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Convergence of Protection Relay and Monitoring System for Next Generation Asset Management

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Abstract

Large Industrial electromechanical assets such as motors, generators and transformers play a critical role in running an industrial process. Any unexpected failure in the asset causes loss of revenue due to production loss as well as repair or replacement of the faulty asset. A failure in electromechanical equipment can be electrical, thermal or mechanical. Proactively detecting and analyzing a failure at early stage can help to take preventive measures and better plan the maintenance strategy. Determining the early detection of the potential failures requires online/offline Monitoring and Diagnostic (M&D) equipment, additional sensors, wiring and installation. This paper discusses convergence of protection relay and asset monitoring and diagnostic system for next generation asset management easing asset maintenance strategy and time, cost, efforts in certain cases. Moreover, it provides insights into working of the M&D solution and how it can help to monitor and identify the factors and failures like electrical, mechanical and thermal failures of assets. To verify the proper working and performance of the proposed method, various tests were performed on the integrated Motor M&D features in relay using actual industrial motors with mechanical faults in a machine repair shop.

Keywords: Asset, Monitoring, Motor, Relay, Transformer, M&D

1. Introduction

Fifty percent of the greenhouse gas emissions come from the electricity production and industry. Our industry consumes largest part of the electricity and only motors, industry's backbone, consumes 45 percent of the total electricity[1]. Moreover, significant power is lost when motors and other components like transformers, loads are running at low efficiency. And therefore, in return these components demand higher energy than required. This as a result increases power production and hence increases of the carbon footprint as well as operational cost. For instance, any disturbance in a motor resulting in disruption of the process can cost multi-million dollars loss of the revenue as well as maintenance cost. According to 1999-2012 Equipment Breakdown Structure (EBS) report published by the Electric Power Research Institute (EPRI), 80 percent of the total outages in the processing plant are unplanned. Various motor reliability surveys and reports[2–6] are published that suggest the failure modes of the electrical machines.

To prevent these assets from failures, various maintenance strategies are adopted by the industry. Three commonly used approaches are reactive, preventive and proactive. A fault that remains undetected leads to the partial or complete damage of the machine and therefore, resulting into unscheduled outage. In reactive approach, after the failure has done the damage, machine is repaired or replaced during the unscheduled outage time. This approach is not acceptable in critical industrial process. In preventive approach, the machine is inspected during the planned or scheduled outage-time and is repaired, if required. This approach helps in detecting the failure at an early stage. The disadvantage of this approach is the requirement of expensive test equipment or third-party service to test and diagnose the possible failure.

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Moreover, possible fault detection remains dependent on the scheduled outage-time, causing latency in early detection of the fault before it evolves into big failure.

Proactive approach, on the other hand, resolves the issue of outage-time dependency by continuously monitoring the machine while it is online. Online monitoring also helps in early detection of the fault and therefore, allows planning the maintenance strategy if required. The proactive approach can help to achieve additional value in the following areas:

- 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.

Conventional protection relaying is reactive in nature and serves the purpose of protection against terminal or ground short circuit faults, monitoring of the motor and transformer operation, thermal overload, etc. However, various faults remain undetected by this protection relay until the fault evolves into severe damage. These undetectable faults can belong to electrical, thermal or mechanical failures, e.g. broken rotor bar in motors and insulation deterioration condition inside the transformer.

This paper discusses convergence of the protection relay and Monitoring and Diagnostic (M&D) technique. Motor M&D technique is based on the Electrical Signature Analysis (ESA) while in transformer it is based on the Dissolved Gas Analysis (DGA). Having advanced M&D integrated solution in a protection relay combines benefits of both protection relaying system as well standalone M&D solutions. The combined solution is a one box solution that is reactive as well as proactive in nature and offers 24/7 continuous monitoring of the assets.

To achieve autonomous M&D, various novel security mechanisms are proposed for the proposed techniques. In this paper proposed integration methodology for motor/ transformer and case study is presented.

2. Integration Architecture/ Methodology

2.1 Relay Based Transformer Asset Management

Transformer Protection Relay (TPR) embeds different advanced protection features and functions which performs the fault diagnosis and protects the transformer from failure due to high stress conditions created during conditions like short circuit and avoids the possible failure of the transformer. Specifically, differential protection element is one of the important functions which detects and protects the transformer during internal fault conditions and at the same time avoids transformer tripping during external fault conditions. TPR also has means to monitor several conditions of the transformer using digital inputs, transducer inputs which majorly include functions like monitoring oil temperature, winding temperature, ambient temperature, oil level, bucholtz relay status, cooling status etc. At the same time, Dissolved Gas Analysis (DGA) devices monitor the different gases dissolved inside the transformer oil whose ppm levels indicate the thermal and mechanical fault conditions at incipient or matured state. TPR devices monitoring electrical characteristics of the transformer and DGA devices monitoring thermal & mechanical characteristics of the transformer doesn't have any convergence in looking at the same transformer condition in a holistic manner today. In order to fill this gap, it is proposed that Transformer Protection relay and the M&D (monitoring and diagnostics) devices are connected and operated in a client-server mode of operation. The architecture design is shown below in Figure 1.

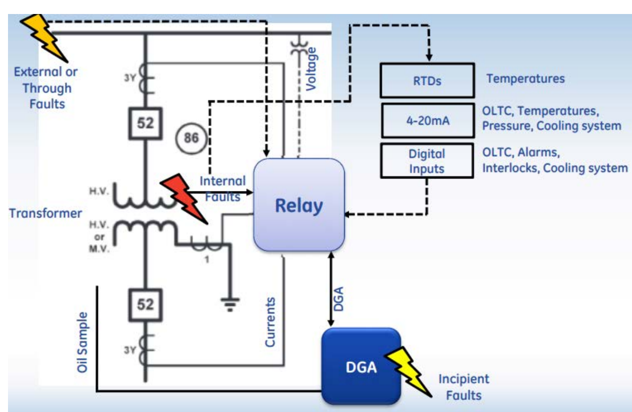

Figure 1. Integrated transformer monitoring architecture.

The proposed architecture provides several benefits and advantages as mentioned below as determining the existing condition of power transformer is an essential step in analyzing the risk of failure.

- Data correlation of electrical, thermal and DGA data helps in monitoring the transformer from different angles and perspectives.
- Analyzing the transformer condition based on electro-mechanical characteristics after a major fault condition or failure or event.
- Seasonal variation of load, power, demand, harmonics and thermal data of the transformer can be verified.
- Consolidated data helps in effective operational monitoring of transformer and planning load demand. One of the most important transformer diagnostic tools is the operating history captured as learned data.
- High magnitude inrush currents during energization can be monitored for harmonic current which indicates the electrical and mechanical stress on the transformer.
- Effect of random switching on the transformer can be analyzed with respect to the load on the transformer during energization. DGA gas values and electrical monitored data during an energization event can be used as reference or baseline values to understand the degradation of the transformer health from energization cycle to cycle.
- Extend the operational service life of the transformer by monitoring electrical and DGA data during faults.
- Correlate pre and post fault electrical and DGA data captured during the fault to understand the electromechanical stresses.
- Avoid dependency on periodic DGA analysis to estimate stress on the transformer during a fault. Pre and post fault DGA data captured during each fault when applied with DGA models will indicate incipient fault conditions or failure modes that have developed or progressed inside the transformer.
- It is generally believed that failure occurs when a transformer component or structure is no longer able to withstand the stresses imposed on it during operation. Hence, it is critical to understand this stress during each major fault occurrence on the transformer such as trip occurred due to fault.
- Although DGA data recorded a few days before the fault occurred may not indicate potential problems, DGA data captured after the fault can show larger amounts of specific gas ppm values based on the failure severity.

2.2 Relay Based Motor Asset Management

Mechanical vibration-based analysis to detect motor mechanical faults has been in use for more than 70 years, with abnormal vibrations the initial sign of a likely mechanical fault. On the contrary, Motor Current Signature Analysis (MCSA) or Electric Signature Analysis (ESA), is used to detect various failure modes in a rotating machine by analysing the stator current signal[7]. The proposed method offers AESA (Autonomous ESA) based technique to detect various failure modes in a rotating machine and its assembly by analyzing the stator phase A current. This method provides detection of motor failures such as stator inter-turn fault, roller/ball bearing fault, and mechanical faults like foundation looseness, load shaft misalignment, static and dynamic eccentricity. The proposed method doesn't require additional measurements such as noise, vibration, or temperature. The algorithm uses FFT computation of the Phase A current signal to determine fault frequencies related to the corresponding fault condition as depicted through architecture in Figure 2.

The algorithm also computes peak magnitude and energy in dB for each fault frequency and calculates the change in dB magnitude with respect to the baseline peak magnitudes (the healthy mode of the motor without misalignment) and energy at the corresponding fault frequency with respect to each load operating zone or load bin. Figure 3 shows a step by step high-level architecture of the proposed AESA-based algorithm. Load Bin, Baseline

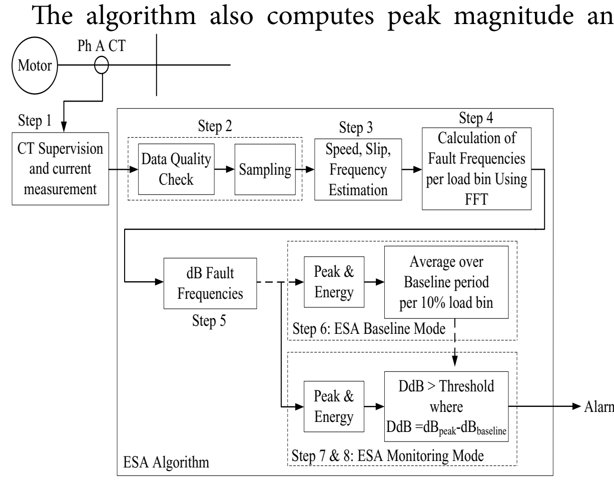

Figure 2. Integrated motor monitoring architecture.

Mode, and Monitoring Mode mechanisms are described in more details in the following sections.

2.2.1 Load Bin Mechanism

The magnitude of the fault frequency is impacted by the motor loading and therefore the magnitude (dB) changes as the motor load changes. The proposed algorithm handles the load changing condition by using a load bin mechanism. A load bin is defined as the load interval of 10% within the 0% to 120% range of motor load operation, with a total of 12 load bins. During AESA baseline mode operation, peak and energy dBs are computed and averaged over the entire configured period and then stored as averaged normalized dB with respect to each load bin of the motor.

2.2.2 Baseline/Learned Mechanism

For an ideal motor having no bearing, mechanical or stator faults, the dB magnitude of any fault frequency corresponding to load bin is ideally -100dB, meaning that the magnitude of fault frequency is zero. However, in practice this may not be the case since a motor without any faults may still generate some or all fault frequencies at low dB levels. The algorithm establishes the baseline dB of the inherent fault frequencies for all possible load bins.

2.2.3 Monitoring Mechanism

In monitoring mode, the AESA algorithm runs FFT on phase A current samples to capture the peak magnitude and energy for each possible harmonic factor ($k = 1,2,3$) related to the bearing, mechanical and stator faults. Computed AESA dB magnitudes at all fault frequencies after each 1-minute interval are compared with baseline magnitudes to extract the maximum change in dB. For secure operation of the fault declaration algorithm, data quality checks and AESA accuracy checks are performed prior to recording data.

2.2.4 Robust Data Quality Check

Before computing the FFT of the current signal, a quality check of the input supply data is performed by the AESA algorithm. If any of the following data checks fail, AESA does not perform the FFT or data recording.

- Fundamental frequency measured must be within +/- 5% limits of the nominal frequency.
- Voltage measured must be within +/- 10 % limits of the nominal voltage.
- THD (total harmonic distortion) of the phase current must be less than 5%.
- ROCOF (rate of change of frequency) computed must be less than 5%.
- Current unbalance in the system computed must be less than 10%.
- High-Level Architecture of the Proposed AESA Algorithm.

3. Benefits of Proposed Methodology

The following are the benefits of convergence in P&C and M&D technologies:

3.1 Relay Based Transformer Asset Management

- P&C relay and M&D devices of transformer will operate in master-slave mode and exchange the data at regular intervals of time.
- Protection relay usually captures electrical characteristics and M&D devices usually capture thermal/chemical characteristics. This convergence helps in monitoring different characteristics of the transformer in a time synchronized manner providing complete overview of the transformer health.
- Data correlation between different electrical, thermal and chemical parameters is possible for relevant sub-system parameters helping in multi-dimensional view of transformer sub-system condition.
- A transformer undergoes stress due to regular loading process and significant stress during fault or event. Hence it will be easier to analyze the stress on the transformer during every event or fault detected by relay.
- During every electrical event or fault detected by relay, it is possible to capture pre and post fault M&D data to understand the impact of event on each sub-system of the transformer and thereby take necessary preventive actions.
- It is possible to generate the integrated fault report and health report combining all the electrical, thermal and chemical characteristics of the transformer.

- It is possible to trend the asset risk vs event risk and understand how specific events are impacting the asset condition.

3.2 Relay Based Motor Asset Management

- M&D of motor can be done through vibration analysis or electrical signature analysis. With electrical signature analysis it is possible to completely embed complete M&D functionality into P&C relay.
- There is no need of separate sensors required for M&D purpose as the CT/PT inputs connected for protection purpose can also be used for M&D purpose.
- There is no need of separate box for M&D as the same protection device will also perform monitoring functionality.
- Rigorous data quality check and steady state check can be performed with protection class accuracy for performing M&D tasks.
- 24x7 online and autonomous continuous monitoring is possible as the protection relay is always connected to motor and is in ON mode.
- Protection relay usually captures electrical characteristics and M&D devices usually capture thermal/mechanical characteristics. This convergence helps in monitoring different characteristics of the motor in a time synchronized manner providing complete overview of the transformer health.
- Data correlation between different electrical, thermal and mechanical parameters is possible for relevant sub-system parameters helping in multi-dimensional view of motor sub-system condition.
- A motor undergoes stress due to regular loading process and significant stress during fault or event. Hence it will be easier to analyze the stress on the motor during every event or fault detected by relay.
- During every electrical event or fault detected by relay, it is possible to capture pre and post fault M&D data to understand the impact of event on each sub-system of the motor and thereby take necessary preventive actions.
- It is possible to generate the integrated fault report and health report combining all the electrical, thermal and mechanical characteristics of the motor.

- It is possible to trend the asset risk vs event risk and understand how specific events are impacting the asset condition.

4. Integrated Motor M&D Case Study

Motor Protection Relay with electrical signature analysis-based M&D algorithms has been tested at one of the workshops to verify the performance of the algorithms. The test setup consists of a healthy motor connected to relay with CT/PT input and then faulty motors with different faults (bearing, mechanical, stator, rotor) connected to relay with CT/PT input. For each fault, data is collected during healthy state of motor and when the motor is in fault condition. Performance of the algorithms is benchmarked by comparing the data collected during healthy and faulty states of the motor. Some of the faults that were tested, motor nameplate details and results are presented below.

4.1 Stator Turn-Turn Fault Test

The following are the nameplate details of motor tested,

- Manufacturer: Siemens Motor.
- Motor Application: Unknown.
- Voltage Rating: 415 ± 10% V.
- Rated FLA: 42 A.
- Rated Power: 30 HP.
- Motor Type: Squirrel Cage Induction.
- Rated Speed: 975 RPM.
- Year: 10/2014.
- No. of Poles: 6.
- No. of Phases: 3.
- No. of Stator Slots: 54.
- Fault: T-T fault (3 turns less in Phase B).

As represented above, the fault magnitudes computed during fault condition and healthy mode are shown in

Figure 3. Motor with Stator T-T fault.

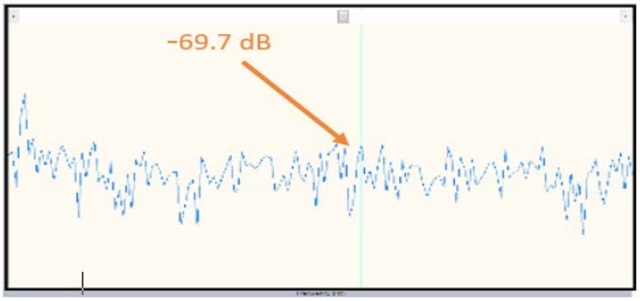

Figure 4. Fault magnitude during stator failure.

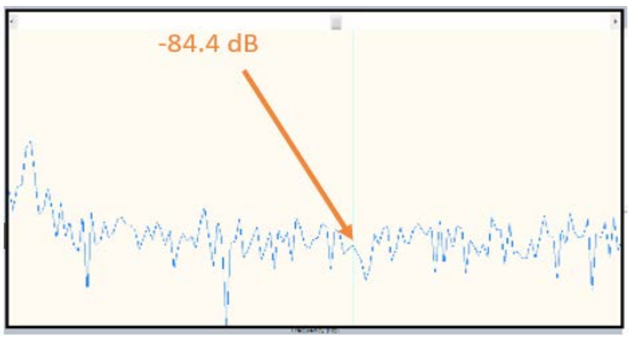

Figure 5. Fault magnitude during stator healthy.

Figures 4 and 5. It can be observed that there is a difference in magnitude of 14.7 dB from healthy state to faulty state of stator condition.

4.2 Bearing Fault Test

The following are the nameplate details of motor tested

- Manufacturer: ABB Motor.
- Motor Application: Blower.
- Voltage Rating:415 ± 10% V.
- Rated FLA: 21 A.
- Rated Power: 15 HP.
- Motor Type: Squirrel Cage Induction.
- Rated Speed – 1455 RPM.
- Year: 1996.
- No. of Poles: 4.
- No. of Phases: 3.
- No. of Stator Balls: 8.
- Cage Diameter: 2.854 in.
- Ball Diameter: 0.6875 in.
- Bearing model (DE): 6309-2Z-C3.
- Fault: Ball defect.

Figure 6. Motor with bearing fault.

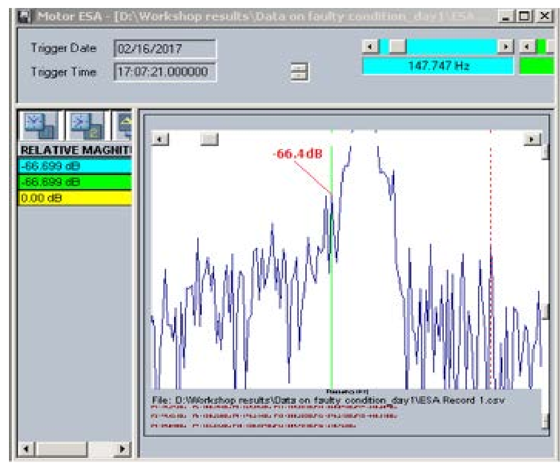

Figure 7. Fault magnitude during healthy condition.

As represented above, the fault magnitudes computed during fault condition and healthy mode are shown in Figures 7 and 8. It can be observed that there is a difference in magnitude of 21.7 dB from healthy state to faulty state of bearing condition.

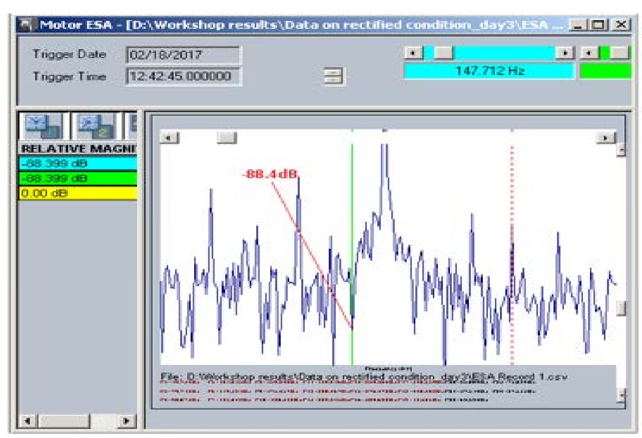

Figure 8. Fault magnitude during faulty condition.

5. Conclusion

Convergence in technology is considered as one of the critical paradigms shift in today's smart grid world. In fact, the smart grid concept itself has been evolved by the convergence of communication and information technology with electrical technology. Protection and Control (P&C) and Monitoring and Diagnostics (M&D) of the electrical assets are two critical important technologies which have been used and applied since ages. However, there is no much convergence in these two technologies and has been applied and analysed separately by operational and maintenance engineers. In this paper, convergence of P&C and M&D technologies has been presented for transformers and motors and it can be concluded that convergence of these two technologies will improve the asset management strategy and helps in event-based monitoring apart from condition-based monitoring.

6. Acknowledgment

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