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Investigative Fault Analysis of 11KV Slip-Ring Induction Motors

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Abstract:- Induction motors are the prime movers in industries that drive all the processes and equipment like heavy-duty gear boxes and mills used for production. A slip ring induction motor is an asynchronous motor in which the speed it operates is not equal to the synchronous speed of the rotor. Although they are very efficient and robust, there are many factors like poor working conditions, heavy operating duty, Poor power supply, etc., that can cause failure in the motor operation. This paper examines different causes of Electrical failures of Slip ring induction motors. We ran diagnostics tests on three fault zones of the motor, viz, the Insulation, Stator, and Rotor using MCE Max Software tester which is a motor circuit evaluator. Analyzing parameters like Resistive Imbalance (RI), Inductive Imbalances (II) etc. which result lead to excess heat generation that causes cracking, and abrasion on the insulation are examined. We also looked at Capacitance to ground (CTG) which shows the level of contamination buildup on the surface of the windings. All 11KV slip ring induction motors irrespective of the type, had a strong positive and negative correlation association between fault indicators on the Motors. This paper did a detailed analysis on the impact of these fault indicators on the overall motor and insulation health and proposed the use of periodic overhaul intensive maintenance plan to combat the negative impact of these fault indicators. Finally, a high CTG, RI, and II, leads to a low polarization index (PI), Low Dielectric Absorption (DA), and a very low Resistance to Ground RTG; showing very poor overall Stator, Rotor, and Insulation health. With periodic intensive overhaul maintenance (PIOM), the ingress of both carbon dust, condensation, environmental contamination and other undesirable build-ups on the windings can be reduced, allowing effective and proper cooling of the drives.

Keywords:- *Resistive Imbalance, Inductive Imbalance, Capacitance to Ground, Polarization Index, Dielectric Absorption, Insulation, Resistance to Ground.*

I. INTRODUCTION

Induction motors are electrical devices that are used to convert electrical energy into mechanical energy. It is generally used for industrial applications due to its self-starting characteristics. Induction motors are the prime movers in industries that drive all the processes and equipment used for production. Without induction motor to drive the heavy-duty gearboxes and mills, production would not be possible. There several types of induction motors used in industry to drive different loads, the load type determines the size of the motor, kilowatt and the torque required [1-3]. A slip ring induction motor is an asynchronous motor in which the speed it operates is not equal to the synchronous speed of the rotor [4]. The rotors of this type of motor are wound type which comprises of a steel core cylindrical laminated and a semi-closed groove, bounded at the outer circumference to accommodate a 3-phase insulated winding circuit. The rotor is usually wound to be equal to the number of poles on the stator. Slip ring induction motors are types of induction motors used in the industry, they are usually used where high torque and low stating current are required. Since it has various advantages such as improved power factor, high starting torque, and low initial current, it finds application in equipment requiring high torque in industries like cement and steel, and in equipment like cranes, mills, induced draft fans, and Electrostatic precipitator fan. The rotor windings consist of a greater number of windings, less current, and higher induced voltage compared to the squirrel-cage rotor [5]. External resistance through slip rings is connected to the windings, which major function is to control the torque/speed of a motor [6].

Although they are very efficient there are many factors like poor working conditions, heavy operating duty, Poor power supply, poor working environment, improper installation of motor and manufacturing factors of the motor, etc., that can lead to failure in the motor operation [7]. If the faults are not identified and rectified beforehand, can pose threat to reliability and safety of operation as well as result in large revenue loss to the industry including the fact that they extremely expensive, therefor fault analysis of these drive is highly important even though they are highly efficient and operate reliably yet they are subject to different types of Faults, which are undesirable. To ensure their efficiency, the root causes of these fault must be identified and nipped to the bud so that the life span of these drives can be prolong [8]. These faults could be either electrical or mechanical, using motor circuit evaluator to focus on the causes of electrical faults by analyzing different fault zones on the wound rotor drives, and proffering solutions to problems arising from high resistive imbalance, capacitance to ground, low polarization index, dielectric absorption and low resistance to ground by assessing how much the variance and deviation from the values of these parameters affect the performance of a Slip-ring induction motor [9].

Having studied previous work that has been done on motor fault diagnosis which brought out that more in-depth research should be done on analyzing motor test results, especially those gotten from Motor Circuit Evaluator (MCE) to determine the actual health of the motors, focusing only 11KV slip ring induction motors. This fact and the deep desire to mitigate Slip-ring motor failures serves as the catalyst that propelled us to carry out this study looking at how the data obtained relate to each other, and what these data is trying to communicate to us concerning the health of the motor parts, like the stator, rotor, windings, insulation system and the ground protection. In the data's obtained a high inductive imbalance is accompanied most times than not with a high resistive imbalance and either a high capacitance to ground or a low polarization index, while some showed inclusive results. Previous works carried out failed to give us a certainty to conclusively say where these data were leading, or how they relate and influences the deterioration of the Motor. This work involves critical analysis of the data presented by these tests, analyses results obtained, finding the correlation in the data presented, and interpreting trends to predict a failure about to occur, the state of the insulation and possible actions to increase the life span of this equipment.

II. STATE OF THE ART

There are over 30 different tests and monitors that can be used to diagnose motor and generator winding condition or the overall status of the insulations. There are tools also that have been used over the years to carry out these tests. If all these tests are to be carried out one will spend considerable amount of money and the long duration of time that this equipment will be out of service [10]. The main aim of motor testing is to prevent unnecessary failure, reveal hidden problems, evaluates dynamic parameters such as distortion, balance, and temperature fluctuations, as well as more static parameters like electrical current leakage, wire damage and insulation [11-13].

The very earliest form of involved visual inspection which before a fault might go unnoticed as some faults are not readily visible to the human eyes. For a reliability-centered maintenance Plant motor testing is often the tool used for predictive and preventive maintenance. The importance of making motor test part of the preventive maintenance is because once a motor is damage, the effect is irreversible (often referred to as core damage); this reduces the efficiency of the motor, or the drive may not run at all [11].

Based on a study of the reliability of IEEE motor, bearing faults are the most frequent root cause of in electric motors (41%), followed by stator fault (37%) and rotor fault (10%) [12]. Several methods have been used to detect the different types of faults in an Induction Motors [14-15]. These apply to the vibration analysis, current spectrum, thermal analysis, and other techniques to detect these faults [16-17].

Studies also exist that reported the impacts of faults on motors, most using simulated motors and MATLAB to examine faults using motor current signature analysis (MCSA) and another method analysed the waveform of input current for a single-phase induction motor capacitor-run. (SIMCR) to detect the faults (refs). The SIMCR was subject to various internal and external faults and the current was measured. Bearing faults and armature faults (broken rotor bar) were applied to the SIMCR and analyses of results obtained showed distortions in the current wave were resultant of these faults (bearing and armature) when the motor operated under different loads with different ratings of running capacitors [18].

In the past relative work was limited in that it was focused on faults on a single-phase induction motor and capacitor run, Split-Phase, 3-phase, and squirrel cage induction motors and not specifically on Slip-ring induction motors [19]. 11kv Slip-ring motors has a wound rotor which can cause a lot of abnormalities in the results obtained when this factor is not taken into consideration. Studies that used analytical models showed analytical models are not as accurate as numerical models, also models based on magnetic circuits, models based on electrical circuits and hybrid models where not as effective as Numerical models are more comprehensive in Induction motor (IM) fault analysis [20-21]. Numerical analysis model which is used by the Motor Circuit Evaluator (MCE), makes performance analysis and fault diagnostics of their lower calculation time important and effective in field equipment analysis [22].

This paper analysis is based on numerical models of Motor Circuit Analysis, proper and predictive maintenance can increase the efficiencies of electrical equipment typically by 20%. Therefore, motor circuit analysis (MCA) is import focus of this work, as MCA enables proactive maintenance or replacement, help prevent motor failures, and improve motor systems energy efficiency. MCA allows the reliability analyst a detail view of the inductance, phase angle, simple resistance, ground insulation condition, complex resistance, and other tests like polarization index to determine the condition of the electric motor (Slip-ring) windings. Also worthy of note is that all previous work was based on online analysis and had limited parameters that was tested, as much as they were useful, when 11000KV is involved, it can pose a lot of dangers to both the testing personnel and the test equipment, this research was done offline which involved more test parameter was available for analysis than if online test was used. The readings are best obtained with the equipment de-energized, for reasons of safety and accuracy. MCA test is an offline for the resistance-to-ground measurement, inclusive of other measurements that makes motor circuit defects easy to find. It measures electrical characteristics like capacitance, inductance and impedance which alerts the analyst about the condition of the windings. turn-to-turn shorts is indicated by Inductance.

The aim is to identify problems and deterioration trend, early in the process that indicates future problems before they amalgamized into expensive repairs or a critical failure resulting in downtime.

This study to do critical analysis on the data presented by these tests, analyze, find the correlation in the data presented and interpret trends to predict a failure about to occur, the state of the insulation and possible actions to increase the life span of these equipment's.

III. RESEARCH METHODOLOGY

The test follows four basic steps which are: planning, field test step, data collection, and analysis. Since motors used are High Voltage device, electrical safety was observed during isolating and data collection. The set-up is shown in figure 1.

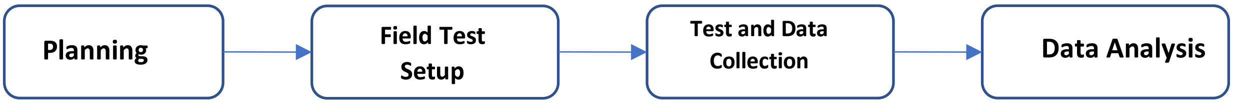

Fig. 1: Methodology block diagram

A. *Planning:*

The test equipment and materials for the planning process are discussed in subsection below

- *Materials and Equipment:*

  The data analysis involved data received from the MCEmax, Model No: 5552(fig 2) and the motor details is shown in Table 1.

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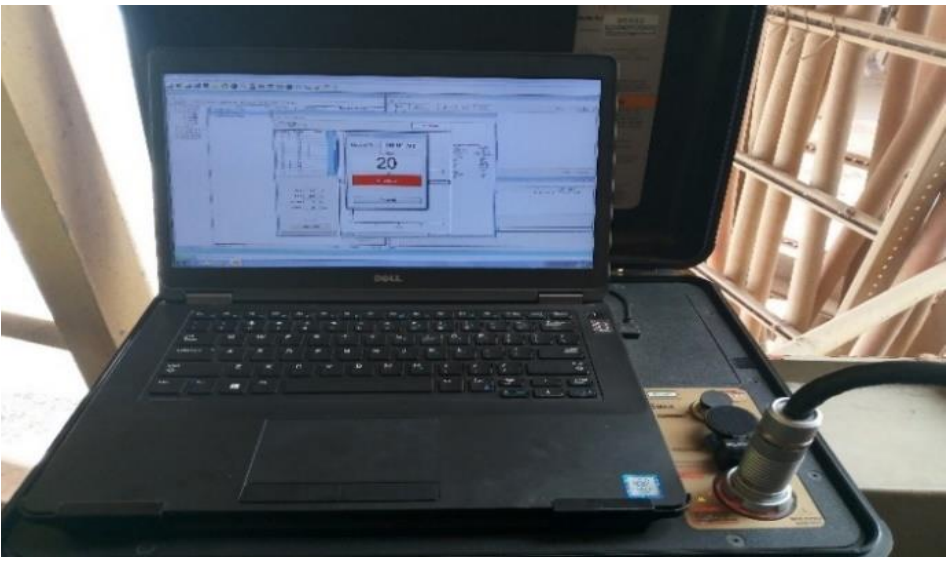


Fig. 2: MCEmax Test Module (PDMA Cooperation)

Table 1: Motor Details

Motor Detail	KW	RPM	Voltage		FLA	
			Stator	Rotor	Stator	Rotor
Motor 1	6300	995	11000	2320	396	1620
Motor 2	4000	996	11000	1550	245	1580
Motor 3	4000	994	11000	1880	247	1350

B. *Field Test Set-Up*

The first step in carryout the test/ maintenance work on the motor in the field, is to get a permit to work clearance, this work permit is a document that allows the isolation of the motor, when this document is duly signed then, the breaker is turned off and racked out, then lock-out Tag-out is place on the breaker to ensure no one turns it on again. After the LOTO has been placed we the proceeded to the motor for the tests.

- *Experimental Procedure:*

  To ensure accurate data collection, all industrial electrical safety precautions was observed before carrying out the test on any of the motors involved in this work, the below steps were taken at the motor.

- Disconnection from all possible energy sources
- Separation from all Parallel Paths (LRS, VFDs, Control Electronics Circuits)
- Release of all store energy.
- Disconnection of all power cables to the motor
- Isolation of the carbon brushes from the Slip-rings.

- Test probes were connected to the motors. The test probes' connection to the stator and rotor are shown in figures 3A, B, and C respectively.

➢ *Verifying Circuit is De-energized*

Due to the high voltage the motors used a hot stick to discharge the motor of every static charge, there after a multimeter meter was used after the disconnection to verify, that the circuit was deenergized. The following steps was used to verify circuit is deenergized:

- Verified proper operation of multimeter
- Verified circuit for medium and high voltage are de-energized with a non-contact AC voltage detector.
- Verified and Ensured induced Phase-to-Phase Voltage < 0.5volts VAC
- Verified and Ensured induced Phase-to-Ground Voltage < 1.5volts VAC
- Verified low level stored voltage Phase-to-Ground is < 15 volts VDC
- Ensured the motor was not rotating by verifying Phase-to-Phase resistance Measurement was not Fluctuating.

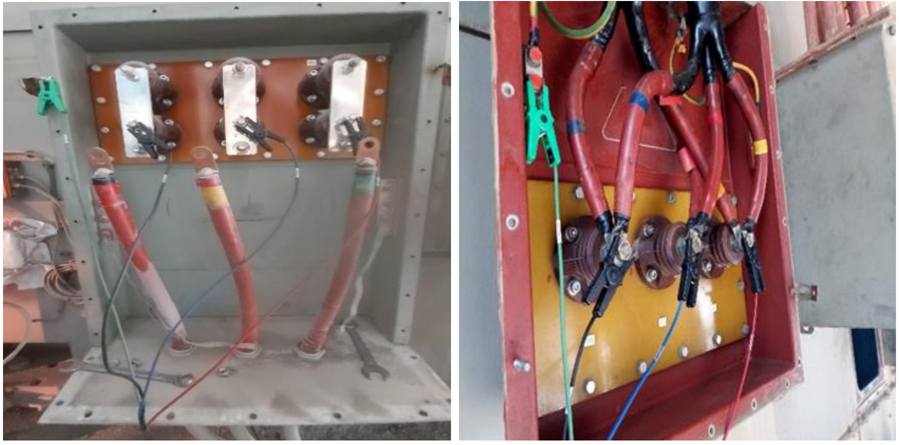

(A) (B)

Fig. 3(A and B): test probes connected to stator

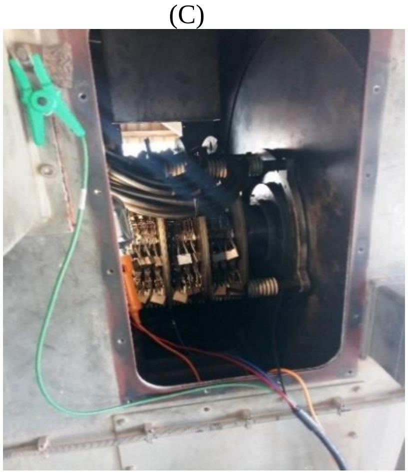

(C)

Fig. 3(C): test probes connected to rotor

C. Test and Data Collection

The following steps was taken to collect test data.

- The tester and the power battery were ensured to be charged.
- MCEGold software was started, Figure 4 shows the Start-up page.
- Test selected as default MCE, name plate details of the motors under test was inputted into the tester.
- Asset test location was selected using a drob-down button. Test positions 0- motor leads for used to test stator and test position 12- Slip-ring, was used to run test for the rotor, Table 2, below shows the test voltage, frequecy, Charge time and Motor Temperature for both the stator and rotor [13]. While Figures 5A and B show Parameter set up and running windows respectively

Table 2: Test Parameters

PARAMETERS	STATOR	ROTOR
Frequency	1200Hz	1200Hz
Charge Time	600 S	600S
Voltage	2500 V	1000V
Motor Temp	38 ^{0}C	40 ^{0}C

Site
Obajana Cement

Login Mode
Stand Alone

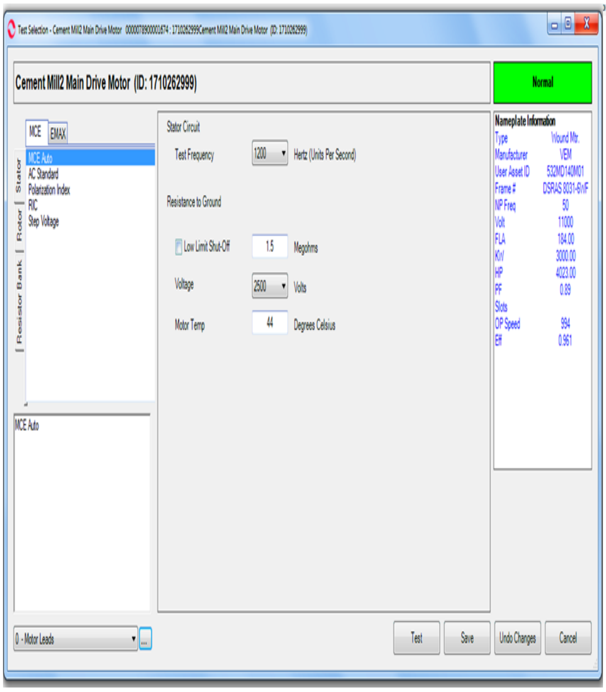
Language
English

Display Mode
MCEGold

Licensed To:
Obajana Cement
Application Mode:
Stand Alone

Version : 3.0.3.156 SP 1

Fig. 4: Start-up page of the MCE Gold Software on the tester



Test Selection - Cement Mill2 Main Drive Motor 0000078900001674 : 1710262999Cement Mill2 Main Drive Motor (ID: 1710262999)

Cement Mill2 Main Drive Motor (ID: 1710262999)

Normal

Stator Circuit

Test Frequency 1200 Hertz (Units Per Second)

Resistance to Ground

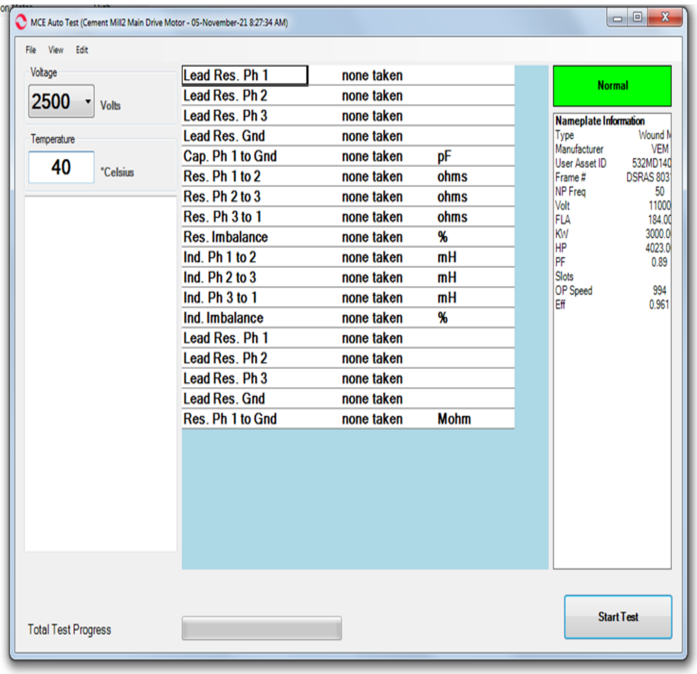
☐ Low Limit Shut-Off 1.5 Megohms

Voltage 2500 Volts

Motor Temp 44 Degrees Celsius

Nameplate Information	
Type	Wound Mtr.
Manufacturer	VEM
User Asset ID	532MD140M01
Frame #	DSRAS 8031-6WF
NP Freq	50
Volt	11000
FLA	184.00
KW	3000.00
HP	4023.00
PF	0.89
Slots	
OP Speed	994
Eff	0.961

Fig. 5(A): Test Parameters value set up Window.



MCE Auto Test (Cement Mill2 Main Drive Motor - 05-November-21 8:27:34 AM)

Voltage 2500 Volts

Temperature 40 *Celsius

Lead Res. Ph 1	none taken	
Lead Res. Ph 2	none taken	
Lead Res. Ph 3	none taken	
Lead Res. Gnd	none taken	
Cap. Ph 1 to Gnd	none taken	pF
Res. Ph 1 to 2	none taken	ohms
Res. Ph 2 to 3	none taken	ohms
Res. Ph 3 to 1	none taken	ohms
Res. Imbalance	none taken	%
Ind. Ph 1 to 2	none taken	mH
Ind. Ph 2 to 3	none taken	mH
Ind. Ph 3 to 1	none taken	mH
Ind. Imbalance	none taken	%
Lead Res. Ph 1	none taken	
Lead Res. Ph 2	none taken	
Lead Res. Ph 3	none taken	
Lead Res. Gnd	none taken	
Res. Ph 1 to Gnd	none taken	Mohm

Nameplate Information	
Type	Wound M
Manufacturer	VEM
User Asset ID	532MD140
Frame #	DSRAS 803
NP Freq	50
Volt	11000
FLA	184.00
KW	3000.0
HP	4023.0
PF	0.89
Slots	
OP Speed	994
Eff	0.961

Fig. 5(B): Test Running Window.

D. *Data Analysis:*

Running these test different Fault Zone Analysis was utilized to ensure that the analysis of actual problem was done and ensuring we were looking at the root cause of a problem not just a secondary problem because of the actual problem. Possible fault zones to be analyzed are grouped into six, specific fault zones that are necessary to be assessed give any overall diagnostic view of the motor condition, which include the insulation condition, power circuit, rotor condition, stator condition, power quality and air gap [22]. The analysis of this work is focused on three (3) of the six fault zones, which are tested during the offline test period, which are the insulation condition, stator condition and rotor condition, the data obtained was sufficient to draw conclusion on these.

- *Insulation Fault Zone*

The insulation fault zones encompass the insulation between the windings and ground both on the stator and rotor. Moisture, age, High temperatures, and dirt contamination contributes to shortening of insulation life span. The insulation may overtime or due to poor operating environment and conditions develop cracks, impurities, or other defects which can limit its ability to withstand its high electrical Voltage. Direct voltage applied across the insulation over the total resultant current is the insulation resistance. The sum of all the currents is measured by the MCE tester, also known as total current and calculates the resistance-to-ground values [22]. The amount of voltage applied must be a based on the nameplate voltage and the basic type of insulation condition class. If test voltages applied are too high, the applied test voltages may over-stress the insulation, which may lead to deterioration. Four test parameters will be used to analyze insulation fault zones condition which are Resistance-to-Ground, Capacitance-to-Ground, Polarization Index and Dielectric absorption.

- *Stator Fault Zone*

The stator is made up of windings, insulation between windings, and laminations or the stator core. This Fault Zone is used to identify the quality and health of the phases of the individual turns and insulation between the turns and coils inside the motor. The root causes of a stator-winding fault may be turn-to-ground short or phase-to-phase or turn-to-turn. A turn-to-turn short occurs result of a short of one or more windings within a coil. This may develop into a very low looped impedance of wire, resulting in excess flow of current through the shorted loop, this generates intense heat in the motor culminating in insulation damage. The MCE tester applies a low voltage DC signal and a high frequency AC signal to the stator windings, using the result obtained to perform the stator analysis. resistance and inductance measurements from these signals, are taken for comparison between historical data and like coils [22]. That is why up-to 3 test history of the motors was used. Test parameters used for analysis are Inductive Imbalance, Resistive Imbalance and Average Inductance.

- *Rotor Fault Zone*

The rotor of the Slip-ring induction motor has similar coils to the stator, these include, the rotor-windings, insulation between the windings, and the Slip-rings of the rotor. Although the rotor is the root cause of a small percentage of the motor problems, it can influence other fault zones most especially the stator to fail. Similar to the stator the MCE tester applies a low voltage DC signal and a high frequency AC signal to the rotor windings via the Slip-rings, using the result obtained to perform the stator analysis. Resistance and inductance measurements from these signals, are taken for comparison between historical data and like coils.

- *Statistical Analysis*

The data obtained were subjected to a one-way analysis of variance (ANOVA), the Pearson product-moment correlation coefficient (PPMC) was used to measure linear association of the strength between Capacitance to Ground (CTG), Resistance to Ground (RTG), Inductive Imbalance (II), Resistive Imbalance (RI), Polarization Index (PI) and the Dielectric Absorption (DA) which is denoted by r. Pearson product-moment correlation helped to draw a line of how best these data fit as influences the other, and the Pearson correlation coefficient, r, also indicated how much these deviate from the other. The Pearson correlation coefficient, r, usually have a range of values from +1 to -1. A value of 0 indicates no association or correlations between these the data variables presented. A positive association is indicated by value greater than 0, which shows that as the value of one of the data increases, simultaneously the value of the other data increases. A negative association is indicated by a value less than 0, which shows that as the value of one set of the data increases, the value of the other set of data decreases [23].

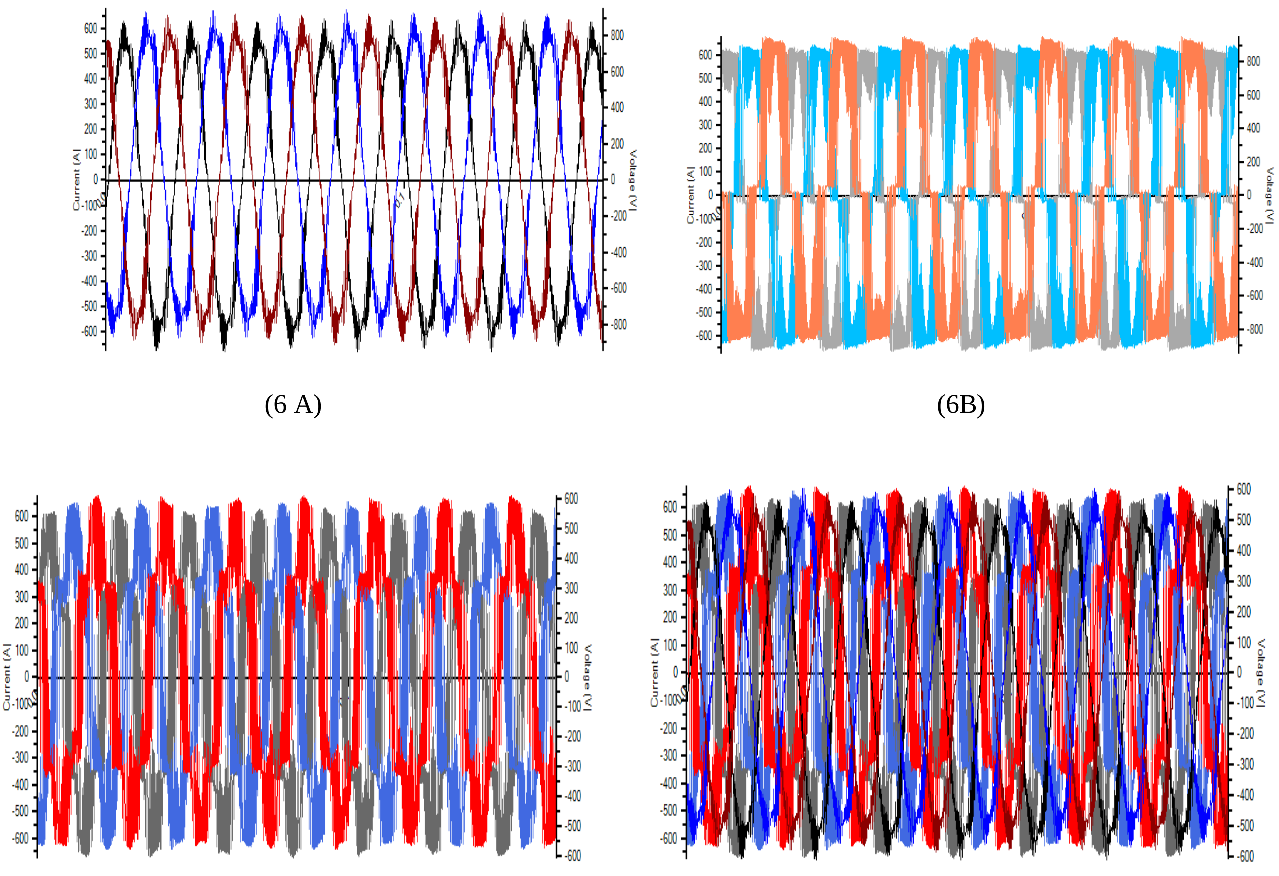
Table 3: Coefficient, r Table

Strength of Association	Positive	Negative
Small	1 to .3	-0.1 to -0.3
Medium	.3 to .5	-0.3 to -0.5
Large	.5 to 1.0	-0.5 to -1.0

IV. RESULTS AND DISCUSSION

A. *Results: Power spectrum of the motors and Polarization Index Graph*

The power spectrum fed to the drives during operation was sampled from one motor, the following spectrums were observed, 3 Phase Current Power Time Domain Spectrum as shown on Figure 6A, 3 phase Rotor Voltage Power Time Domain Spectrum as shown on Figure 6B, 3 phase Stator Voltage Power Time Domain Spectrum shown on Figure 6C, 3 Phase Voltage and current Power Time Domain Spectrum shown on Figure 6D. Also sampled were the polarization index graphs of Motor 1, 2 and 3, which is shown by Figures 7A, B and C respectively.



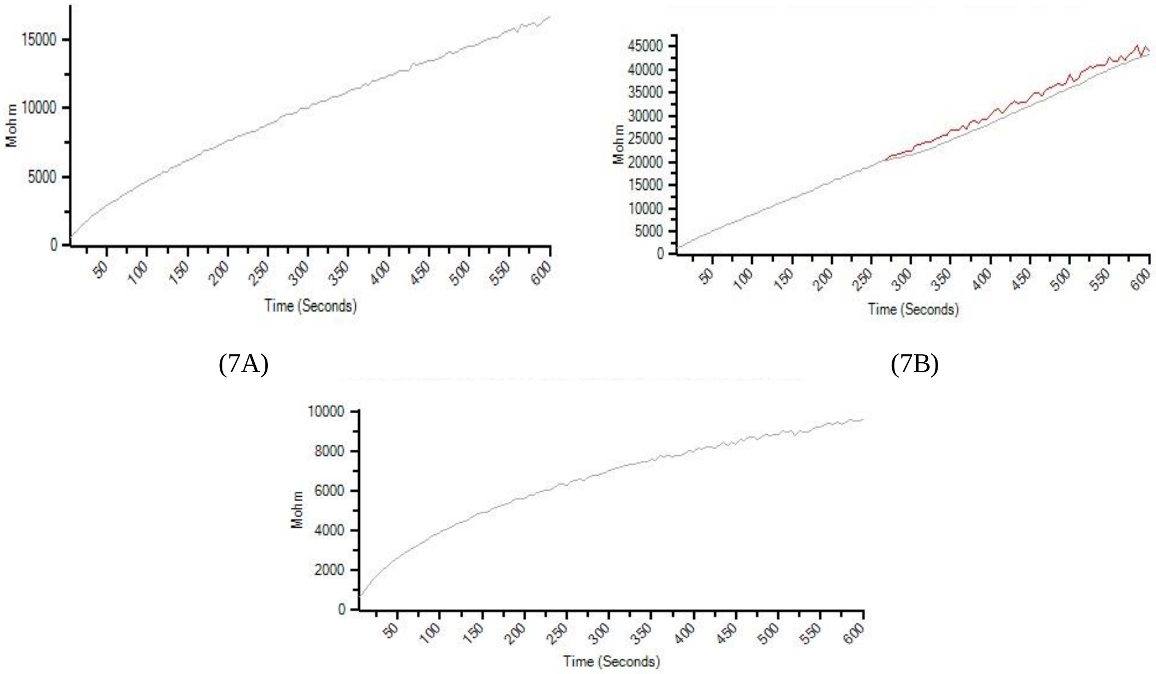
(6 A)

(6B)

(6C)

(6D)

Figure 6A, 3 phase Rotor Voltage Power Time Domain Spectrum as shown on Figure 6B, 3 phase Stator Voltage Power Time Domain Spectrum shown on Figure 6C, 3 Phase Voltage and current Power Time Domain Spectrum shown on Figure 6D.



(7A) (7B)

(7C)

Fig. 7: The polarization index graphs of Motor 1, 2 and 3, which is shown by Figures 7A, B and C respectively.

B. PPMC on Assessing the Associations Between Fault Indicators in The Stator of Slip Ring Motors (Active Determinant Parameters)

The bivariate correlation procedure computed using Pearson's product moment correlation (Table 4) for all slip ring motors irrespective of type, revealed that there were associations between fault indicators on the Motors with both positive and negative correlations was recorded. Capacitance to Ground (CTG) showed strong positive correlations with Resistive Imbalance (RI) (r = 0.88) and Inductive Imbalance (II) (r = 0.75) showing that a high degree of debris deposit on the either the stator or the rotor leads directly to a high internal condensation of moisture, highly resistive contacts, probably a turn to turn short and increases the probability of the motor failure. These associations were statistically significant ($p<0.01$ and $p<0.05$ respectively). Dielectric Absorption (DA) had a very strong and positive association with Polarization Index (PI) (r = 0.96) showing a healthy absorption of electrons (stator/rotor) the better the polarization index, the healthier the windings and insulation which was statistically significant ($p<0.01$). Strong negative correlation (r = -0.87) was only recorded between Dielectric Absorption and Capacitance to Ground, showing that the higher degree of contamination within the system, the lower the ability of the windings to absorption current or voltage. There were no significant ($p>0.05$) associations between the parameters.

Table 4: PPMC on Assessing the Associations Between Fault Indicators in the Stators

	Resistance Imbalance	**Inductance Imbalance**	**Capacitance to Ground**	**Resistance to Ground**	**Polarization Index**	**Dielectric Absorption**
Resistive Imbalance	1.00					
Inductive Imbalance	0.50	1.00				
Capacitance to Ground	0.88^{**}	0.75^{*}	1.00			
Resistance to Ground	-0.09	-0.35	-0.24	1.00		
Polarization Index	-0.30	-0.44	-0.66	0.38	1.00	
Dielectric Absorption	-0.53^{*}	-0.58	-0.83^{**}	0.36	0.96^{**}	1.00

Values represent the correlation coefficients (r-values) **. Correlation is significant at 0.01 levels (2-tailed).
*. Correlation is significant at 0.05 levels (2-tailed).

C. PPMC on Assessing the Association Between fault indicators in the Stator of Motor 1

The bivariate correlation procedure computed using Pearson's product moment correlation (Table 5) revealed that there were associations between the fault indicators in Motor 1 with both positive and negative correlations recorded. Capacitance to Ground was positively and strongly correlated with Resistive Imbalance (r = 0.99) and resistance to ground (r = 0.76). Inductive Imbalance was negatively and strongly correlated with Polarization Index (r = -0.91) and Dielectric Absorption (r = -0.97). The associations were not statistically significant.

Table 5: PPMC on Assessing fault indicators in the Stator of Motor 1

	Resistive Imbalance	**Inductive Imbalance**	**Capacitance to Ground**	**Resistance to Ground**	**Polarization Index**	**Dielectric Absorption**
Resistive Imbalance	1					
Inductive Imbalance	0.37	1				
Capacitance to Ground	0.99	0.27	1			
Resistance to Ground	0.69	-0.42	0.76	1		
Polarization Index	-0.73	-0.91	-0.65	0.005	1	
Dielectric Absorption	-0.58	-0.97	-0.49	0.19	0.98	1

Values represent the correlation coefficients (r-values)

D. PPMC on Assessing the Association Between fault indicators in the Stator of Motor 2

The bivariate correlation procedure computed using Pearson's product moment correlation (Table 6) revealed that there were associations between the fault indicators in Motor 2 with both positive and negative correlations recorded**.** Capacitance to Ground was strongly and positively correlated with Resistive Imbalance (r = 1.00) and Inductive Imbalance (r = 0.75). The association of Capacitance to Ground with Resistive Imbalance was statistically significant ($p<0.01$). This implies that a high value of Capacitance to Ground is always associated with high values of Resistive Imbalance and Inductance imbalance, showing that a high degree of debris deposit on the winding of the stator leads directly high internal condensation of moisture or generation of heat. Also, Capacitance to Ground (CTG) was strongly but negatively correlated with Resistance to ground (r = -0.94), Polarization Index (PI) (r = -0.96) and Dielectric Absorption (r = -0.96). This implies that high values of this parameter CTG (Capacitance to Ground) are always associated with low values of resistance to ground, Polarization Index and Dielectric Absorption (**deterioration of insulation**). Resistance to ground was strongly and positively correlated with Polarization Index (r = 0.81) and Dielectric Absorption (r = 0.81). the implication is that high values of resistance to ground is always associated with high values of Polarization Index and Dielectric Absorption (showing a healthy insulation condition). A unitary positive association which was statistically significant ($p<0.01$) was observed between Dielectric Absorption and polarization index.

Table 6: PPMC on Assessing fault indicators in the Stator of Motor 2

	Resistive Imbalance	**Inductive Imbalance**	**Capacitance to Ground**	**Resistance to Ground**	**Polarization Index**	**Dielectric Absorption**
Resistive Imbalance	1.00					
Inductive Imbalance	0.76	1.00				
Capacitance to Ground	1.0^{**}	0.75	1.00			
Resistance to Ground	-0.94	-0.93	-0.94	1.00		
Polarization Index	-0.96	-0.54	-0.96	0.81	1.00	
Dielectric Absorption	-0.96	-0.55	-0.96	0.81	1.00^{**}	1.00

Values represent the correlation coefficients (r-values) **. Correlation is significant at 0.01 levels (2-tailed).

PPMC on Assessing the Association Between fault indicators in the Stator of Motor 3,

The bivariate correlation procedure computed using Pearson's product moment correlation (Table 7) revealed that there were associations between the parameters of fault indicators in Motor 3 with both positive and negative correlations recorded**.** Capacitance to Ground was strongly and positively correlated with Inductive Imbalance (r = 0.99). This implies that a high value of Capacitance to Ground is always associated with high values of Resistive Imbalance and Inductance imbalance. Dielectric Absorption was strongly and positively correlated with Polarization Index (r = 0.99) and Resistance to ground (r = 0.74). The implication is that high values of resistance to ground is always associated with high values of Polarization Index and dielectric absorption. Also, Dielectric Absorption was strongly but negatively correlated with Inductive Imbalance (r = -0.97) and Capacitance to Ground (r = -0.99). This implies that high values of this parameter were always associated with low values of Inductive Imbalance and Capacitance to Ground. Again, Polarization Index showed a similar association with Inductive Imbalance (r = -0.99) and Capacitance to Ground (r = -0.99). The association of Polarization Index and Inductive Imbalance was statistically significant (p<0.05).

Table 7: PPMC on the Association Between the fault indicators in Stator of Motor 3

	Resistive Imbalance	**Inductive Imbalance**	**Capacitance to Ground**	**Resistance to Ground**	**Polarization Index**	**Dielectric Absorption**
Resistive Imbalance	1.00					
Inductive Imbalance	-0.51	1.00				
Capacitance to Ground	-0.57	0.99	1.00			
Resistance to Ground	-0.99	0.58	0.64	1.00		
Polarization Index	0.59	-0.99	-0.99	0.66	1.00	
Dielectric Absorption	0.68	-0.97	-0.99	0.74	0.99	1.00

Values represent the correlation coefficients (r-values)

E. *Comparing the stator of three different slip ring induction motors*

Results of the descriptive statistics on the fault indicators to compare the three different slip ring induction motors presented in Table 8 revealed that the values of all the indices of fault (except inductive imbalance) were higher in Motor 2 than in Motor 1 and 3. Nevertheless, ANOVA analysis and Turkey post-hoc test revealed that there were no significant (p>0.05) differences in the mean values of these parameters on comparing the three slip ring motors.

Table 8: Comparative fault analysis in three slip ring induction motors

Indices of Fault	**Motor 1**	**Motor 2**	**Motor 2**
Resistive Imbalance	0.18 ± 0.01	31.87 ± 54.11	0.16 ± 0.01
Inductive Imbalance	0.30 ± 0.42	1.14 ± 1.05	1.19 ± 1.03
Capacitance to Ground	254633.33 ± 1124.69	352633.33 ± 2551.22	311000.00±112711.98
Resistance to Ground	3933.33 ± 1305.12	4200.00 ± 1014.89	2206.09 ± 618.79
Polarization Index	4.85 ± 0.21	6.72 ± 2.60	4.66 ± 1.99
Dielectric Absorption	1.59 ± 0.02	1.63 ± 0.13	1.57 ± 0.09

Values are expressed as Mean ± S.D; n=3

F. *PPMC on Assessing the Associations Between Fault Indicators in the Rotors of Slip Ring Motors*

The bivariate correlation procedure computed using Pearson's product moment correlation (Table 9) for all the slip ring motors irrespective of type, revealed that there were associations between fault indicators the Motors with both positive and negative correlations recorded. Capacitance to Ground showed strong negative correlations with resistance to ground (r = -0.95), Polarization Index (r = -0.96) and Dielectric Absorption (r = -0.96). These associations were statistically significant (p<0.01). Dielectric Absorption had a very strong and positive association with polarization index (r = 0.99) and resistance to ground (r = 0.99) which were statistically significant (p<0.01). Inductive Imbalance had a Strong positive association with Resistance to Ground (r = 0.79), Polarization Index (r = 0.74) and dielectric absorption (r = 0.74). These associations were statistically significant (p<0.05).

Table 9: Pearson Product Moment Correlation on the Association Between the fault indicators in the rotor of slip ring Motors

	Resistive Imbalance	**Inductive Imbalance**	**Capacitance to Ground**	**Resistance to Ground**	**Polarization Index**	**Dielectric Absorption**
Resistive Imbalance	1.00					
Inductive Imbalance	-0.41	1.00				
Capacitance to Ground	0.54	-0.68	1.00			
Resistance to Ground	-0.45	0.79	-0.95	1.00		
Polarization Index	-0.47	0.74	-0.96	0.99	1.00	
Dielectric Absorption	-0.44	0.75	-0.96	0.99	0.99	1.00

G. *Comparing the Rotor of three different slip ring induction motors*

Results of the descriptive statistics on the fault indicators to compare the three different slip ring induction motors presented in Table 10 revealed that the Resistance to ground, Polarization Index and Dielectric Absorption in the rotor of motor 2 were significantly ($p<0.05$) higher when compared to the values recorded in motor 1 and motor 3. Nevertheless, Capacitance to Ground was significantly ($p<0.05$) lower for the rotor of motor 2 when compared to that of motor 1 and motor 3. The value of Inductive Imbalance in the rotor of motor 2 was higher than that of motor 1 and motor 3 but the difference was only significant ($p<0.05$) when compared with motor 1. Other parameters were lower in the rotor of motor 2 compared to what was recorded in motor 1 and 3 but it was only significantly ($p<0.05$) different when comparing Capacitance to Ground in motor 2 to that of motor 1.

Table 10: Comparative fault analysis in three slip ring induction motors

Indices of Fault	**Motor 1**	**Motor 2**	**Motor 3**
Resistive Imbalance	10.97 ± 0.01	0.91 ± 0.22	4.68 ± 2.45
Inductive Imbalance	0.25 ± 0.12	1.18 ± 0.57^{a}	0.59 ± 0.19
Capacitive to Ground	317500.00 ± 12586.89	257500.00 ± 800.00^{a}	321866.67±14087.70^{b}
Resistance to Ground	349.06 ± 231.75	11173.23 ± 1569.31^{a}	43.21 ± 29.82^{b}
Polarization Index	1.09 ± 0.05	5.65 ± 0.07^{a}	0.97 ± 0.04^{b}
Dielectric Absorption	1.08 ± 0.02	1.78 ± 0.05^{a}	0.99 ± 0.01^{b}

Values are expressed as Mean ± S.D; n=3

H. *Comparing the Stator and Rotor of three different slip ring induction motors*

Table 11 compare's fault indicators in the stator and rotor of the three different slip ring induction motors. The results revealed that significant ($p<0.05$) differences between stator and rotor were only recorded for resistance to ground, Polarization Index and Dielectric Absorption. Nevertheless, it was only resistance to ground that had the stator and rotor of motor 1, 2 and 3 showing significant ($p<0.05$) difference. Statistically significant ($p<0.05$) difference in Polarization Index between the stator and rotor was only recorded for motor 3 while for dielectric absorption, it was only recorded for motor 1.

Table 11: Comparing the Stator and Rotor of three different slip ring induction motors

Parameters	**Motor 1**		**Motor 2**		**Motor 3**	
	Stator	**Rotor**	**Stator**	**Rotor**	**Stator**	**Rotor**
Resistance Imbalance	0.18 ± 0.01	10.97 ± 0.01	31.87 ± 54.11	0.91 ± 0.22	0.16 ± 0.01	4.68 ± 2.45
Inductance Imbalance	0.30 ± 0.42	0.25 ± 0.12	1.14 ± 1.05	1.18 ± 0.57	1.19 ± 1.03	0.59 ± 0.19
Capacitance to Ground	254633.33 ± 1124.69	317500.00 ± 12586.89	352633.33 ± 2551.22	257500.00 ± 800.00	311000.00± 112711.98	321866.67± 14087.70
Resistance to Ground	3933.33 ± 1305.12	349.06 ± 231.75*	4200.00 ± 1014.89	11173.23 ± 1569.31**	2206.09 ± 618.79	43.21± 29.82***
Polarization Index	4.85 ± 0.21	1.09 ± 0.05	6.72 ± 2.60	5.65 ± 0.07	4.66 ± 1.99	0.97 ± 0.04***
Dielectric Absorption	1.59 ± 0.02	1.08 ± 0.02*	1.63 ± 0.13	1.78 ± 0.05	1.57 ± 0.09	0.99 ± 0.01

Values are expressed as Mean ± S.D; n = 3

I. MCA State Prediction

After analysis of the data obtained from the slip ring induction motor fault indication parameters using the Motor Circuit Analysis (MCA), and the 3 fault zones, which are the stator, rotor and insulation fault zone, we conclusively were able to make the following predictions of the state of the motor fault zones and postulated a corrective action required for their improvement.

- For the stator and rotor fault zones: if the Capacitance to ground CTG, Inductive imbalance II, and Resistive Imbalance RI, were closely monitored and controlled, through periodic overhaul intensive maintenance (PIOM), the high negative impact of these parameters will be reduced.
- A high resistive and inductive imbalance on the stator is an indication of a either turn-to-turn short or phase to phase short or it can also be as result of influence of the rotor fault zone, which will lead to excess heat generation, because if we lose the resistance in any of the phases of the motor (Stator or Rotor) that will create a current imbalance resulting in excess heat, also with the inductive imbalance if we lose turns in any of the phases it will result in higher imbalance in inductive measurement between the phases generating heat and which directly impacts the motor insulation, PIOM will Mitigate this.
- These three parameters CTG, RI and II had a great impact on the insulation fault zone. A high Resistive Imbalance and Inductive Imbalances result leads to excess heat generation which causes cracking, moisture contamination, brittleness and abrasion on the insulation. According to IEEE for every 10% increase in temperature above design temperature reduces the insulation life span by half (50%), as insulation have a negative resistance to temperature.
- CTG also gives an early indication of the degradation in the insulation, since it was tested with a high frequency AC which gave a clearer view of the contamination present on the insulation, CTG value shows the cleanliness of the windings and network of cables. The higher the value of CTG the higher the contamination buildup on the surface of the windings and cables leading to higher capacitance readings. Contamination prevents effective cooling and heat dissipation of the drives hence the onset of early degradation.
- A high CTG, RI, and II, leads to a low polarization index PI, Low Dielectric Absorption DA, and a very low Resistance to Ground RTG, showing very poor overall insulation health.
- Among the 3 motors used in this test, motor two show significantly higher deterioration rate, than the other two motors (1 and 3), considering that both motors 1 and 3 are from the same manufacturer, brought to bear that consideration should be given to this aspect.

V. CONCLUSION

This paper successfully used MCE/MCA Offline test to run diagnostics on the fault zones and fault indication parameters of Slip-ring induction motors. Using the fault zone analysis method with data obtained from MCE/MCA was sufficient to indicate onset of a fault on the wound rotor Slip-ring Induction motors. With periodic overhaul intensive maintenance (PIOM), the ingress of both carbon dust, environmental contamination and other undesirable builds on the windings can be reduced, allowing effective and proper cooling of the drives. Taking these proactive predictive and preventive steps using the motor circuit evaluator coupled with fault zone analysis and PIOM will help detect/mitigate early degradation of insulation that can lead to other faults on the equipment, greatly improve overall health and performance of both the stator and rotor, also allowing these faults to be nipped in the bud before they amalgamize into expensive repairs and unwanted downtime while extending the equipment useful life cycle and efficiency of the motor.

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