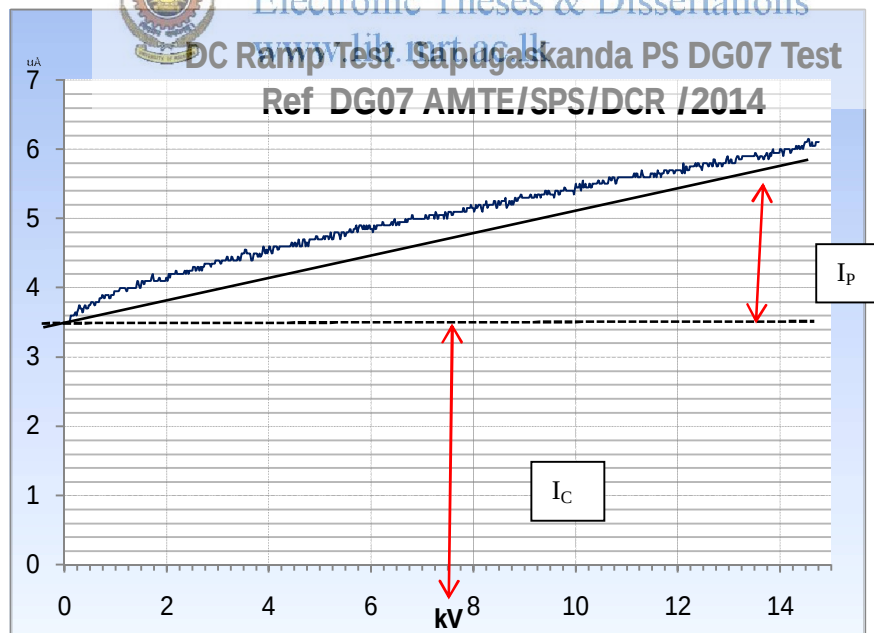


Figure 5:11 DC ramp test after maintenance of phase Y of G7, Sapugaskanda plant

$I_C = 4.0 \mu A$

$I_P \text{ at } 14 \text{ kV} = (6.0 - 4.0) \mu A = 2.0 \mu A$

$I_L \text{ at } 14 \text{ kV} = \text{negligible}$

According to above illustrated figures 5.8 & 5.9 show the poor conditions of stator winding insulations. After winding cleaning process, the figures 5.10 & 5.11 show the improvement of the insulation levels. Therefore DC ramp test method is the ideal tool to evaluate the stator insulation condition.

Table 5-5 Comparison with DC ramp result of Phase Y, Generator 07

	Before Maintenance	After Maintenance
Total leakage Current at 14kV	9.1 μ A	6.1 μ A
Capacitive current (I_C)	4.7 μ A	4.0 μ A
Polarization current (I_P) at 14 kV	3.2 μ A	2.0 μ A
Surface leakage current (I_L) at 14 kV	1.2 μ A	Negligible
Leakage current increment w.r.t voltage increment at 7kV	0.46 μ A/kV	No increment

According to the above comparison, we can identify a considerable improvement achieved from the maintenance. MAN plant of Sapugaskanda power station operates in a polluted environment with oil and dust for more than 15 years. Also those eight generators are having 3.1 – 3.4 range of PI index. (PI index table is attached in Appendix C.2.) Therefore it should add periodical DC ramp measurement for every 12,000 Rhr running hours and carry out special winding cleaning such as Dry ice cleaning during each and every 48,000 Rhr routine maintenance due to the high pollutant level of winding as observed from above testing and maintenance procedure.

5.1.4.2 Vibration test conclusion

8L 64/58 eight numbers of engines are fixed on a concrete base with dampening springs in the MAN plant. Since those engines are reciprocating type, horizontally connect to the generator as shown in the following figure 5.12.



Figure 5:12 Layout of MAN plant Genset

Vibration test has not been carried out from the beginning in this power station. Since there are no previous test data, faulty identification and trend analysis are difficult. However by understanding the vibration profile, we can diagnose any abnormality of the rotor and accordingly access effect for the stator winding.



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Chapter 4 Vibration Results

As described in Chapter 4 vibration results were taken for all four numbers of generators. Following Figure 5.12 shows the vibration profile of generator number 05 while running the Genset before taken for the 6,000 Rhr routine maintenance.

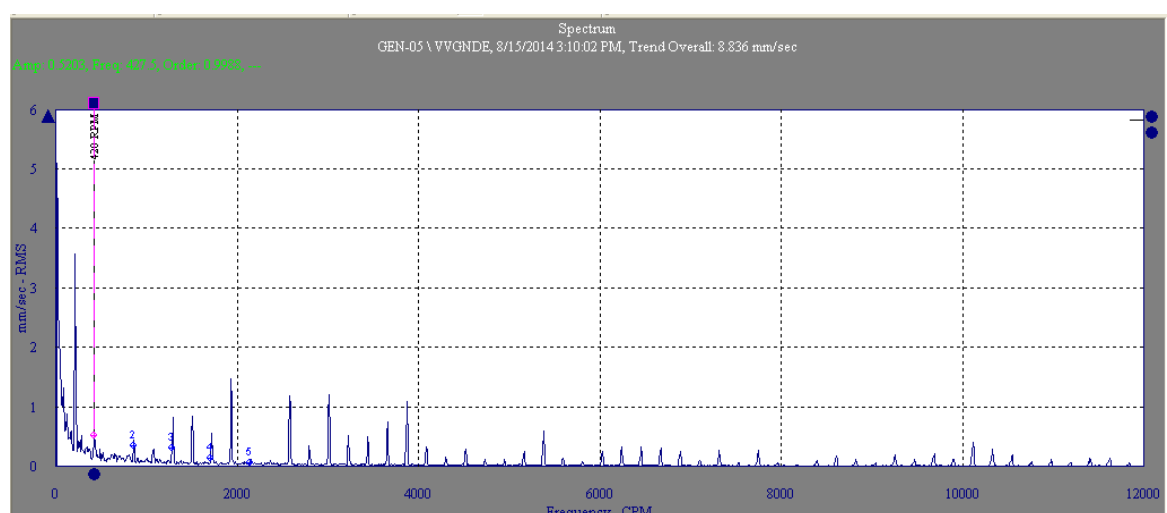


Figure 5:13 Vibration profile of Generator 05, Sapugaskanda plant

Above shown figure 5.13 consists with following list of foundation and harmonics levels,

Table 5-6 Classification of harmonics

	Harmonic Values		
	Amplitude (mm/S)	Frequency	% of Fund.
Fund	0.52	427	
2nd	0.334	855	64.23%
3rd	0.3018	1283	58.04%
4	0.124	1710	23.85%
4.5	1.461	1935	280.96%
5	0.0511	2138	9.83%
6	1.179	2580	226.73%
7	1.193	3015	229.42%
9	1.079	3878	207.50%

ISO 8528-9:1995, gives allowable vibration parameters for reciprocate internal combustion engines; refer Appendix B.1. It can be identified that the above generator is 10 MW larger horizontally coupled engines with 428 rpm engine speed and mounted on soft foundation. Therefore overall vibration velocity can be identified as less than 15 mm per Second at generator end for the acceptable vibration conditioned. Above generator overall vibration is 8.836 mm per second which is at acceptable level.

Above profile shows high magnitude of low frequencies and high frequencies. This will cause engine mechanical looseness due to any problems in the bearings or soft foundation mounting. Especially, when sub synchronous harmonic peak (4.5 X) is caused by oil whirling in pedestal bearing. Additionally those higher frequencies are due to engine valves operations, turbo charger speed, adjacent engines, etc.

This profile shows fundamental frequency as 427 rms. Also it can be identified as medium speed machines, since high vibration profiles cannot be firmly analyzed due to high inbuilt vibrations of those engines. Therefore the result taken in the present condition profile, can be compared with graph and will be taken in due course. Therefore presently took vibration profiles can be maintained as references. Since

vibration profiles are not fully accurate, it is recommended to do the vibration testing approximately 6,000 Rhr cycle. Then it can be observed any deviation during 6,000 Rhr routine maintenance work.

5.2 Kelanithissa Power Station.

Small gas turbine of this power plant, is used as a peaking power station and GT 7 is operated under the dry season in Sri Lanka. Gas turbines are acting as prime movers and those are coupled to high speed cylindrical rotor type synchronous generators. Diesel is used as fuel for those gas turbines, so the unit cost of generation is higher comparatively to other power stations.

All seven numbers of generators were introduced in three stages. First two stages (Year 1980 & 1981) are similar types of gas turbines (20MW) and installed in similar environment conditions.

5.2.1 Kelanithissa Small Gas Turbine

There are six cylindrical rotor type synchronous generators (which are coupled with gas turbine) had been installed in 1980-1981. Presently four generators are operating out of six generators. Details of generators are attached in appendix A.1.

5.2.1.1 OEM Recommended Maintenance Schedule

Generator Original Equipment Manufacturer (OEM) – BRUSH Ele. Mac. UK has instructed to carry out maintenance of the generators as below

- Clean dirt using dry compressed air
- Every one year inspect the winding and if there are excessive deposit dust or oil, clean using inhabitant such as 111 trichloroethane.
- Every one year check the air gap.
- Every three years, check the winding heads, the involutes and slot wedging. Also check the ventilation ducts in the stator body.

5.2.1.2 Present Practice of the Maintenance

The Gas turbine routine maintenance, as instructed by Original Equipment Manufacturer (OEM) – John Brown Engineering, has to attend maintenance in every 5,000 running hours. Accordingly gas turbines (prime mover) are taken out for instructed maintenance.

Presently it is practicing electrical maintenance parallel with the mechanical maintenance to reduce the outage period of the plant. Below table 5.8 shows the summery of the present generator maintenance practice for small gas turbine of the Kelanitissa power station.

Table 5-7 Routine maintenance shedhule of Kelanitissa small GTs

Cumulative Running Hour	Routine Maintenance Type	Maintenance of Generator
5,000 Rhr	5,000 Rhr	- Take IR reading - Winding cleaning using low pressure air
10,000 Rhr	10,000 Rhr	- Take IR reading - Stator winding manual cleaning with recommended solvent
15,000 Rhr	5,000 Rhr	All task at 5,000Rhr continued.
20,000 Rhr	20,000 Rhr	All task at 10,000Rhr continued. - Check the insulation condition of the stator winding and re-varnish or other remedies appropriately.
25,000 Rhr	5,000 Rhr	All task at 5,000Rhr continued.
30,000 Rhr	10,000 Rhr	All task at 10,000Rhr continued.
35,000 Rhr	5,000 Rhr	All task at 5,000Rhr continued.
40,000 Rhr	40,000 Rhr	All task at 40,000Rhr continued. Check the winding heads, involutes and slot wedging. Check ventilation ducts in the stator body.

5.2.2 Case study of small gas turbine

The review of maintenance plan was based on the DC ramp test and Vibration test of the generator since there is no installed partial discharge monitoring system and it is not practical and not economical to introduce Sapugaskanda Power Station according

to their retirement dates. Only four out of six small gas turbine generators are serving energy for more than 33 years. KPSGT03 and KPSGT06 are out of order due to abnormal vibrations occurred from the turbine side and other is generator winding failure and gas turbine failure. And rest of the four numbers of generators (KPSGT01, KPSGT02, KPSGT04, KPSGT05) are going to retire in due course. Therefore this kind of sophisticated techniques is not viable in this power station.

5.2.2.1 DC ramp test conclusion

During the 80,000 Rhr routine maintenance work of the Kelanithissa Power Station, Gas turbine No 03 stator and rotor winding were closely monitored. Therefore DC ramp test was carried out on 20th February 2013. The obtained curves are as follows;

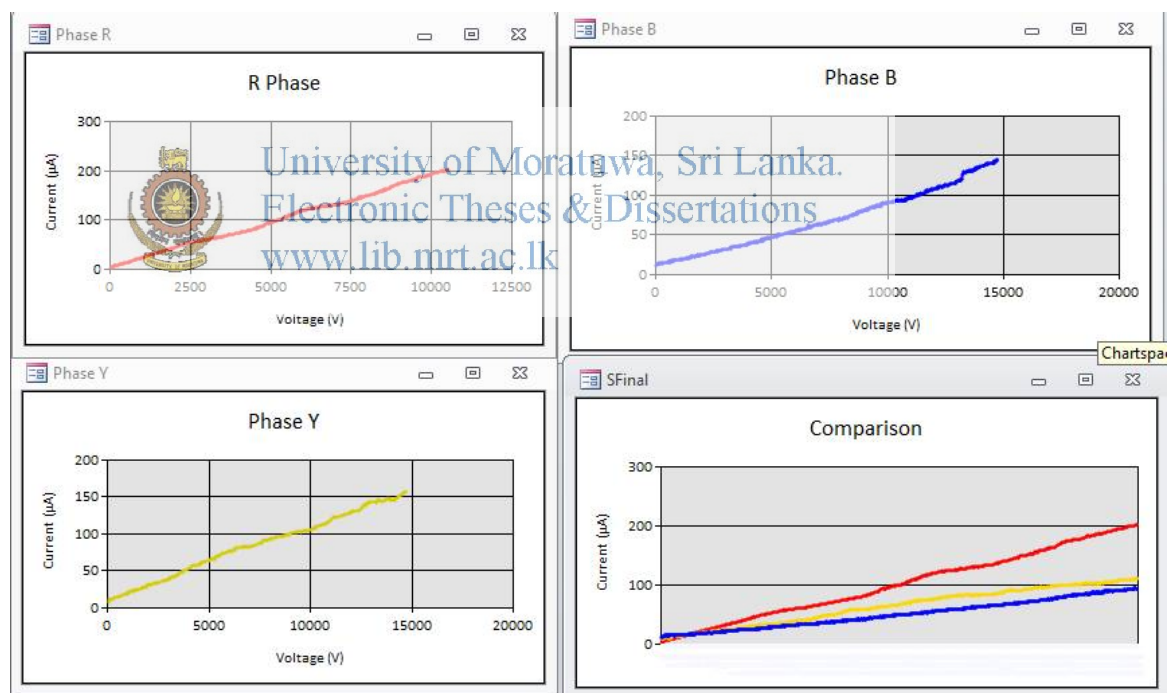


Figure 5:14 DC ramp test before maintenance of GT 3, Kelanitissa plant

Observation

- Insulation type is synthetic resin bonded mica glass tape.
- Leakage currents are higher owing to higher contamination of oil & dust.
- R phase has heavy surface contamination than other phases.
- High contamination of dust is observed.

- DC ramp test for R phase was interrupted at 10.495 kV, since higher total leakage current (more than 200 uA at 10 kV) of the winding.
- Other two phases show approximately 150uA at 15 kV. Therefore it is required for a special maintenance to overcome those issues.

During this 80,000 running hour maintenance, stator windings were observed and cleaned with a cleaning inhabitant.

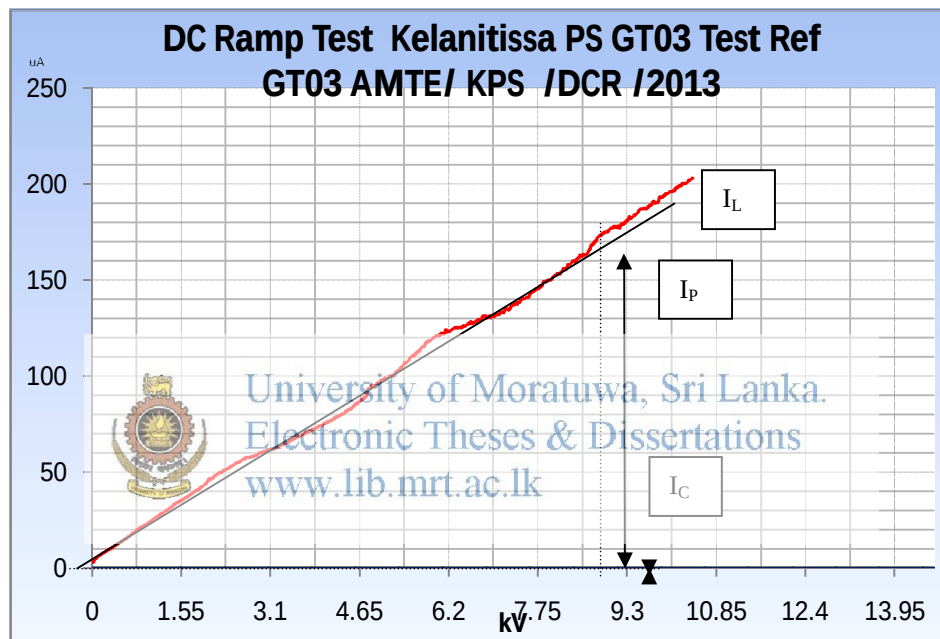


Figure 5:15 DC ramp test before maintenance of R phase of GT 3, Kelanitissa plant

According to the above profile, following parameters can be calculated.

$$I_C = 4 \mu A$$

$$I_P \text{ at } 9.3 \text{ kV} = (168 - 4) \mu A = 164 \mu A$$

$$I_L \text{ at } 9.3 \text{ kV} = (180 - 168) \mu A = 12 \mu A$$

$$\begin{aligned} \text{Slope variation at } 9 \text{ kV} &= \frac{(168-4)}{(9.3-0)} \\ &= 17.63 \mu A/kV \end{aligned}$$

Therefore it was recommended to attend complete stator winding cleaning. After the cleaning process and necessary maintenance work, the DC ramp test was carried out. Recorded graphs are as follows;

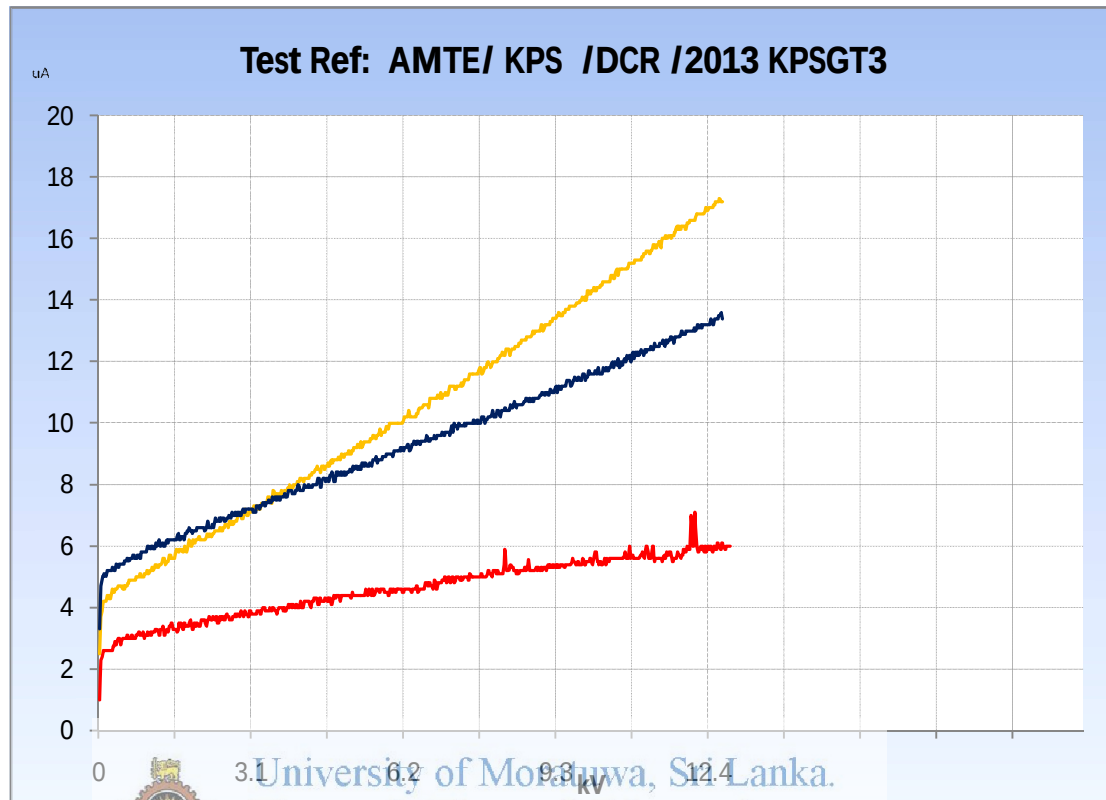


Figure 5.16 DC ramp test after maintenance of GT 3, in Kelanitissa plant

According to the above illustrated figures 5.14 & 5.15 show the bad conditions of stator insulations. After winding cleaning process, the figures 5.16 show the improvement of the insulation levels. Therefore DC ramp test method is the ideal tool to evaluate the stator insulation condition.

After winding cleaning process, total leakage currents were considerably decreased in every phase. Also total leakage current and current profiles are acceptable according to lorelynn mary rux [11]

Small gas turbines of Kelanitissa power station are serving power for 33 years. Also it is operating in a polluted environment with dust. Therefore it is directly affecting to the stator winding condition. Also those four generators are having 2.9 – 3.2 range of PI index. Therefore routinely measurement is required in recommended time intervals. Additionally it should add periodical DC ramp measurement in every

10,000 Rhr running hours and carry out special winding cleaning such as Dry ice cleaning during every 40,000 Rhr routine maintenance due to the high pollutant level of winding in this plant and abnormal leakage current from DC ramp test which was observed in gas turbine generator no 03.

5.2.2.2 Vibration test conclusion

Presently available four gas turbines are operating at 5100 rpm. Those gas turbines are running with lesser vibration in normal condition comparatively to diesel engines. Both turbine and the generator are fixed on soft foundation. Following figure 5.17 shows horizontal layout of small gas turbine.



Figure 5:17 Layout of KPSGT02, Kelanitissa plant

During the continuous running of the generators, at several times vibration reports have been taken. Vibration test gives more information to diagnose any abnormality of the rotor and accordingly access effect for the stator winding.

As described in Chapter 4, vibration results were taken for all four numbers of generators. Following Figure 5.18 shows the vibration profile of generator number 05 while running the gas turbine before taken for the 5,000 Rhr routine maintenance.

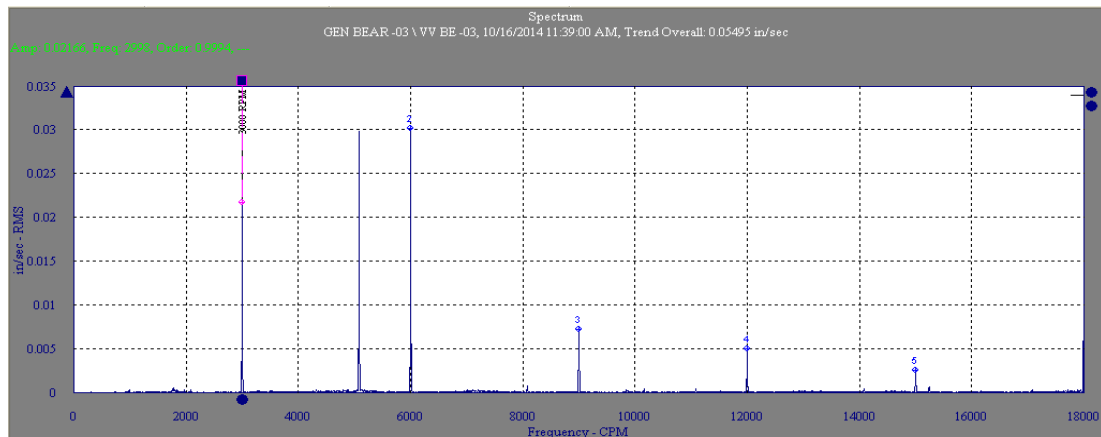


Figure 5:18 Vibration profile of Gas turbine 05, Kelanitissa plant

Above shown figure 5.18 consists with following list of foundation and harmonics levels,

Table 5-8 Classification of harmonics

Fund	Harmonic Values		
	Amplitude (mm/S)	Frequency	% of Fund.
Fund	0.0216	2998	
-	0.02967	5079	
2 nd	0.0301	6002	139.35%
3 rd	0.0072	9000	24.27%
4	0.0049	11998	16.28%
5	0.0025	15002	34.72%

ISO 8528-9:1995, gives allowable vibration parameters for reciprocate internal combustion engines; refer Appendix B.1. It can be identified that the above generator is 10 MW larger horizontally coupled engines with 428 rpm engine speed and mounted on soft foundation. Therefore overall vibration velocity can be identified as less than 15 mm per Second at generator end for the acceptable vibration conditioned. Above generator overall vibration is 8.836 mm per second which is at acceptable level.

Above profile shows 139.35 % of second harmonic amplitude with fundamental frequency. This will cause coupling imbalance between generator and turbine. Also

profile shows peak at 5079 rpm due to the gearbox vibration, since turbine speed drop down from 5100 rpm to 3000 rpm using gear box

This profile shows fundamental frequency as 2998 rms. Also it can be identified as high speed machines. Since this generator rotor is operating at high speed, vibration monitoring is critical and it requires periodical monitoring.

In this case, rotor coupling is required to inspect after taken for an outage. This kind of symptom can be identified using vibration test measurement. Accordingly it will help to plan their outages to prevent more harmful forced outages. Therefore it is recommended to conduct vibration measurement test each before 5,000 Rhr routine maintenance cycle before taken for the outage.

5.2.3 Kelanitissa Gas Turbine No7

KPSGT 07 is also called Fiat gas turbine. This Fiat gas turbine is generating power during dry season with power crisis. Presently it can serve a huge power within a very short period. Therefore KPSGT 07 is most important to maintain stability of the power system. Since KPSGT 07 is operating as a standby plant. It may cause a higher generation cost. Generator details are attached in Appendix A.1.

5.2.3.1 OEM Recommended Maintenance Schedule

Generator Original Equipment Manufacturer (OEM) – GEC ALSTHOM has instructed to carry out maintenance of the generators as below

- Every 16,000 running hour, clean dirt using dry compressed and air if there are excessive deposit dust or oil, clean using inhabitant
- Every one year check the air gap.
- Every three years, check the winding heads, the involutes and slot wedging. Also check the ventilation ducts in the stator body.

5.2.3.2 Present Practice of Maintenance

The Gas turbine routine maintenance, as instructed by Original Equipment Manufacturer (OEM) – Fiat Avio, has to attend maintenance in every 8,000 running hours. Accordingly gas turbines (prime mover) are taken out for maintenance as instructed.

Presently it is practicing electrical maintenance parallel with the mechanical maintenance to reduce the outage period of the plant. Below table 5.8 shows the summery of the present generator maintenance practice for Fiat turbine of the Kelanitissa power station.

Table 5-9 OEM Recommended Maintenance Schedule

Cumulative Running Hour	Routine Maintenance Type	Maintenance of Generator
8,000 Rhr	8,000 Rhr	- Take IR-reading - Stator winding manual cleaning with clean and dry pressure air
16,000 Rhr	16,000 Rhr	All task at 8,000Rhr continued. - Stator winding manual cleaning with recommended solvent
24,000 Rhr	8,000 Rhr	All task at 8,000Rhr continued.
32,000 Rhr	16,000 Rhr	All task at 16,000Rhr continued.
40,000 Rhr	8,000 Rhr	All task at 8,000Rhr continued.
48,000 Rhr	48,000 Rhr	All task at 16,000Rhr continued. Check the insulation condition of the stator winding and re-varnish or other remedies appropriately. Check slot wedge for tight fit Check end turn bracing
96,000 Rhr	96,000 Rhr	All task at 48,000Rhr continued. Close inspection of stator windings and rotor by ejecting of the rotor.

5.2.4 Case study of Gas Turbine No7

The reviewing of exist maintenance plan was based on the DC ramp test and vibration test since those are the only available technique for this generator. This 115MVA capacity generator is serving power generation for more than 17 years to

the power system of Sri Lanka. Recently the generator had been tripped few times and it was observed PD symptoms of the stator winding as shown in figure 5.19.



Figure 5:19 PD Symptoms observed from GT 07 on 2014.08.13

Online partial discharge monitoring system gives lots of information regarding partial discharges at the preliminary level. Therefore it can be obtain advantages which are mentioned in section 3.3.

Early detection of the PD symptoms helps to plan the outages and take the corrective actions to maintain the system reliability. Also it will significantly reduce the maintenance cost.

5.2.4.1 DC ramp test conclusion

During the 96,000 Rhr routine maintenance work of the Kelanithissa Power Station Gas turbine No 07 stator and rotor winding were closely monitored. Therefore DC ramp test was carried out on 2012.04.12. The obtained curves are as follows,

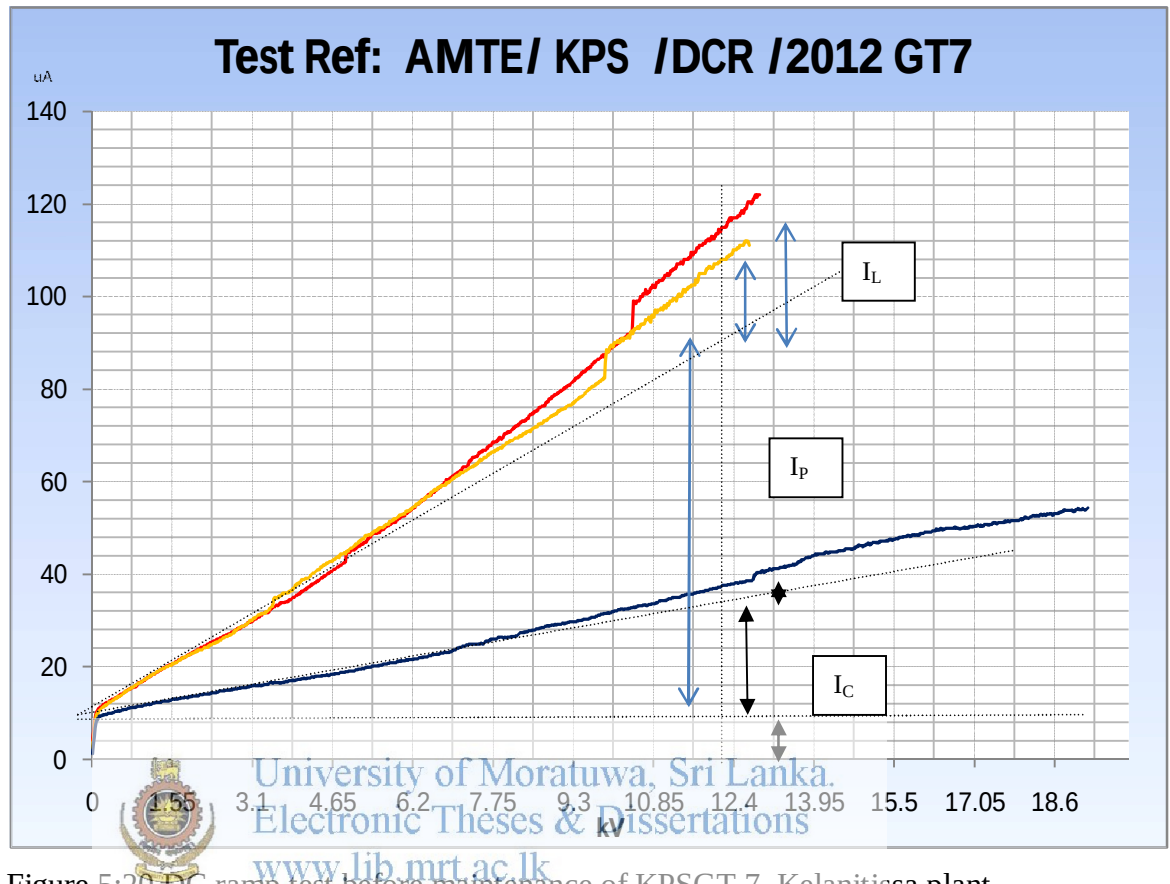


Figure 5:20 DC ramp test before maintenance of KPSGT 7, Kelanitissa plant

The insulation materials are epoxy resin/glass cloth & mica paper tape. According to the above profile, following parameters can be calculated [11]. High quality epoxy-mica insulation when tested with DC ramp, is attached in Appendix C.1

Table 5-10 Comparison of DC ramp result

	R Phase	Y Phase	B Phase
Capacitive current - I_C	9 μA	9 μA	9 μA
Polarization current - I_P at 12.4 kV	81 μA	81 μA	25 μA
Surface leakage current - I_L at 12.4 kV	26 μA	20 μA	4 μA

During this 96,000Rhr maintenance, winding cleaning special test was carried out in order to achieve performance of windings. Following figure 5:21 shows the dry ice cleaning process carried out on 2012.08.08.



Figure 5:21 Dry ice cleaning work of KPSGT7 during 96,000 Rhr maintenance

After complete cleaning process of generator, DC ramp test was carried out. During this test following graphs were taken to identify the status of the generator stator winding.

After the complete cleaning process of Gas turbine generator No 07, DC ramp test was carried out. During this test, the following graphs were taken to identify the status of generator stator winding.

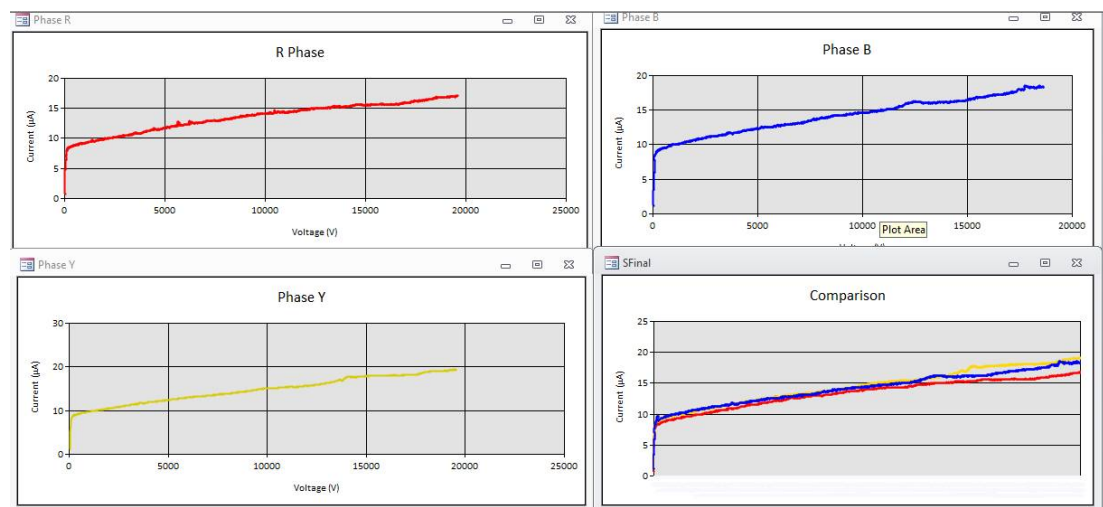


Figure 5:22 DC ramp test result after maintenance of KPSGT7, Kelanitissa plant

According to the above figure 5.22, leakage current of all three phases are considerably reduced. At all phases leakage currents are less than 20 μA at the 18 kV. It implies stator winding cleaning process helps to improve insulation level. Also it can be interpreted by the DC ramp test.

KPSGT7 generator installed in 1996 and delaying routine maintenance due to continuous power generating requirement, the stator winding condition has been maintained in poor condition. Therefore early detection of such as high dirt and moisture content will be more advantage to planning the maintenance activities.

This generator is operating in a polluted environment with oil and dust and PI index is 3.1. Therefore routine measurement is required in recommended time intervals. Additionally it should add periodical DC ramp measurement for every 8,000 Rhr running hours and carry out special winding cleaning such as Dry ice cleaning during each and every 24,000 Rhr routine maintenance due to the pollutant level of winding in this plant.



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5.2.4.2 Vibration test conclusion

Both Fiat gas turbine and generator (KPSGT7) are operating at 3000 rpm speed. This kind of gas turbine is running with lesser vibration in normal condition comparatively diesel engines. Both turbine and the generator are fixed on a concrete base with dampening springs. Following figure 5.23 shows horizontal layout of gas turbine No 7. (also called Fiat turbine)



Figure 5:23 Kelanitissa Gas turbine No 07

Since this gas turbine operating at 3,000 rpm speed, vibration is more harmful to the rotating parts and then effect to generator stator also. Comparatively capacity of the generator, adverse effect to the power system is also considerably high. Therefore it is necessary to have special tools for measuring vibration before propagation and damage to other parts.

As described in Chapter 4, vibration result is taken of the generators. Following Figure 5.25 shows the vibration profile of the generator while running before taken for the 8,000 Rhr routine maintenance.

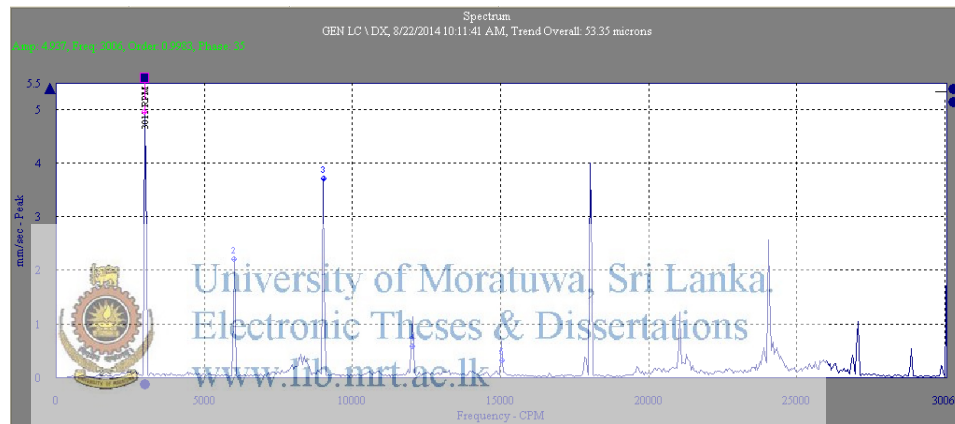


Figure 5:24 Vibration test result of Gas turbine Generator No 07 of Kelanitissa plant

Above shown figure 5.25 consists with following list of foundation and harmonics levels,

Table 5-11 Classification of harmonic component

	Harmonic Values		
	Amplitude (mm/S)	Frequency	% of Fund.
Fund	4.937	3006	
2nd	2.207	6012	44.70%
3rd	3.705	9018	167.87%
4	1.141	12024	30.80%
5	0.6725	15030	58.94%
6	3.992	18036	593.61%
7	1.219	21042	30.54%
8	2.565	24048	210.42%
9	1.043	27054	40.66%
10	0.5361	28858	51.40%

According to ISO 10816, it can be identified KPSGT7 generator horizontally coupled gas turbines which are mounted on soft foundation. Therefore overall vibration velocity should be less than 1.8 mm/sec for the acceptable conditioned vibration. However generator shows 4.937 mm per sec magnitude of foundation, therefore it is necessary to attend planned outage for inspect the status of both generator and turbine. Refer Appendix B.2

Above profile 6X and 8X amplitudes are significantly higher than the fundamental frequency. It may be cause mechanical looseness of the component. Since harmonics levels are significantly high, it is require arranging immediate outage.

This profile shows fundamental frequency as 3,006 rms. therefore it can be identified as high speed machines. High vibrations are cause to damage to both generator and gas turbine because it is running at high speed. Considering severity of this generator, it is recommended to do the vibration testing approximately 4,000 Rhr cycle. Then it can be help to plan the inspection and do the corrective action every 4,000 Rhr routine maintenance work accordingly.



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5.3 Kelanithissa Combined Cycle Power Station.

The 165 MW naphtha-fuelled combined cycle power station was commissioned in August 2002.[7] It consists of one 110 MW gas turbine, one 55 MW steam turbine, and one exhaust heat recovery boiler. Plant can be operated in two modes as open (i.e. Gas turbine only) cycle or combined cycle (i.e. Both Gas turbine and steam turbine).

5.3.1 Gas turbine of Kelanitissa Combined Cycle Plant

132 MVA cylindrical rotor type synchronous generator is coupled with gas turbine of the kelanitissa combined cycle power station. Generator details are attached in Appendix A.3

5.3.1.1 OEM Recommended Maintenance Schedule

Generator Original Equipment Manufacturer ALSTOM France and UK has instructed to carry out maintenance of the generators as below

- Every 16,000 running hour, clean dirt using dry compressed and air if there are excessive deposit dust or oil, clean using inhabitant
- Every one year check the air gap.
- Every three years, check the winding heads, the involutes and slot wedging. Also check the ventilation ducts in the stator body.
- Every 96,000 running hour, remove the generator rotor and closely monitor both rotor and stator winding.

5.3.1.2 Present Practice of the Maintenance

Both gas turbine routine and steam turbine maintenance, as instructed by Original Equipment Manufacturer (OEM) – Marubeni Engineering, has to attend maintenance in every 8,000 running hours. Accordingly gas turbines (prime mover) are taken out for instructed maintenance.

Presently it is practicing electrical maintenance parallel with the mechanical maintenance to reduce the outage period of the plant. Below table 5.8 shows the summery of the present generator maintenance practice of the Kelanitissa combined cycle power station.

Table 5-12 OEM Recommended Maintenance Schedule

Cumulative Running Hour	Routine Maintenance Type	Maintenance of Generator
8,000 Rhr	8,000 Rhr	- Take IR reading
16,000 Rhr	16,000 Rhr	All task at 8,000Rhr continued. - Stator winding manual cleaning with clean and dry pressure air
24,000 Rhr	24,000 Rhr	All task at 16,000Rhr continued. - Stator winding manual cleaning with recommended solvent
32,000 Rhr	8,000 Rhr	All task at 8,000Rhr continued.

40,000 Rhr	16,000 Rhr	All task at 16,000Rhr continued.
48,000 Rhr	48,000 Rhr	All task at 16,000Rhr continued. - Check the insulation condition of the stator winding and re-varnish or other remedies appropriately. - Check slot wedge for tight fit - Check end turn bracing
96,000 Rhr	96,000 Rhr	All task at 48,000Rhr continued. - Close inspection of stator windings and rotor by ejecting of the rotor.

5.3.2 Case study of Gas turbine

This 132MVA capacity generator is serving power generation for more than 14 years to the power system of Sri Lanka. This generator, namely KCCPGT is used for a less hydro generating period in Sri Lanka. Gas turbine is operating on open cycle process. It act as prime movers and those are coupled to high speed cylindrical rotor type synchronous generators. During the winding inspection on routine maintenance work, the PD symptoms are identified on end windings of the stator winding as shown in figure 5:25

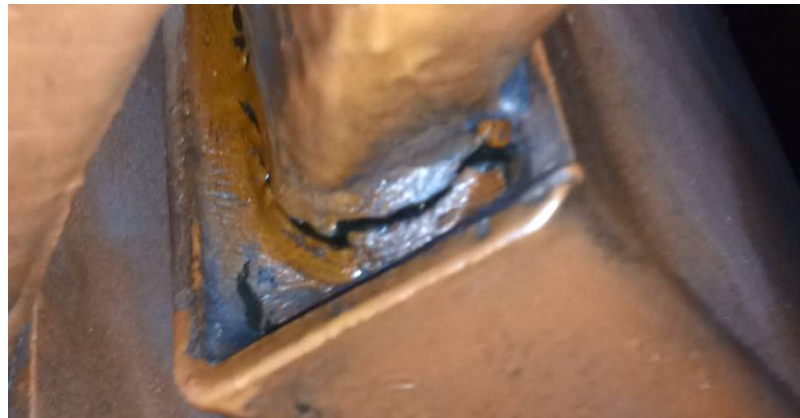


Figure 5:25 PD Symptoms observed from KCCPGT on 2014.08.08

Online partial discharge monitoring system gives lots of information regarding partial discharges at the preliminary level. Therefore it can be obtain advantages which are mentioned in section 3.3. Early detection of the PD symptoms help to

planned the outages and takes the corrective actions to maintain the system reliability. Also it will significantly reduce maintenance cost.

During the case study, DC ramp test results were only considered, because existing Bently Nevada 3500 instrument is monitored continuous vibration of both gas turbine and steam turbine of the plant.

5.3.2.1 Vibration test conclusion

Both Gas turbine generator vibration and steam turbine generator vibration are monitored by Bently Nevada 3500 instrument. The instrument is continuously monitored the vibration of the generator rotors. According to the commissioning reports of these plants, the allowable limits are as table 5-13

Table 5-13 Reference vibration level of Kelanitissa combined cycle plant

	Present level(mm/sec)	Alarm level(mm/sec)
Gas turbine generator	0.02 – 0.03	0.2
Steam turbine generator	0.015 – 0.03	0.15

Since those generators have been installed from 2000-2001, present condition is at acceptable range. Also from the beginning of this plant, there are no vibration faulty records in the plant. Since available vibration monitoring is sufficient for the continuous monitoring, it can be identify any increment of vibration level of the generator. Therefore it was not obtain vibration test because existing online system more reliable for the vibration measurement. Accordingly preventive maintenance can be scheduled.

5.3.2.2 DC ramp test conclusion

During the 24,000 Rhr routine maintenance work of the Gas turbine generator of Kelanitissa Combined cycle power station, the stator and rotor winding were closely monitored. Following figure 5.17 shows DC ramp test was carried out on gas turbine generator before cleaning process.

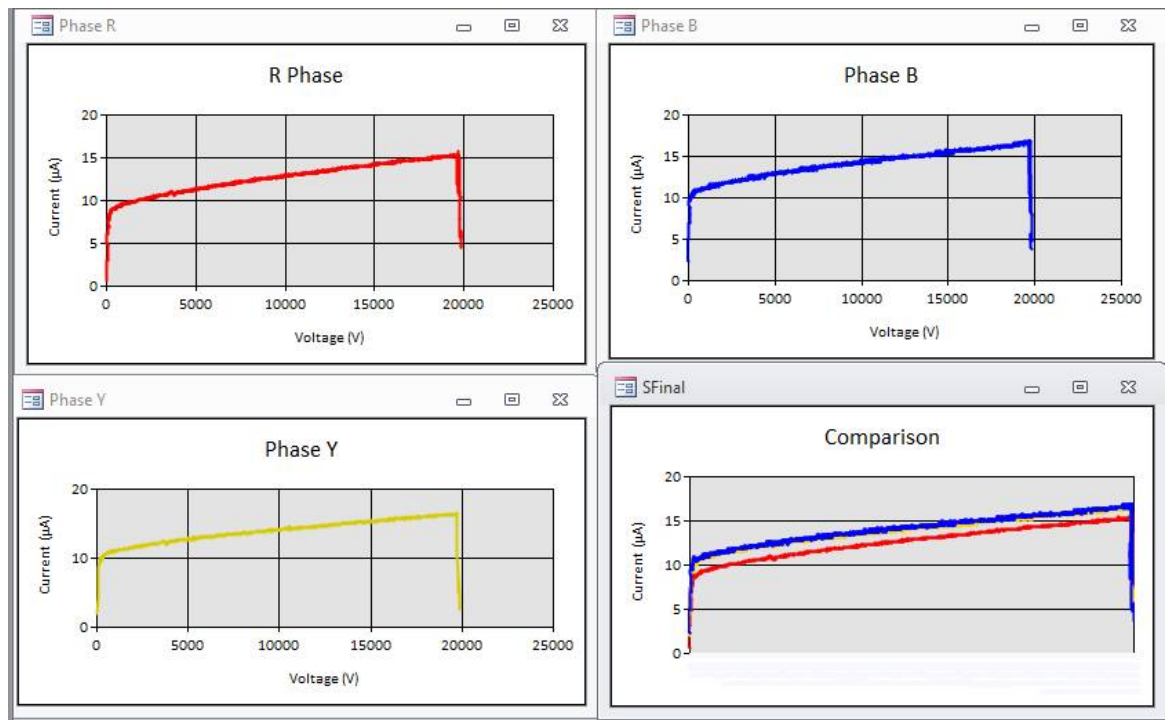


Figure 5:26 Before maintenance of GT of Kelanitissa Combined cycle power station



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Observation from the DCR ramp test Figure 5.26

- Tested after cleaning the winding and heaters ON for 24 Hrs.
- Insulation materials: Glass polyester/mica paper tape/bonding epoxy resin.
- No abnormalities observed.

However all the data taken from DCR 50 instrument, was plotted using EXCEL for the close observation shown figure 5.27

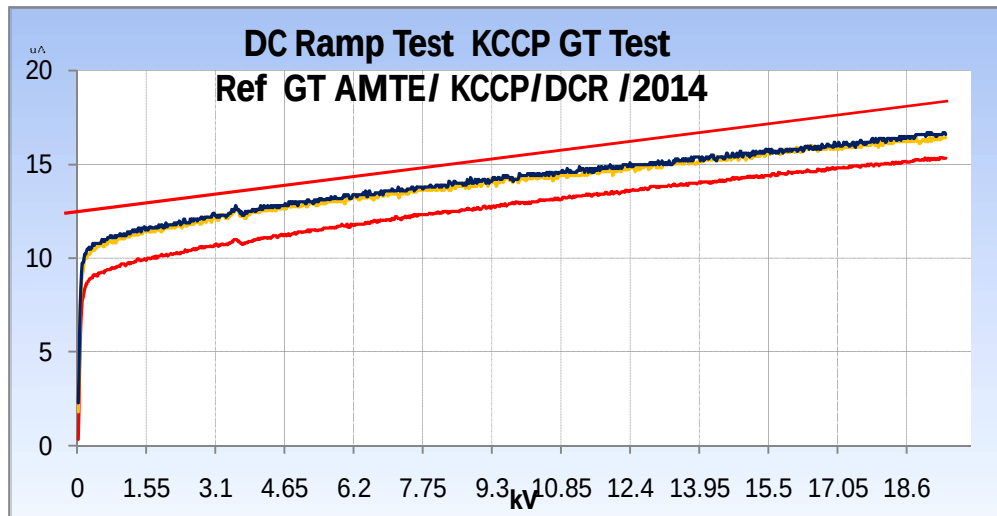


Figure 5:27 DC ramp test before maintenance of Gas turbine generator, Kelanitissa Combined Cycle power station.

According to Prof. Lorelynn Mary Rux, generator stator winding insulation materials such as Glass polyester/mica paper tape/bonding epoxy resin behave as shown in above figure 5.18. refer Appendix C. Therefore present condition of the winding is at an acceptable level. Also this plant is newly constructed and generator is located at a clean environment. Therefore environment stresses are not significantly affected. Since the polarization index of this generator is 3.5, generator preventive maintenance is not required within shorter periods according to present condition. Therefore DC ramp testing is recommended to obtain every 12,000 running hour intervals.

5.3.3 Steam turbine of Kelanitissa Combined Cycle Plant

75.955 MVA cylindrical rotor type synchronous generator is coupled with steam turbine of the kelanitissa combined cycle power station. Generator details are attached in Appendix A.3.

Generator original equipment ALSTOM France and UK has given maintenance instruction same as 110 MW gas turbine generator of the combined cycle machine. Also present maintenance practice also same as gas turbine generator.

5.3.4 Case study of Steam Turbine

This 75.955MVA capacity generator is serving power generation for more than 13 years to the power system of Sri Lanka. This generator, namely KCCPST is used for a less hydro generating period. While in combined cycle the flue gas is directed through Heat Recovery Steam Generator (HRSG) using diversion damper. Thereafter that steam flow drives steam turbine adding another 75.955 MW addition to gas turbine. Steam turbine act as prime movers and those are couple to high speed cylindrical rotor type synchronous generators.

Recently there were two occasions recorded which were given differential earthing faulty condition. During the winding inspection, it was not found any abnormality of the winding. Normally combined cycle power plant is generating 2.5 GWhr in daily basis. 30% of power generation is powered by steam turbine without additional fuel cost. Therefore steam turbine generator is a vital asset to the power system of Sri Lanka.



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Online partial discharge monitoring system gives lots of information regarding partial discharges at the preliminary level. Therefore it can be obtain advantages which are mentioned in section 3.3.

Early detection of the PD symptoms help to planned the outages and do the corrective actions to maintain the system reliability. Also it will significantly reduce maintenance cost.

5.3.4.1 DC ramp test conclusion

During the 24,000 Rhr routine maintenance work of the Steam turbine generator of Kelanitissa combined cycle power station, the stator and rotor winding were closely monitored. Therefore DC ramp test was carried out on 16/05/2014. The obtained curves are as follows;

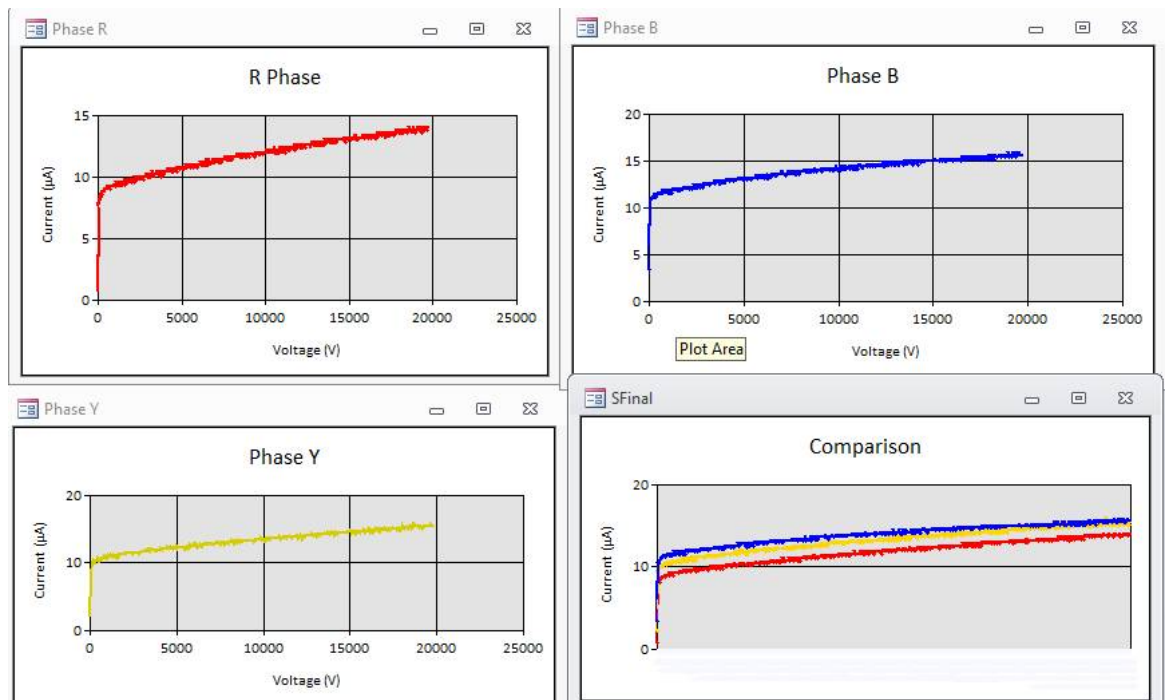


Figure 5:28 DC ramp test before maintenance of Steam Turbine Generator ,Kelanitissa Combined cycle power station

- Tested after cleaning the winding and heaters ON for 24 Hrs.
- Insulation materials: Glass polyester/mica paper tape/bonding epoxy resin.
- No abnormalities observed.

However all the data taken from DCR 50 instrument, was plotted using EXCEL software as shown figure 5:29

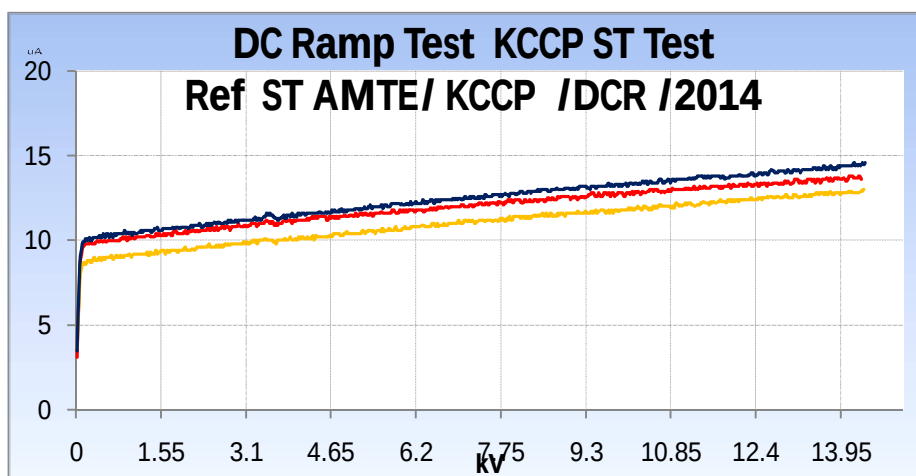


Figure 5:29 DC ramp test before cleaning of Steam turbine generator.

According to Prof. Lorelynn Mary Rux, generator stator winding insulation materials such as Glass polyester/mica paper tape/bonding epoxy resin behave as shown above in figure 5.29. Therefore present condition of the winding is at an acceptable level.



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CHAPTER 06

6 CONCLUSION

Generator condition monitoring acts as an excellent transducer for detecting electrical and mechanical faults in the Synchronous generators. Modern developed test methods DC ramp, Partial discharge and vibration measurement help to identify the faulty symptoms before propagation faults and eliminate major forced outages. Three main power plants called Kelanitissa plant, Sapugaskanda plant and Kelanitissa Combined Cycle plant were analyzed for scheduling of preventive maintenance based on above mentioned test results.

According to the conducted test, following test schedules can be recommended with reference to the power station after identification of the generator stator winding status.

6.1 Review of Sapugaskanda Power Station

Presently practicing maintenance pattern and tests are based on a parallel maintenance pattern with Diesel Engines maintenance which was initiated from the beginning of the power station. According to discussed stresses are the cause to winding condition changes and the overall performance.

6.1.1 Review of maintenance schedule of Pielstick plant

Below mention test procedures are recommended to include their present maintenance plans.

- Since DC ramp test is carried out in every 6,000 Rhr running hour, it is not require to obtain the insulation resistance test results on the same outage period.
- There is no available vibration detection method in practice, hence it is required to conduct vibration test just before every 6,000 Rhr maintenance for the identification of rotor misalignment, imbalance, looseness, etc. Also by doing this vibration test, it will help to identify air gap changes between

rotor pole and stator, pedestal bearing faults or misalignment of rotor shaft, etc.

- Partial discharge detecting system was not proposed since partial discharge symptoms have not been seen for those four generators of Pielstick plant.
- Present generator maintaining practices are recommended to continue based on the tests performances.

6.1.2 Review of maintenance schedule of MAN plant.

Below mentioned test procedures are recommended to include their present maintenance plans.

- Since DC ramp test is carried out in every 12,000 Rhr, it is not required to obtain the insulation resistance test results on the same outage period.
- There is no available vibration detection method in practice, hence it is required to conduct vibration test just before every 6,000 Rhr maintenance for the identification of rotor misalignment, imbalance, looseness, etc. Also by doing this vibration test, it will help to identify air gap changes between rotor pole and stator, pedestal bearing faults or misalignment of rotor shaft, etc.
- Partial discharge detecting system was not proposed since partial discharge symptoms have not been seen for those eight generators of MAN plant
- Present generator maintaining practices are recommended to continue based on the tests performances.

6.2 Review of Kelanitissa Power Station

Presently practicing maintenance pattern and tests are based on a parallel maintenance pattern with Gas turbine maintenance which was initiated from the beginning of the power station. According to discussed stresses are the cause to winding condition changes and the overall performance.

6.2.1 Review of maintenance schedule of Small Gas Turbine

Below mentioned test procedures are recommended to include their present maintenance plans.

- Since carryout of DC ramp test in every 10,000 Rhr running hour, it is not required to obtain the insulation resistance test results on the same outage period.
- There is no available vibration detection method in practice, hence it is required to conduct vibration test just before every 5,000 Rhr maintenance for the identification of rotor misalignment, imbalance, looseness, etc. Also by doing this vibration test, it will help to identify air gap changes between rotor pole and stator, pedestal bearing faults or misalignment of rotor shaft, etc.
- Partial discharge detecting system was not proposed since partial discharge symptoms have not been seen for those four generators of small gas turbines
- Present generator maintaining practices are recommended to continue based on the tests performances.



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6.2.2 Review of maintenance schedule of Fiat Genarator

Below mentioned test procedures are recommended to include their present maintenance plans.

- Since DC ramp test is carried out in every 8,000 Rhr running hour, it is not required to obtain the insulation resistance test results on the same outage period.
- There is no available vibration detection method in practice, hence it is required to conduct vibration test just before every 4,000 Rhr maintenance for the identification of rotor misalignment, imbalance, looseness, etc. Also by doing this vibration test, it will help to identify air gap changes between rotor pole and stator, pedestal bearing faults or misalignment of rotor shaft, etc.
- Present generator maintaining practices are recommended to continue based on the tests performances.

In propose practice, from DC ramp test or vibration test, inside voids cannot be identified. As discussed in chapter 3, the PD activity is unstable, which means it may not be active today, but tomorrow. However PD symptoms were observed in gas turbine No 07. It was observed during the routine maintenance. If partial dischargers were initiated, there is severe attack to chemical structures of the winding. Therefore extensive and expensive force outages are occurred. By considering the generating capacity and the loading pattern of this generator, it is required to install online partial discharge monitoring system to increase the lifespan.

6.3 Review of Kelanitissa Combined Cycle Power Station

Presently practicing maintenance pattern and tests are based on a parallel maintenance pattern with Gas turbine and steam turbine maintenance which were initiated from the beginning of the power station. According to discussed stresses are the cause to winding condition changes and the overall performance.



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6.3.1 Review of maintenance schedule of Gas Turbine Generator

Below mentioned test procedures are recommended to include their present maintenance plans.

- Since DC ramp test is carried out in every 24,000 Rhr running hour, it is not required to obtain the insulation resistance test results on the same outage period.
- Presently continuous vibration detection method is available in practice. This system gives vibration alarm & tripping condition according to the installation condition. Therefore continuous feedback can be obtained for smooth operation of the power station.

In propose practice, from DC ramp test or vibration test, inside voids cannot be identified. As discussed in chapter 3, the PD activity is unstable, which means it may not be active today, but tomorrow. However PD symptoms were observed in Gas

turbine of the plant. It was observed during the routine maintenance. If partial dischargers were initiated, there is severe attack to chemical structures of the winding. Therefore extensive and expensive force outages are occurred. By considering the generating capacity and the loading pattern of this generator, it is required to install online partial discharge monitoring system to increase the lifespan.

6.3.2 Review of maintenance schedule of Steam Turbine Generator

Below mentioned test procedures are recommended to include their present maintenance plans.

- Since DC ramp test is carried out in every 24,000 Rhr running hour, it is not required to obtain the insulation resistance test results on the same outage period.
- Presently continuous vibration detection method is available in practice. This system gives vibration alarm and tripping condition according to the installation condition. Therefore continuous feedback can be obtained for smooth operation of the power station.

In propose practice, from DC ramp test or vibration test, inside voids cannot be identified. As discussed in chapter 3, the PD activity is unstable, which means it may not be active today, but tomorrow. However PD symptoms were observed in Gas turbine of the plant, since Steam turbine also has similar manufacturing features from the same supplier as Gas turbine. Also both gas turbine and steam turbine are operating in parallel in normal operation pattern. Therefore voids will be occurred in steam generator due similar stresses occurred as in Gas turbine. Since partial dischargers were initiated, there is severe attack to chemical structures of the winding. Therefore extensive and expensive force outages may occur. By considering generating capacity and the loading pattern of this generator, it is required to install online partial discharge monitoring system to increase the lifespan.

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8 APPENDIX - A

A.1 Generator Details of Kelanitissa Power Station.

Generator Name	Manufacturer	Year of Install	Rated Output (MVA)	Rated Voltage (kV)	Insulation Class	Cooling type	Duty	Present Status
KPSGT1	BRUSH Ele. Mac. UK	1980	33.12	11.5	F	Air	Cont.	Available
KPSGT2	BRUSH Ele. Mac. UK	1980	33.12	11.5	F	Air	Cont.	Available
KPSGT3	BRUSH Ele. Mac. UK	1980	33.12	11.5	F	Air	Cont.	Not Available
KPSGT4	ALSTHOM Atlantique	1981	26.69	11	F	Air	Cont.	Available
KPSGT5	ALSTHOM Atlantique	1981	26.69	11	F	Air	Cont.	Not Available
KPSGT6	ALSTHOM Atlantique	1981	26.69	11	F	Air	Cont.	Available
KPSGT7	GEC ALSTHOM	1996	150	15	F	Air	Cont.	Available

A.2. Generator Details of Sapugaskanda Power Station

Generator Name	Seirial Number	Manufacture	Year of Installed	Rated Output (MVA)	Rated Voltage (kV)	Power factor	Rated Speed (rpm)	Air gap (mm)	Insulation Class	Cooling type	Duty
SPSG1	411942	ALSTHOM Atlantique Belfort-France	1984	25.625	11	0.8	428.6	12 mm	F	Air	Cont.
SPSG2	411943	ALSTHOM Atlantique Belfort-France	1984	25.625	11	0.8	428.6	12 mm	F	Air	Cont.
SPSG3	411944	ALSTHOM Atlantique Belfort-France	1984	25.625	11	0.8	428.6	12 mm	F	Air	Cont.
SPSG4	411945	ALSTHOM Atlantique Belfort-France	1984	25.625	11	0.8	428.6	12 mm	F	Air	Cont.
SPSG5	D9260205601	SIEMENS Germany	1998	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.
SPSG6	D9260205602	SIEMENS Germany	1998	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.
SPSG7	D9260205603	SIEMENS Germany	1998	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.
SPSG8	D9260205604	SIEMENS Germany	1998	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.
SPSG9	D9260207401	SIEMENS Germany	1999	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.
SPSG10	D9260207402	SIEMENS Germany	1999	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.
SPSG11	D9260207403	SIEMENS Germany	1999	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.
SPSG12	D9260207404	SIEMENS Germany	1999	12.9	11	0.8	428.6	6.5 mm	F	Air	Cont.

A.3. Generator Details of Kelanitissa Combined Cycle Power Station

Generator Name	Serial No.	Manufacture	Year of Installed	Rated Output (MVA)	Rated Voltage (kV)	Power factor	Rated Speed (rpm)	Insulation Class	Cooling type	Duty
KCCPGTG	500486	ALSTOM France and UK	2000	132	15	0.8	3000	F	Air	Continuous
KCCPSTG	500602	ALSTOM France and UK	2001	75.955	11.5	0.8	3000	F	Air	Continuous

APPENDIX - B

Appendix B.1 ISO 8528-9:1995

Declared engine speed	Rated power output of the generating set (less $\phi = 0.21$)	Vibration displacement A_{rms}			Vibration velocity v_{rms}			Vibration acceleration a_{rms}		
		RIC engine A_{RIC} mm	generator 1 value 1 mm	generator 2 value 2 mm	RIC engine v_{RIC} mm/s	generator 1 value 1 mm/s	generator 2 value 2 mm/s	RIC engine a_{RIC} m/s ²	generator 1 value 1 m/s ²	generator 2 value 2 m/s ²
nominal	≤ 15 II-cylinder engine	—	1.3	1.3	—	0	00	—	44	50
	≤ 300 kW ≤ 5 000	—	0.8	0.85	—	00	00	—	31	38
	≤ 10	—	0.82 (4)	0.84	—	0.10	0.10	—	25 (4)	31 (4)
> 1 200 but ≤ 3 000	≤ 10	—	—	—	—	—	—	—	—	—
	> 10 but ≤ 50	—	0.64	—	—	0.0	—	—	29	—
	> 50 but ≤ 100	—	0.4	0.4	—	25	30	—	16	19
> 120 but ≤ 200	> 100 but ≤ 200	0.72	0.4	0.4	—	25	30	28	16	19
	> 200	0.72	0.32	0.45	—	20	28	28	13	16
	> 200 but ≤ 1 200	0.72	0.25	0.34	—	0.0	0.4	20	13	16
> 1 200 but ≤ 1 500	> 1 200	—	0.25	0.28	—	16	22	—	11	14
	> 1 250	—	0.24 (0.16 (4))	0.32 (0.34 (4))	—	15 (10 (4))	20 (16 (4))	28	13 (10 (4))	19 (15 (4))
	> 1 500	—	—	—	—	—	—	—	—	—

NOTE — The relationship between vibration velocity and vibration frequency is shown in figure 6.

1. The values A_{RIC} and A_{rms} are determined from the following equations by using the values given in the table for v_{rms} :

$$A_{RIC} = 0.0103 \times v_{rms}$$

$$A_{rms} = 0.005 \times v_{rms}$$

2. In the case of large hours coupled generators (see the values measured at point 5 (see figure 1 all) meet the values for generators.

3. The stated values for RIC engines are applicable for engines with power output a) of more than 100 kW, 1 for engines a) with power output below 100 kW, no typical value after.

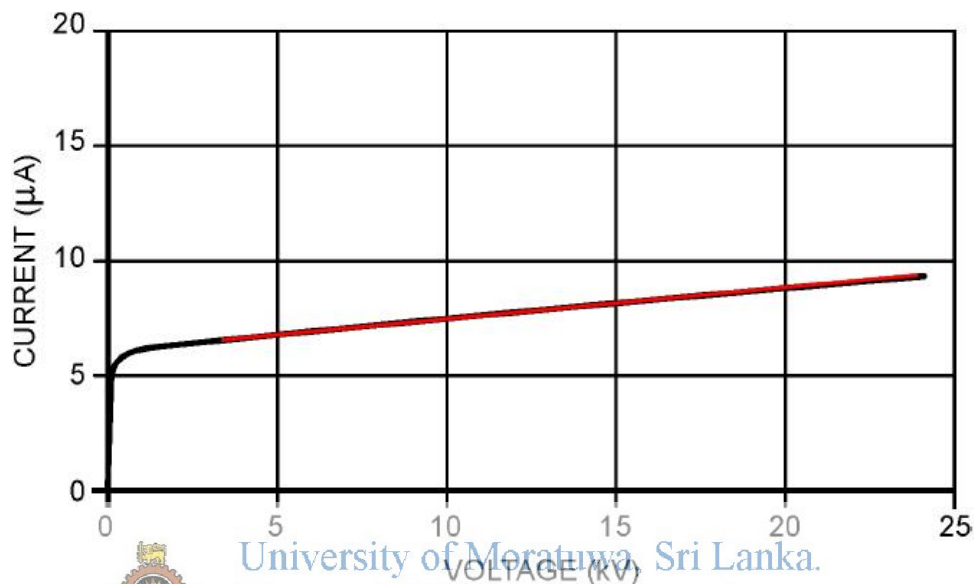
4. These values are subject to agreement between the manufacturer and customer.

5. The values given in parentheses are applied to generators mounted on solid concrete foundations. In these cases the actual measurement for points 1 and 2 in figure 1 at point 5 shall be 50 % of the values given in parentheses.

Appendix B.2 – ISO 10816 guide lines

VIBRATION SEVERITY PER ISO 10816						
Machine			Class I small machines	Class II medium machines	Class III large rigid foundation	Class IV large soft foundation
	in/s	mm/s				
Vibration Velocity Vrms	0.01	0.28				
	0.02	0.45				
	0.03	0.71		good		
	0.04	1.12				
	0.07	1.80				
	0.11	2.80		satisfactory		
	0.18	4.50				
	0.28	7.10		unsatisfactory		
	0.44	11.2				
	0.71	18.0				
	1.12	28.0				
	1.80	45.0				

C.1 High quality epoxy-mica insulation when tested with DC ramp



Typical ramped voltage test result for a new epoxy-mica insulation. The relatively flat I - V response indicates that the dipole polarization current component is relatively small compared to the geometric capacitance charging. As evidenced by the smooth and linear trace, the leakage current is negligible and no signs of space charge polarization or partial discharges are observed.

Source- The physical phenomena associated with stator winding insulation condition as detected by the ramped direct high-voltage method By Lorelynn Mary Rux

C.2 PI index of thermal complex generator

Power Station	Generator No	Year of manufactured	Insulation class	PI index
Kelanithissa P.S.				
	GT 1	1981	F	2.9
	GT 2	1981	F	3.0
	GT 3	1981	Presently Not Available	
	GT 4	1982	F	3.1
	GT 5	1982	F	3.2
	GT 6	1982	Presently Not Available	
	GT 7	1997	F	3.1
Sapugaskanda P. S.				
Stage 1	G1	1983	F	2.3
	G2	1983	F	2.4
	G3	1983	F	2.3
	G4	1983	F	2.1
Stage 2	G5	1997	F	3.1
	G6	1997	F	3.2
	G7	1997	F	3.1
	G8	1997	F	3.2
Stage 3	G9	1998	F	3.3
	G10	1998	F	3.4
	G11	1998	F	3.2
	G12	1998	F	3.2
Kelanithissa Combined Cycle P.S.				
	GT	2000	F	3.6
	ST	2001	F	3.7