Integrated generator rotor and stator winding condition monitoring

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Traditionally, maintenance was performed at power plants on the most critical machines on a time-based schedule; however, this often resulted in activities occurring before they were necessary. Over the past 20 years, there has been a shift in the industry towards condition-based maintenance. This strategy requires the collection of a variety of data to detect most ageing-related mechanisms, which can be used to better schedule and plan maintenance. Initially, data collection was carried out manually and performed infrequently, but once the benefits of condition monitoring started to be realised, this shifted to continuous real-time monitoring. Today, there is another shift away from application-specific software to accessing a variety of data on a common platform, allowing for a more comprehensive analysis. The most critical machines in a power plant are the turbine generator sets. The generator rotor and stator windings are generally very reliable; however, they do age over time, reducing electrical and mechanical strength. This paper focuses on detecting turbine generator rotor and stator winding problems prior to failure using an integrated approach. A case example will be discussed, which includes partial discharge, rotor flux and stator end-winding vibration.

1. Introduction

Generator stator windings, rotor windings and cores have a variety of failure mechanisms[1,2], many of which are due to long-term ageing of the electrical insulation, copper conductors and/or the stator and rotor cores/forgings. These ageing mechanisms are principally driven by currents, voltages, mechanical stresses and environmental factors, which gradually reduce the electrical and mechanical strength of the insulation, copper and steel. Eventually, the strength is sufficiently reduced to puncture the insulation or fatigue crack the metal, resulting in an unplanned outage. Most of these failure mechanisms can be easily found and assessed during inspection, assuming the minor and major outages are scheduled suitably. This time-based or preventative maintenance approach often results in outages that are not needed, since the generator is found to be in good condition. In addition, the reduced availability caused by the inspection and test outages reduces the revenue to that plant.

The disadvantages of time-based maintenance have created a desire for a move to condition-based or predictive maintenance, where the generator is removed from service for an inspection/test when a developing problem is indicated though condition monitoring. A large number of condition monitors have been developed over the past 25 years to detect many failure processes when the generator is online during normal operation. Initially, there were a number of issues with the credibility of the monitors due to false positive and false negative indications and the monitors themselves also tended to have reliability problems. However, more recently the effectiveness of the monitors has been improving.

Many monitors are needed to detect the most likely problems in a generator related to ageing mechanisms and unfortunately almost all of these operate in isolation, using different communication structures, software platforms, database storage structures and information display formats. The differences between online monitors make it difficult for plant owners to combine the information from all the monitors to determine whether or not there are developing problems. An effort by the Institute of Electrical and Electronics Engineers (IEEE) to create a common platform for generator condition monitoring has not been successful. The International Electrotechnical Commission (IEC) has undertaken no such effort, at least for the rotor and stator winding monitors. No doubt, a large generator manufacturer that also supplies condition monitors probably uses a common platform, but all analysis tends to occur at the manufacturer's site, out of the control of the user. Recognising these factors, there seems to be a need for independent suppliers of generator condition monitoring systems to develop a common platform that can be used with a large number of online monitors.

2. Winding failure processes

There are likely over 30 or so distinct failure processes in generator rotor and stator windings[1,2]. Whether a particular failure process occurs or not depends on the design, cooling system, operating environment and the past maintenance carried out on the machine. The most likely stator problems include, among others:

- Thermal ageing
- Thermomechanical ageing (load cycling)
- Loose windings in the slot
- End-winding vibration
- Water leaks in direct cooled windings
- Electric stress coating deterioration
- End-winding electrical tracking due to contamination
- Insufficient space between the end windings
- Loose stator cores
- Core insulation thermal ageing.

The more likely rotor winding deterioration processes include:

- Thermal ageing
- Thermomechanical ageing (load cycling)
- Copper dusting
- Contamination
- Centrifugal force.

Each of these mechanisms proceeds at its own rate and, often, the repair process for the individual mechanisms is different. Therefore, it is important to know which mechanism (if any) is occurring.

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3. Online generator monitors

Online generator monitoring instrumentation requirements depend on a variety of factors, including machine rating, type of construction and cooling method. These can generally be selected based on the cost and criticality of the generator and this involves a balance between failure cost *versus* repair and lost production cost. The monitors require sensors to be installed on the components of interest. Data collection, communication and analysis occur at regular intervals depending on the monitoring requirements, hardware capabilities and set-up.

3.1 Stator monitoring

Resistance temperature detectors (RTDs) or thermocouples can be used to monitor stator bar temperature. These are typically installed between the top and bottom bar in the slot and measure the highest temperature. The higher the temperature and the longer the duration at elevated temperatures, the greater the likelihood of thermal deterioration or thermal cycling issues.

Monitoring high-frequency voltage pulses in stator windings with a partial discharge (PD) monitor can allow for the measurement of activity resulting from insulation deterioration inside the windings, between the windings and the slots and on the end windings. Small electrical sparks in air-filled voids within the insulation create small voltage pulses and as the size of the voids increases so does the magnitude of the partial discharge pulses. Simply put, the location of the voids within the insulation will determine the pulse polarity and phase position of the partial discharge, which can indicate various failure mechanisms, including thermal cycling, thermal ageing, looseness, contamination, etc. There are many online PD monitoring systems for generators. The most common uses either capacitive sensors directly on the high-voltage bus (two per phase to identify system noise based on pulse direction) or antennae installed in the slots with the line end bars (one per parallel per phase, no noise separation required)[3]. Given that the failure mechanisms associated with partial discharge are slow in developing, a monitor with continuous data storage is not necessary. Instead, smart data acquisition should be incorporated to collect data automatically to provide meaningful trend data at various stages of the generator load cycle.

Ozone gas is a by-product of surface partial discharge in air-cooled machines. Ozone monitoring will indicate partial discharge on the surface of stator windings that is the result of loose windings, semi-conductive deterioration and insufficient spacing in the end winding. Sensors installed within the generator enclosure or in the air exhaust can continuously measure ozone concentration. Care must be taken when evaluating concentration levels, as generator operating voltage, air humidity and power will affect the ozone produced by a stator winding[1].

Generator condition monitors (GCMs) are used to detect stator core lamination insulation burning in hydrogen-cooled machines. They detect particulates from burning core lamination insulation. Together with tagging compounds, they can also be used to detect hot spots on the rotor and stator windings[1,2].

Stator end-winding vibration issues are found on large generators with especially long winding overhangs that are not sufficiently supported. Monitoring this vibration by installing sensors on the end windings, connections, support brackets, water manifolds, etc, will indicate when the support structure loosens. There is a practical limit to the number of locations and components that will be monitored, so offline impact testing should be incorporated to determine the locations of the components that are most likely to vibrate at maximum amplitudes during operation[4]. Metallic accelerometers used to collect vibration data may compromise the electrical clearances of the end-winding to ground and can result in partial discharge. Instead, fibre-optic accelerometers should be used, as they are not sensitive to the electrical fields present in the high-voltage stator end-winding area. Historically, a double-integrated signal from acceleration to displacement has been used to assess the structural integrity of the stator end-winding support system, but with the advancement of fibre-optic technology, more data at a broader frequency is being collected, resulting in a need to not only assess end-winding displacement, but velocity and acceleration as well.

For certain direct water-cooled windings, it is possible to detect sensitively when small water leaks may be occurring that can degrade and fail the stator ground insulation. Determination of whether if this deterioration process is occurring can be inferred from the leakage of hydrogen into the stator cooling water. One major manufacturer has developed such a system, called SLMS-HP, based on an undisclosed method[5]. The system can apparently detect hydrogen to water leaks as low as 6000 cm^3 per day.

3.2 Rotor monitoring

Rotor winding temperature can be monitored by accurately measuring the voltage and current applied to the slip rings. The rotor winding resistance, calculated with Ohm's Law, will vary with temperature. Once calibrated, the average rotor winding temperature can be inferred. In those machines without slip rings, the voltage and current feeding the rotor can be measured indirectly by measuring the excitation voltage and current.

Vibration monitoring with sensors installed on the bearing housings and shaft journals will monitor the forces produced by a generator. These forces cause vibration and may change in direction and amplitude with time, result in friction between rotating and stationary components, cause impacts or cause randomly generated vibration. The vibration amplitudes are proportional to dynamic forces, meaning that increased forces will reduce generator life. In general, problems that cause high vibration amplitudes are rotor imbalance, shaft misalignment, looseness, bearing wear/misalignment, rubbing and electrical problems. Specifically, in two-pole generators, bearing vibration can indicate the presence of shorted turns in the rotor winding caused by thermal or thermomechanical problems, copper dusting and/or contamination. Vibration monitoring is often part of the protection system, as high vibration at these locations should automatically trip and shut down the generator to prevent catastrophic failure.

Rotor flux monitoring will provide information on the integrity of rotor winding turn insulation. A turbine generator rotor consists of a solid forging made from magnetic alloy steel and copper windings, assembled in slots machined in the forging. Problems with rotors result from exposure of winding copper and insulation to high centrifugal loads and thermal expansion forces, leading to breaks in the winding insulation and to copper cracking and contamination. A magnetic flux sensor installed on a stator tooth in the air gap is sensitive to radial flux density as the rotor passes by the probe. Shorted rotor winding turns result in reduced slot leakage flux and are an indication of insulation failure in the rotor winding. In conventional flux monitoring, distortion of the radial flux signal is minimal where the air gap flux density curve crosses through zero, which is a function of generator load. Because of this, it is necesary to take multiple readings at various generator load points for maximum sensitivity to shorted turns. However, it has been recently demonstrated that accurate detection of rotor winding shorted turns can be obtained with a reduced need to vary the load on the generator with suitable instrumentation and algorithms[6]. Alternatively, smart triggers can be used to automatically capture the flux information during normally occurring load variations.

Shaft current and voltage monitoring will help to detect poor grounding of the shaft and avoid bearing and seal damage when high shaft voltage is present by monitoring the condition of the shaft grounding brush. Measuring the shaft current may require a modification to the grounding brush, while a voltage sensing brush usually needs to be installed to transition shaft grounding protection to a shaft monitoring system. Shaft current and voltage monitoring should be continuous, as the duration from a grounding brush beginning to wear to when the stray currents start flowing between the shaft and the bearings can be quite short. The resulting bearing pitting may cause permanent damage to the shaft and bearings.

4. Integrated platform

Deterioration of generator components is usually a relatively slow process, where the time between condition detection and failure may be several years. Thus, measurements that are taken periodically can be adequate for detecting problems. However, a continuous, automated and fully-integrated monitoring system has many advantages:

- Site operations and maintenance staff in plants are under increasing workloads. Integrated monitoring systems allow for automated measurements to be made, sparing the time and expenses involved in having to send personnel to the plant.
- Monitored conditions are often affected by operating conditions, including winding temperature, load, voltage, current, etc. An automated monitoring system avoids this problem by continuously measuring the generator operating conditions and then trending and correlating the condition measurements, taking into account the operating state of the machine.
- Collecting data during varying conditions can itself be useful in the data interpretation process. For example, for stator partial discharge measurements at different load points, the winding is subjected to different stator bar forces, thus winding looseness can be inferred by comparing full load and no load test results. An integrated automated monitor such as this gives maintenance engineers a more complete picture of the condition of the machine when using data collected in this manner.
- Expert systems or intelligent software can be used to correlate data from various sensors into one platform. An integrated condition monitoring system can augment the capabilities of more complex data types such as PD, flux and end-winding vibration by processing data into simplified information. An integrated platform will corroborate fault diagnosis from multiple monitors to provide a cooperative approach to condition-based monitoring.

An integrated platform to collect data from a range of sensors can be used for trending and assessing the stator and rotor conditions. Each generator to be monitored requires one instrument to be mounted outside of the machine, near the sensors. Coaxial and fibre-optic cables connect the sensors to the instrument. The instrument raises an alert if a particular activity is more than a predefined value for the current machine operating conditions. Ethernet is used to connect the monitor to the plant local area network for configuration and data downloading. This allows personnel in distant offices to define or change trigger conditions and alert levels and to download test results for display and analysis. The archived data can also be downloaded locally over a USB port. The software included with the instrument is a single platform for generator definition, sensor configuration, data downloading and data analysis. A common Microsoft Access database is used to archive data from all technologies, along with relevant operating data. Viewers for looking at historical trends, correlating data and performing detailed analysis are used to assess the health of the generator. A layout of this system is shown in Figure 1.

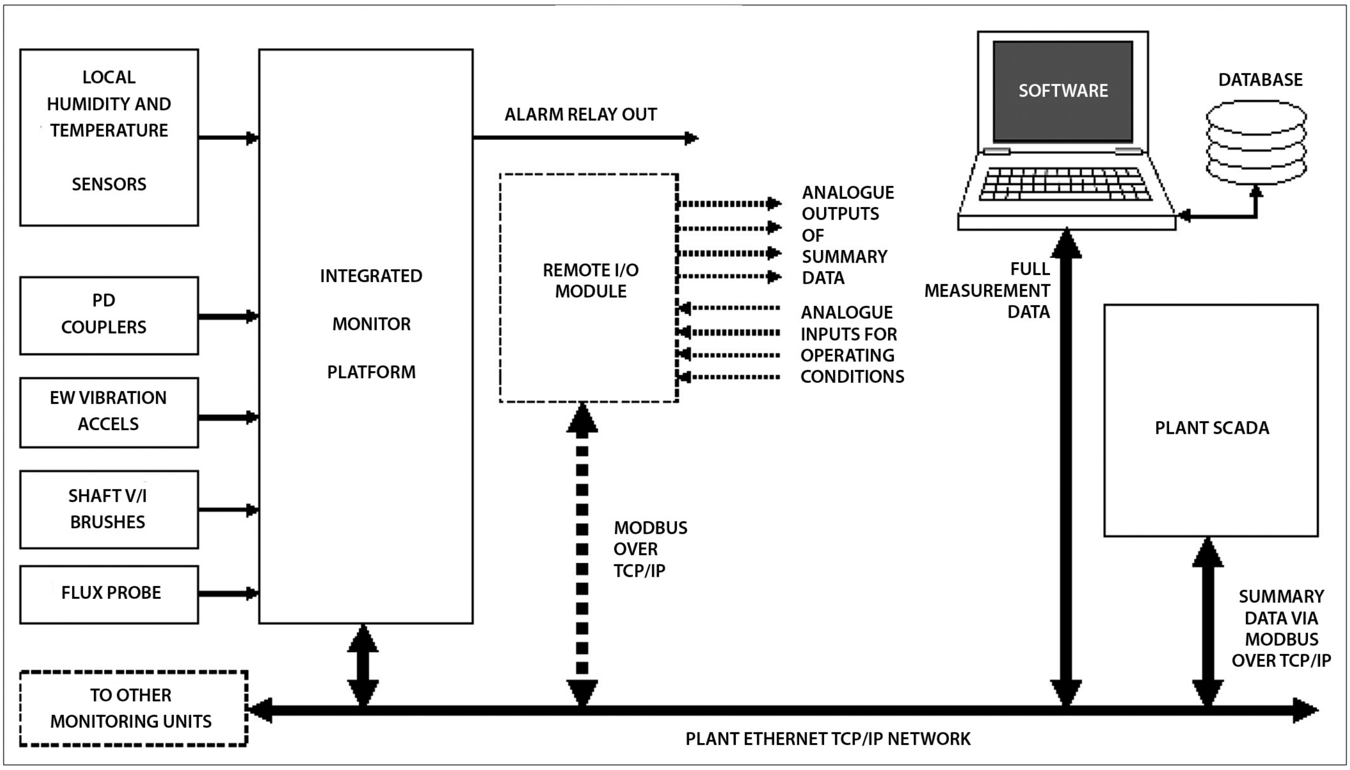

Figure 1. Layout of generator integrated monitoring platform

Using such a platform, it is often possible to predict 'expected' values for sensors based on mathematical models of machine parameters. These predicted values can then be compared to the actual measured values and deviations analysed to detect failure modes. For example, the predictions of stator end-winding vibration can be made based on the stator current and winding temperature of the generator. If the temperature is constant, Ampère's Force Law can be used to calculate the force between two current-carrying conductors, which is directly related to vibration. This relationship with collected data is shown in Figure 2. Once calibrated with baseline data, any change in current (force) can be used to calculate the expected end-winding vibration and any deviation can be attributed to a change in the end-winding structural support structure. For many sensors, the alarm thresholds may also be significantly different depending on the operating mode of the machine.

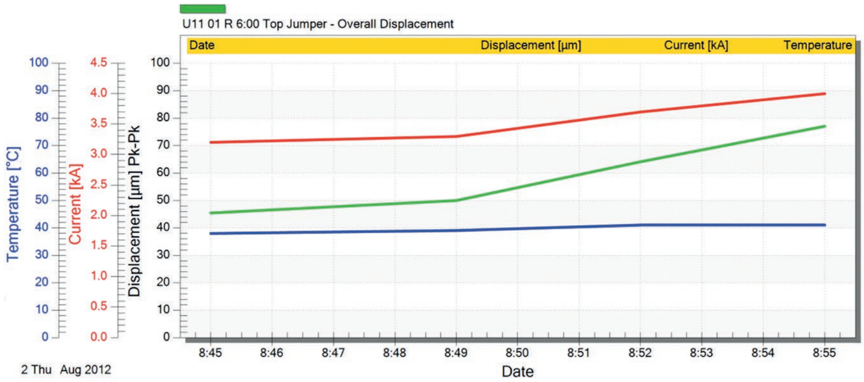

Figure 2. End-winding vibration, stator current and winding temperature over time

The assessment of the generator stator insulation system is enhanced by having access to an extensive PD database. The collective experience and results are regularly summarised in statistical tables and available to all users[7]. This data is also used to automatically configure alert levels, ensuring objective interpretation of insulation condition. Smart triggers are utilised to collect data at various generator load and winding temperature conditions.

Advanced algorithms can be employed to analyse flux data on rotor windings, regardless of load changes. This technology provides the highest accuracy in identifying rotor shorts regardless of flux density zero crossing location. Additionally, smart triggers are also used to collect data automatically at various generator loads.

End-winding vibration data is continuously collected from fibre-optic accelerometers and provides alerts concerning high overall displacement. Additional analysis capabilities enable displays in displacement, velocity or acceleration across the frequency range of interest.

MODBUS over Ethernet protocol is included for interfacing with third-party applications, allowing for the ability to receive machine operating condition data for parameters such as active power, reactive power, stator voltage, winding temperature and hydrogen pressure from plant systems. This capability improves data trending by providing context to the PD, flux and end-winding vibration measurements. Signals proportional to the monitor's summary values and status data can also be transferred to plant systems for central trend display. A block diagram for the signal communication possibilities between the monitor and plant system is shown in Figure 3.

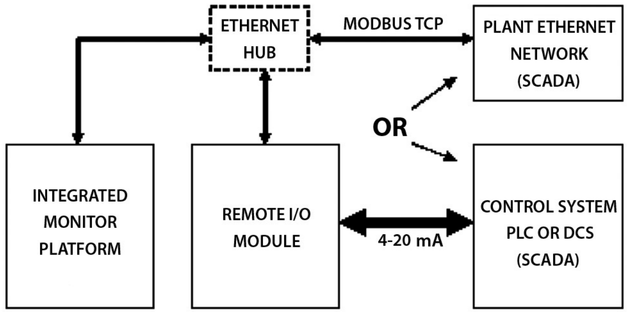

Figure 3. Block diagram of signal communication with integrated monitor

5. Conclusion

The primary benefits of incorporating online monitoring systems are the avoidance of unplanned outages by detecting deterioration at the earliest onset and extension of the time between planned outages, as equipment is removed from service less frequently than other maintenance schemes. This reduces the risk of damage during outage, as the disassembly, outage and reassembly can result in inadvertent damage. Maintenance and repair costs can also be saved, as generally they are reduced if action is taken at earlier stages of generator deterioration. In general, the life of the generator is extended by carrying out repairs before major damage occurs. Integrating multiple monitoring technologies provides the benefit of not only detecting subtle changes in the generator early enough to prevent lost production, but also of increasing the confidence of the generator condition assessment by taking a collaborative approach to condition-based monitoring.

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