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The future of Electrical Signature Analysis (ESA) for machine protection

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SUMMARY

Motors play a key role in running industrial processes. Also, motors carry a heavy load for resuming the proper functioning of industrial plants and avoid loss of production; hence it is imperative to assure availability of the motors by considering the proper protection scheme as well as appropriate asset monitoring. Such task requires significant amount of accurate data and additional tools including sensors, monitoring devices and accessories.

The main purpose for motor component monitoring is to keep industrial processes running through predictive monitoring of critical motor components. Upon detection of a developing problem the motor component monitoring provides a root cause diagnostic report with adequate amount of information. To achieve such level of reporting and analysis Electrical Signature Analysis is used to detect various failure modes in a rotating machine by analysing stator voltage and current signal which provides easier and early detection of mechanical failures and avoiding the process interruption. For accurate analysis ESA systems rely upon FFT (Fast Fourier Transformation) analysis for mechanical condition analysis such as vibration.

The Multilin 869 Motor Protection relay uses the ESA based method to detect various failure modes in a rotating machine for detection of motor incidents such as stator inter-turn, bearing and mechanical faults. Unlike traditional methods the 869 ESA method does not require additional hardware and such objective is achieved using the FFT computation of the current signal which is already in use for various protection elements within the relay. So far this addresses the individual motor needs.

Rapid changing of technology has already started to push the monitoring and analysis of power systems towards a significant paradigm shift. The following have contributed to such important changes:

- Generation of enormous amount of data by field devices such as Multilin 869 relay
- Enhanced processing capability of Intelligent Electronic Devices (IEDs)
- Expansion in use of IoT enabled field devices
- Moving towards centralized “Big Data Analytics”

This paper aims to discuss the available technology for asset profiling using Electrical Signature Analysis and the future of this technology in terms of large data analytics and asset profiling for preventive maintenance. Further details regarding Electrical Signature Analysis architecture, algorithm, data quality check and modes of operation will be provided together with application examples. Also, some use case scenarios for individual motor application and its input for large data analytics platform will be provided. Additionally, the utilization of individual motor ESA data as an input for profiling the extended number of motors and self learning algorithms for enhancement of the functionality of such machine profiles will be part of this paper.

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KEYWORDS

electric motors, monitoring and diagnosis, electrical signature analysis, cloud

I. INTRODUCTION

Motors are one of the most important components of an industrial facility that ensure its reliable and safe operation. Due to several reasons, such as wearing, aging, degrading environmental and operating conditions, motors may fail or operate abnormally.

Electric motor reliability was published in 1983 Electric Power Research Institute (EPRI) project performed by General Electric (GE) [1]. Other surveys were also carried out to understand the failure modes of electrical machines [2]-[3]. The summary of electric motor failure causes is illustrated in Fig.1. Most of the failure modes are related to stator and rotor systems. Stator failure modes include overloading, insulation degradation, contamination, etc.; and the root cause of majority stator failure is thermal stress resulting in electrical stress. Overloading of the machines increases thermal stress on the machines, and hence the insulation of the windings, especially between turns. This causes stator inter-turn failures and consequential ground or phase faults. Rotor failures include broken rotor bar in induction machines, bearing faults, shaft eccentricity, etc.

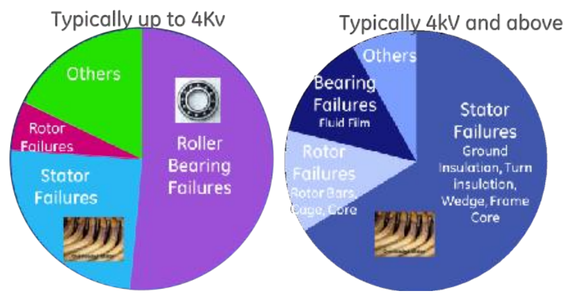

Fig. 1 Electric machine failures-typical [1],[2].

II. MACHINE M&D- Why? How? What?

A. Why Machine M&D?

As the age of the machine increases, the probability of its failure (mean time to fail) rises too. There are several other parameters expediting the age of a machine, for example, overloading, irregular temperature control, improper mechanical loads on the shaft, environmental conditions, etc. Monitoring & Diagnosis (M&D), also known as condition monitoring, is essential to detect critical asset degrading conditions before they evolve into the permanent faults and cause system shutdowns. Followings are the major advantages of M&D applied to critical motors:

- Preventive Maintenance (PM) or Condition Based Maintenance (CBM);
- Asset Performance Management (APM);
- Risk mitigation by asset level visibility and Risk Assessment (RA);
- Root Cause Analysis (RCA) or post-event analysis
- Early-Warning or Alarming to schedule maintenance and outage
- Reduce process loss (outage time) to limit loss of revenue
- Reduce cost and time of motor repair

The principal aim is to develop schemes for reliable detection of faults at an early stage which will allow controlled and scheduled maintenance instead of sudden failure, thus reducing production losses, outage time and damage to the equipment. Accurate diagnosis and timely, targeted maintenance improve the availability of motors and can help to achieve major cost savings.

B. How to achieve Machine M&D?

There are several methods to condition monitoring or machine M&D, in general categorized as follows:

1) Autonomous Online M&D: continuously monitoring applied to while motor is running, and analysis is performed without human intervention
2) Autonomous Offline M&D: scheduled monitoring applied when motor is stopped, and analysis is performed without human intervention.

3) Manual Online M&D: continuously monitoring applied to while motor is running, and analysis is performed manually on the collected data.
4) Manual Offline M&D: scheduled monitoring applied when motor is stopped, and analysis is performed manually on the collected data.

Normally, online M&D requires additional devices connected to the sensors applied on the machine; whereas, offline M&D requires scheduled shutdown to perform the tests. Autonomous M&D needs enough processing capabilities and memory within a M&D device; whereas, manual M&D takes man-hours from an expert team to perform analysis and prepare motor health reports.

C. What is Continuous Machine M&D with no Additional Devices to Install?

This paper proposes continuous monitoring and diagnosis (M&D) of the critical rotating machines as a part of Motor Protection Relay (MPR) also referred as proactive protection Intelligent Electronic Device (IED). As the MPR are installed on every critical machine, there is no need for any additional devices to install to perform autonomous online M&D.

In most cases, although MPR may be witnessing evolution of the machine failure, does not take any action due to its primary job to react (in terms of alarm or trip) on failure/damage detection. The objective of this paper is to present M&D methods for stator turn failure and broken rotor bar detection. Once the winding insulation deteriorates, it generally results in an inter-turn fault involving a few turns of the winding being within the same phase to ground or different phases. The fault current causes severe localized heating and the fault rapidly spreads to a larger section of the winding. If the fault is detected at its early stage, the shutdown of the machine can be planned and appropriate actions like rewinding may be taken. If not, once the fault propagates and the motor is forced out of service, a huge downtime is needed to replace or rewind the motor.

III. Complete Motor M&D

To illustrate the complete motor M&D, electric motor failure modes are categorized into three streams: Mechanical, Electrical (including Electromagnetics) and Thermal.

A. Mechanical Abnormalities

Major mechanical abnormalities are shown in Fig.2. Proactive functions for many mechanical abnormalities can be achieved using Electrical Signature Analysis (ESA), also known as Motor Current Signature Analysis (MCSA). ESA is based on sensing stator current components at specific frequencies which are direct by-product of unique rotating air-gap flux components caused by faults such as bearing anomalies, static or dynamic eccentricity, shaft misalignments, foundation looseness, and broken rotor bars using advanced Fast Fourier Transform (FFT). There is no need for additional sensors or probes as Mechanical failure algorithms based on ESA use the same 3-phase stator currents from the current transformers fed into the protection IEDs. Industrial application experiences of such techniques are shared in the book "Current Signature Analysis for Condition Monitoring of Cage Induction Motors" by William Thomson and Ian Culbert, and various journal publications. Used over few decades, ESA techniques are currently applied using portable test-sets or spectrum analyzer for period testing or standalone devices for continuous monitoring.

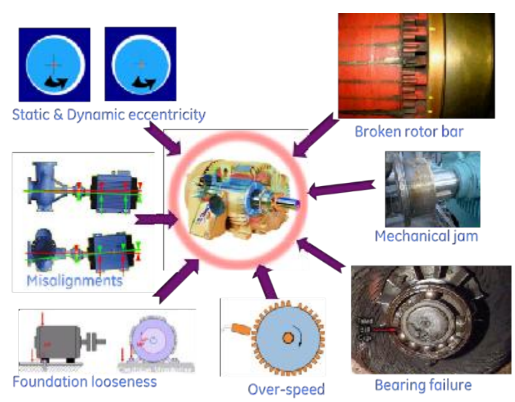

Fig. 2 Major mechanical abnormalities

B. Thermal Abnormalities

Various factors causing thermal abnormalities are presented in Fig.3. The root cause of most stator failures is thermal stress resulting in electrical stress. Overloading of a machine increases thermal stress on the machine, and hence the winding insulation, especially between the turns, degrades. This causes stator inter-turn failures and eventually evolves to ground or phase faults. Advancements in Motor Thermal Model to proactively monitor Thermal Capacity Used (TCU) in correlation with presented parameters from Fig.3 is used to give early warning on preventive maintenance due to Thermal stress.

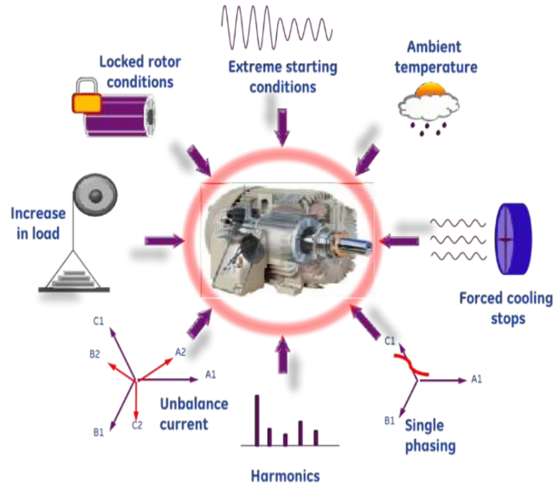

Fig. 3 Major thermal abnormalities

C. Electrical Abnormalities

The major categories of electrical abnormalities and failures are illustrated in Fig.4. Stator inter-turn insulation failure can be detected before it evolves into phase or ground faults. Furthermore, proactive electrical functions are applied using multiple flexible elements, such as: i) capture duration and the number of unbalance currents and voltages; ii) slowly increasing trends in sensitive ground currents; iii) power supply quality; iv) motor loading/operating profiles; etc. Once the winding insulation deteriorates, it generally results in an inter-turn fault involving a few turns of the winding within the same phase to ground or different phases. The fault current causes severe localized heating and the damage rapidly spreads to a larger section of the winding. If the insulation deterioration is detected at an early stage, shutdown of the machine can be planned and appropriate actions can be taken.

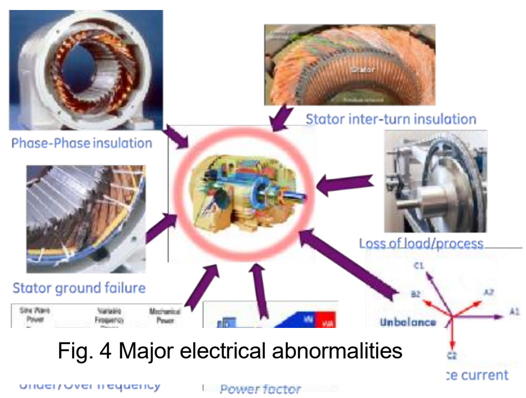

Fig. 4 Major electrical abnormalities

IV. STATOR INTER-TURN FAULT (SITF) DETECTION

A. Principle of SITF Detection

The stator winding of a three-phase induction motor is shown in Fig.5. In the present analysis, the stator inter-turn fault is present on phase A.

The normalized cross-coupled impedance (ratio of Znp to Zpp) is the key operating signal that can effectively detect stator turn fault given by Equation (1).

$$\frac{Z_{np}}{Z_{pp}} = \frac{V_2 - Z_{nn} I_2}{V_1} \qquad (1)$$

$$OP = \frac{Z_{np}}{Z_{pp}} - Z_{UBbase} \qquad (2)$$

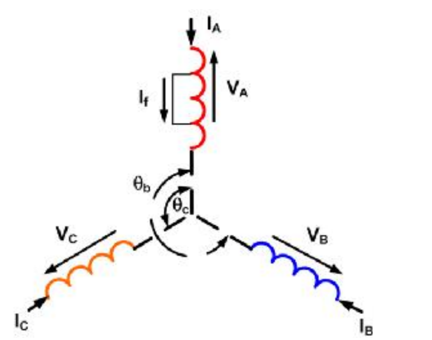

Fig. 5 Stator inter-turn fault illustration in 3- phase winding of the machine

where,

Z_{pp} = positive sequence impedance;

Z_{np} = cross-coupled negative-to-positive sequence impedance;

OP = Operating quantity

Z_{UBbase} = learned unbalance base impedance;

V1 = positive sequence voltage calculated from the motor terminal voltages;

V2 = negative sequence voltage calculated from the motor terminal voltages;

I1 = positive sequence current calculated from the motor terminal currents;

Z_{nn} = negative sequence impedance

Equation (1) illustrates the following properties of the method,

1. Load independence: Since the equation does not involve positive sequence current (essentially the load current), the parameters of interest remain the same under different load conditions.
2. Robustness to system imbalance: Any supply voltage imbalance will give rise to a negative sequence component in voltage, also causing an increase in the negative sequence current. This is distinct from the negative sequence current resulting from an inter- turn fault. Equation (1) compensates for the effect of voltage imbalance and responds only to the latter.
3. Machine independence: The parameter Znp is machine dependent, i.e. it depends on power, voltage, pole and frequency rating of the machine. However, once it is normalized with respect to its own base impedance (Zpp) the ratio is independent of the machine rating. This enables a uniform threshold across all machine ratings.

B. RTDS testing of SITF detection

A model for 1 MVA, 2.3kV motor model with stator inter-turn fault in A-phase of the winding was developed in RTDS (Real Time Digital Simulator) as shown in Fig.6 . The test result of 5% fault of the stator winding is shown in . The results illustrate that during normal operating conditions, the learned operating quantity measured for this machine is 0.043 (due to inherent unbalance in the machine windings). Due to the stator inter-turn fault, the maximum operating quantity jumps to 0.135 from 0.043, this is a significant change and can be used to alarm the operator or trip the motor.

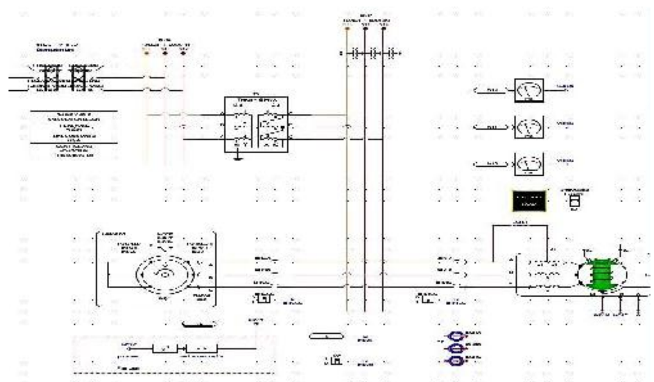

Fig. 6 RTDS model of 1 MVA, 2.3k motor model with Stator

V. Broken Rotor Bar M&D USING ELECTRICAL SIGNATURE ANALYSIS (ESA)

A. Principle of Broken Rotor Bar (BRB) Detection

Broken rotor bar is a serious problem with certain induction motors due to their severe duty cycles. Broken rotor bar or end rings are mainly caused by frequent direct online starting of the motor, pulsating mechanical loads such as reciprocating compressors or imperfections in manufacturing process of the rotor cage [1]. Broken rotor bar in the incipient stages does not directly create any serious performance issue or cause the induction motor to fail, but they can have serious secondary effects (such as vibration. This can result in broken rotor parts hitting the winding or stator core and cause serious damage to the motor and resulting in loss of production and costly repair.

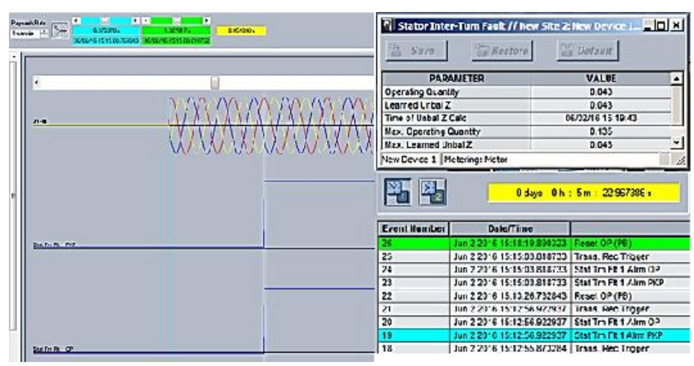

Fig. 7 Stator inter-turn fault detection with test results

Rotor faults mainly include breakages in rotor bars and end-rings. Fig.8 displays a theoretical representation of induced rotor fault signature components in stator currents.

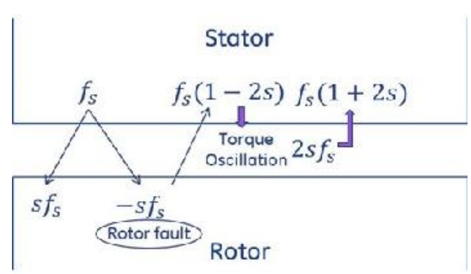

Fig. 8 Theoretical representation of induced rotor fault signature in stator currents

Under healthy rotor conditions, there will be only the slip frequency (sf_s) current in the rotor. A broken rotor bar creates an asymmetry in the rotor circuit which in turn creates a negative rotating magnetic field at slip frequency

(- sf_s) in the rotor. This negative slip frequency component in the rotor creates $f_s(1-2s)$ component in the stator. This causes electromagnetic torque and speed oscillation at twice the slip frequency. This results in $f_s(1+2s)$ and other harmonics in stator current at $f_s(1 \pm 2ns)$, where n is an integer and s is the slip [6].

The conventional approach of the rotor fault detection is based on the extraction of frequency components from stator current, which is produced due to rotor fault. The Fourier transform of the signal clearly presents the frequency spectrum of the signal. Fast Fourier Transform (FFT) is an efficient algorithm to extract the frequency components of the signal. So, the conventional approach is the use of FFT of stator current and identification of the fault signature from the frequency spectrum.

One of the possible solutions to increase the contrast between fault signature and supply frequency is the Coherent Demodulation Approach. This approach is based on the multiplication of the current signal with any supply fundamental frequency signal. The supply frequency signal is readily available in the voltage signal. Hence, for coherent demodulation, the current signal is multiplied by the corresponding phase or line voltage signal. As shown an example in Fig.9, if in the normal FFT of a rotor faulted machine the frequency components are 50Hz, 45Hz and 55Hz, in the demodulated signal the components are at DC, 5Hz, 95Hz, 100Hz and 105Hz.

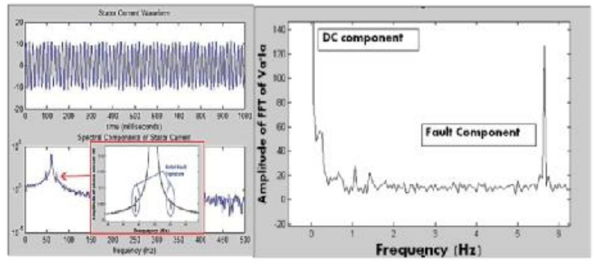

Fig. 9 FFT of stator currents vs modified modulated approach.

B. Testing of BRB Detection

The proposed detection technique was experimentally verified on an induction motor. The proposed detection technique can identify the partial breakage in the rotor bar. To verify this feature of the technique, experiments were performed with partial bar breakage by drilling a hole on one of the bars at varying depths.

The rotor used in the experiments had a height of 18mm and 22 total bars. Hence, for complete bar breakage a hole of 18 mm depth was required. Drilling on the rotor bar was done in steps of 4mm, 8mm, 12mm, 16mm and 20mm of depth. illustrates the experiment's partial bar breakages and corresponding results of detection.

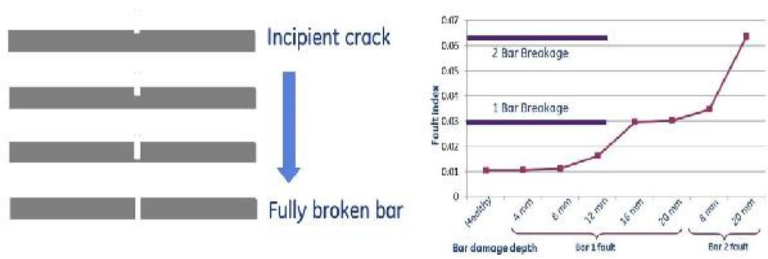

Fig. 10 Experiment of partial bar breakage and results of breakage detection

Advantage of protection relay with in-built M&D comes with add-on advantage of features like learned data, health report etc. as explained in section IV. These features not only help in evaluating motor condition using historical, rate of change data derived from M&D algorithms but also helps in correlating signature data with other relay computed or measured data like loading, temperature, power quality, thermal capacity used etc.

VI. Motor M&D Diagnosis and Reporting

A. Motor Reports

Following is the list of available motor monitoring and diagnosis for further investigation.

i. Motor learned data
ii. Motor health report
iii. Event & transient recorder
iv. Data logger
v. Motor start records & start statistics
vi. Fault reports
vii. Environmental health report

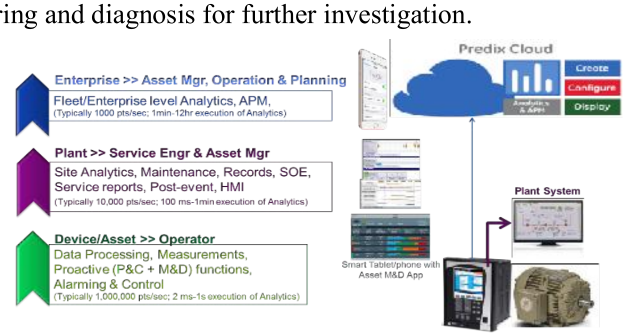

Fig. 11 Hierarchical asset management architecture

B. Hierarchical Asset Management Architecture

Fig.11 illustrates a proposed hierarchical asset management architecture enabled by a proactive asset management IED. Proactive functions which require high-speed data sampling are executed within the IED; plant level monitoring is performed from the motor IED's metering and status values on the plant's existing DCS/SCADA system; selected information over the independent port can also be streamed to a private enterprise level system or secured industrial internet cloud (e.g. Predix cloud shown in Fig.11). A hierarchical approach allows only selective (application-driven) information from the proactive IED to reduce bandwidth requirements and achieve enterprise-level asset management, risk analysis, fleet management, asset performance management, etc. The use of Machine Learning techniques will lead to performance of multiple rule-based analytics and extraction of meaningful data and Artificial Intelligence and cloud computing will turn the rule-based applications into models that can produce reports and proactive algorithms for variety of applications. Also, the increase in the number of such application will allow the algorithm to gain more accuracy in modeling and reporting.

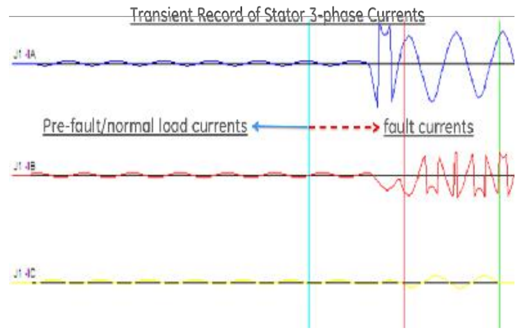

Fig. 12 Damaged motor transient record of stator currents.

SETTING	PARAMETER
Function	Latched Alarm
Neg Seq Imp Autoset	Auto
Neg Seq Impedance	10.00 ohms
Calculation Window	0.100 s
Pickup Stage 1	0.100
Pickup Delay Stage 1	0.00 s
Pickup Stage 2	0.800
Pickup Delay Stage 2	1.00 s
Dropout Delay	0.00 s
Learn Turn Fault Data	NO
Block	Off
Relays	Relay Disabled
Events	Enabled
Targets	Latched

New Device 1 | Setpoints: Monitoring

Fig. 13 Typical settings for stator inter-turn fault detection.

VII. EVENT ANALYSIS

In November 2015, a 22000 HP synchronous motor differential protection relay trip the compressor at a mining plant in Dominican Republic. The Motor Protection Relay (MPR) applied to the machine has captured transient record and event log. Traditional digital protection relay supported recording/logging functionalities, which has enabled further diagnosis of this event. A transient record was downloaded from the relay immediately, as shown in Fig.12.

While analyzing the transient current waveform from the figure, it was observed that stator winding currents in phases-A & B were abnormally very high, and this was the cause for motor differential protection trip. The field support team opened the stator of the machine and found out that synchronous motor stator winding was completely damaged. A lab setup was carried out to inject the pre-fault 3-phase currents into advanced Motor protection and M&D relay with stator inter-turn fault detection algorithm. shows the settings of the SITF function.

The 3-phase currents for this A-B fault are divided into two parts in Fig.12: 1) pre-fault/normal load currents; 2) fault currents (A-B fault which cased motor stator differential trip). To test the SITF detection for this stator damage event, the algorithm is applied to pre-fault currents which seem to be symmetrical normal load. Fig.14 shows the pre-fault transient record of the stator 3-phase currents. It can be observed that Stator Turn fault operated after 0.100 sec, after the set value of calculation window.

Fig.15 shows the metering value before waveform playback (i.e. Fig.15(a)), and after injecting pre-fault waveform (i.e. Fig.15(b)). It

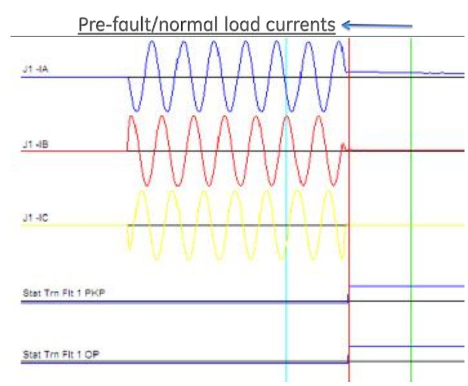

Fig. 14 pre-fault current waveform detected

PARAMETER	VALUE
Operating Quantity	0.043
Learned Unbal Z	0.043
Time of Unbal Z Calc	06/02/16 14:41:54
Max. Operating Quantity	0.043
Max. Learned Unbal Z	0.043

New Device 1 | Metering: Motor

(a)

PARAMETER	VALUE
Operating Quantity	0.043
Learned Unbal Z	0.043
Time of Unbal Z Calc	06/02/16 15:19:43
Max. Operating Quantity	0.135
Max. Learned Unbal Z	0.043

New Device 1 | Metering: Motor

(b)

Fig. 15 SITF Metering data: (a) Learned values before pre-fault waveform; (b) operating quantity from pre-fault waveform.

can be observed that before injecting the waveform, the learned unbalance from RTDS model is 0.043 pu. Upon injecting pre-fault current, the operating unbalance impedance increased to 0.135 pu.

VIII. CONCLUSIONS

This paper describes the motor monitoring and diagnostics functionalities supported in advanced Motor Protective Relay (MPR). Two novel methods are proposed for the detection of stator inter-turn failure and broken rotor bar for motors. Stator inter-turn failure is based on normalized Znp calculations and it is independent of loading, system unbalance or machine winding unbalances. The proposed method is validated using Real Time Digital Simulator (RTDS) at various percentage of A-phase stator winding fault. It is not only a unique turn fault indicator but also very robust so far as variation of measurement error and temperature is concerned. Broken rotor bar detection using coherent demodulation is also discussed which provides better detection compared to the conventional FFT method. It is shown with test motor that the unique fault signature can detect partial rotor bar damage. Furthermore, Motor diagnosis and reports are presented from the MPR, which are easy to review online or offline by operator or service/maintenance engineer. The next step for such application will be the use of AI and large data analytics and enhancement in capability of modeling algorithms in order to perform accurate profiling and creating models fitting for variety of motors. The use of cloud-based application, elimination of additional probes and sensors lead to significant reduction in CAPEX and OPEX.

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