Online Monitoring - Early detection and diagnostics of initiating damage in turbogenerators

Author:
Frank Ewert
Siemens AG
Energy Sector
Service Division
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1 Abstract

Increasing use of wind and solar energy is making it necessary to operate fossil power plants at medium and peak load with rapid changes in load which, particularly in older units, severely stresses many components. A power plant's availability depends crucially on the reliability of the major high-voltage components such as the generator, the isolated phase bus (IPB) and the machine transformer. Electric failures inside these components can lead to serious damage with long shutdown times.

Hence, early detection and diagnosis of initiating damage in this high-voltage area is of essential importance to the economic efficiency of a power plant. This paper describes online measurements available as an aid for early detection of, e.g. partial discharge, end winding vibration and rotor shorted turn monitoring.

2 Introduction

The influence of renewable energy resources – especially wind energy – is increasing. This trend is making it necessary to operate fossil power plants more and more in the medium and peak load range to stabilize the electrical grid. In large fossil power plants, especially, the higher number of load cycles associated with this medium and peak load operation aggravates thermo-mechanical stressing of the core components such as the generator. This typically results in accelerated aging of the machines and the risk of damage and unexpected failures.

As a preventive measure, inspections at more frequent intervals provide an insight into the condition of the generator, but at the cost of expensive power plant outage time. To minimize loss of revenue, it is helpful to use online condition monitoring and diagnostic systems to obtain information about the state of the machine during operation. This facilitates targeted, condition based maintenance.

a) Online monitoring of partial discharges enables the user to detect abnormal conditions in the electrical insulation system of the generator as well as the IPB and the transformers.

b) Online monitoring of stator end winding vibration yields information about the actual vibration during operation, e.g. depending on the specific load point.

c) Online monitoring of the air gap magnetic flux helps to identify interturn short circuits within the rotor windings.
Only the interaction of these online monitoring systems in correlation with the operating parameters enables a powerful generator diagnostic.

3 Generator Monitoring Overview

Generators spend many years in service in power plants. Operation and aging can gradually cause damage to their high-voltage insulation. If early detection of changes in the components is made possible by in-process long-term diagnosis, unscheduled and expensive outages can be prevented and measures can be scheduled and taken to extend the service life of generators. Monitoring systems are available for various parameters. This paper focuses on monitoring partial discharges (PD), end winding vibration (EWV) and interturn short circuits (ISC). Other systems are also available for shaft voltage/current and fiber optic stator and rotor temperature monitoring but are not mentioned here.

The typical Siemens generator monitoring concept comprising the main monitoring systems mentioned above is illustrated in Fig. 1.

![Fig. 1: Overview of SIEMONplus monitoring system](image)

Monitoring usually starts with the sensors which are installed inside the generator (vibration and flux) or in the direct vicinity of the generator, for example, inside the iso-phase bus...
(partial discharge). The signals from the sensors are routed to a data acquisition unit (AU) located in the turbine hall. All relevant data is stored on the AU and can be downloaded for diagnosis. By adding a central server to this system, up to 20 generators can be monitored and the data can be stored, visualized and compared with each other. The server can be easily connected to any I&C system such as a plant information (PI) system and T3000 system or to a superordinate system like the WIN_TS system. Once connected to one of these systems, the data can be automatically transferred to the Siemens Power Diagnostic Center (PDC), where the data is constantly screened by means of highly sophisticated rule-based analyses which includes automatic comparison of the measured data with all relevant and available generator parameters. In the event of any deviations from normal behavior, the Siemens experts are alerted to perform a detailed evaluation of the data and to provide recommendations to the customer.

4 Partial Discharge (PD) Monitoring

Electrical faults in high-voltage components like a turbine generator do not occur suddenly. In almost all cases however, defects get announced by PDs bridging part of the high-voltage insulation and are detectable with radio frequency (RF) measurement methods [1].

The distribution of the discharges with respect to the phase angle of the generator voltage is characteristic of the cause of discharges and allows conclusions to be drawn as to the level of the risk to continued operation of the high-voltage equipment. The PD measuring system can be normalized according to IEC/TS 60034-27-2. Transforming the measured voltage signals to charge units, as a measure of the electrical energy transferred, and analysis of the respective phase resolved partial discharge (PRPD) pattern make it possible to estimate the risk. Although the generator, as the most expensive electrical component, is generally the main target of supervision, the entire high-voltage area including the main and auxiliary transformers is monitored by recording PD signals.

4.1 PD Sensors – Coupling Capacitors (CC)

To detect PDs, special coupling capacitors have to be installed in existing voltage transformer cabinets (Fig. 2a), inside the isolated phase bus (IPB) (Fig. 2b), inside generator neutral
cabinets (Fig. 2c), inside generator terminal boxes (Fig. 2d) or at other suitable places in the high-voltage area of the power plant.

The coupling capacitors are used to pick up the PD signals from the high-voltage line. The capacitors usually have a capacity in the range of 1nC to 9nC. Coupling capacitors with lower capacities are not used as their sensitivity is typically insufficient to meet Siemens' requirements. Experience shows that a broadband system which combines both the low frequency range (below 3 MHz) and the high frequency range up to 50 MHz is the best solution. The reason for this is that a low frequency range ensures a high measurement sensitivity for PDs coming from inside the winding and that are damped while running through the winding.

The high frequency range is less susceptible to interference and is necessary for detailed analyses such as localization of a PD source by a time-of-flight (ToF) measurement.

The capacitors are usually equipped with integrated overvoltage protection and have an insulated signal output to avoid any eddy currents along the cable shields. Possible locations for the installation are shown in Fig. 2:

![Possible locations for installation of coupling capacitors](image)

*Fig. 2: Possible locations for installation of coupling capacitors (CC) in large power plants; a) CC inside a voltage transformer cabinet; b) CC inside IPB; c) CC inside generator neutral cabinet; d) CC inside generator terminal box*
4.2 PD Analysis

Phase Resolved Partial Discharge (PRPD) Pattern

The best known and most powerful tool is analysis of the PRPD patterns (Fig. 3). These patterns typically show the PD distribution map of PD magnitude vs. AC cycle phase position, for visualization of the PD behavior during a predefined measuring time. These patterns can be classified and interpreted using the international pattern catalog (IEC/TS 60034-27-2).

*Fig. 3: Examples of PRPD Patterns*

Trending over the lifetime

Monitoring of a generator usually starts with the fingerprint measurement, which is the first measurement taken after the monitoring system was commissioned and with the generator at base load. This fingerprint measurement is used as a reference for any future analysis. The measurement further serves to identify narrow-band interference and to eliminate it by means of digital interference suppression in order to improve the sensitivity of measurement. Once the fingerprint measurement has been taken, trending (Fig. 4) is used to detect any deviation from the normal behavior and from the fingerprint measurement.

*Fig. 4: Example of PD trends*
The following PD parameters are usually observed:
- $Q_{IEC}$ [nC] apparent charge according to IEC60270
- $Q_{max}$ [nC] maximum charge
- $N$ [1/s] PD rate
- $QR$ [nC²/s] quadratic charge rate

For a successful generator diagnostic it is not enough to trend only the PD parameters. It is very important to trend operating parameters and parameters from other diagnostic applications simultaneously so as to make direct correlation with the PD data possible. The Siemens system is capable of recording operating parameters via analog inputs (4 to 20mA), but more common is an Ethernet connection to the I&C system or other superordinate systems (e.g. WIN_TS system) which usually provide the parameters via an integrated OPC server. The most important operating parameters of the generator are the following:
- slot temperatures
- cold and warm gas temperatures
- stator currents of all three phases
- stator voltages of all three phases
- active and reactive power
- exciter current

Oscillograms
As a basis for time-of-flight (ToF) measurement to locate PD events, it is important to evaluate high-resolution oscillograms (Fig. 5) taken with a sampling frequency of up 125MS/s 4 channels simultaneously over one AC cycle of the high voltage (50Hz → 20ms).

Fig. 5: Example of an oscillogram
Furthermore, the oscillograms can be used to determine the slew rates of the PD impulses to obtain information about the source or origin of any PD impulses. For example, the slew rate of PD impulses coming from inside the insulation system which travel through the generator winding are damped much more than impulses coming from outside the generator, e.g. impulses of an IPB supporter with a poor contact to the lead.

**Time-of-flight (ToF) measurements for PD localization**

Most PD monitoring systems on the market include a feature for performing ToF measurements for fault localization (Fig. 6).

![Fig. 6: Example of a ToF measurement](image)

Based on a high bandwidth and high sample rates, the signal behavior of PD pulses can be analyzed as function of place [3]. The signal shape of the PD pulse and comparison for both test points give some knowledge about the discharge source. The difference in the propagation times of the measured pulses can be determined and the possible region of the originating PD activity can be narrowed down. In this way the travel direction of the pulses can be directly calculated initially.

If there are well defined signal propagation paths between two test points (e.g. along the IPB), analysis of the travel time makes it possible to calculate the distance of the PC source with respect to both test points. If the time difference is below the calibrated travel time between the two test points, the PD source is located between both test points and can be pinpointed with an accuracy depending on the steepness of the pulses and the geometry of the propagation paths.

**Suppression of interference**

In general, PDs measured in power plants are overlaid by a lot of noise signals which have to be eliminated prior to further processing. These signals can be generically divided into sinusoidal and pulse-shaped signals.
Sinusoidal noise, e.g. transmission signals on the power lines, often fully mask any PD pulses contained in the measured signal. Because each data set is highly resolved in time domain, it can be filtered digitally by transforming it to frequency domain, filtering the resulting signal from the dominating resonance frequencies using digital notch filters, and transforming it back to time domain [5].

Typical pulse-shaped signals are, for example, the six equidistant commutation impulses of the static excitation system (6-pulses bridge). These impulses are caused by switching of the semiconductors in the static exciter power converter and they are typical of operation of generators with static excitation system with slip rings (Fig. 7).

![Fig. 7: Example of an unfiltered (left) and filtered signal (right)](image)

These high-frequency pulses couple from the generator rotor winding via the air gap into the stator winding and represent a normal phenomenon in all generators with static excitation. They can be used as a sensitivity check for PD online monitoring systems which operate in wide band mode in the low frequency range to IEC 60034-27-2.

Fig. 7 shows the effect of filtering the typical six equidistant impulses of the static excitation system.

**Test procedure**

A defined test procedure with consecutive load and temperature conditions should be performed to guarantee a successful diagnostic. The load and temperature conditions should be varied according to the measurement sequence described below:

1. Measurement at low load and thermally stable winding conditions
2. Measurement at high load directly after fast load increase
3. Measurement at high load and thermally stable winding conditions
4. Measurement at high load with significant change of reactive power and thermally stable winding conditions
5. Measurement at low load directly after fast load decrease
4.3 Example of PD – Slot Discharges

Slot discharges typically appear between the outer corona protection (OCP) and the stator core. The typical pattern of slot discharges is an asymmetrical distribution of discharges covering the amplitude and number within the two half-waves, as can be clearly seen in the PRPD pattern presented in Fig. 8.

![Fig. 8: Example of PD - slot discharges](image)

In the negative half-wave higher PDs appear. In both half-waves the PDs appear between the zero crossing and maximum/minimum of the high-voltage cycle. The PRPD patterns of slot discharges typically show a triangular shape [4, 5].

5 Stator End Winding Vibration (EWV) Monitoring

All forces that act periodically cause elastic structures to vibrate. Such forces occur in every generator. Vibration represents a cyclic load for the affected components, and increased vibration levels means an increased load, the load being proportional to the vibration amplitude. High levels of vibration cause the end-winding assembly to loosen and can lead to rubbing and fracture of the affected components [6].

The end-winding sections of a generator are excited particularly by:

- the core which vibrates at twice the line frequency and
- current forces and
- bearing and shaft vibration.

The unusually high currents and torques associated with line short-circuits, lightning strikes and out-of-phase synchronization have a particularly pronounced effect on the end windings of generators. Although generators may not necessarily be damaged by such events, it cannot be completely ruled out that such events can cause a certain amount of damage to the stator
winding. To prevent any secondary damage, the affected generator must be inspected to identify and repair potentially loose braces or ties particularly in the end-winding section. The condition of the generator end windings is typically examined visually. Loosening of end-winding assemblies causes secondary damage and increases the cost and effort of any repair measures. Omitted or late repair can mean the generator having to be completely re-wound. End-winding vibration monitoring is thus a useful tool for evaluating the condition of the generator end windings and also minimizes the risk of a re-wind.

5.1 EWV Sensors – Fiber Optic Accelerometers (FOA)

Online monitoring of end winding vibrations is performed by recording local accelerations during regular operation. Special fiber optic accelerometers are placed on the bar end connections of the stator end windings (see Fig. 9) taking into account the results of an offline modal analysis (bump test). These sensors are free of any metal parts and do not interfere with the electromagnetic field in the end-winding area. A minimum of six, but better eight, sensors per end winding should be used to allow a reliable data analysis.

![Fig. 9: Application of fiber optic accelerometers inside a stator end winding basket. The fiber optic accelerometers are non-metallic and do not interfere with the electromagnetic field in the end winding area.](image)

5.2 EWV Analysis

Real-time signals are usually used to check the general functionality of the sensors. The signals from the up to 16 fiber optic sensors are simultaneously acquired with a sampling frequency of 10 kS/s to enable online modal analyses.
A fast fourier transformation (FFT) is used to translate the time-domain signals into the frequency domain. Here the first and second harmonics of the line voltage are typically observed together with their respective amplitudes. They usually represent the vibration level in [µm] and are individually trended for each sensor signal separately. The trend of the vibration values can be displayed and correlated to operating parameters, for example active power, reactive power and exciter current, which may have a direct influence on the end winding vibration behaviour.

**Advanced analysis**

Modern end winding vibration monitoring systems provide an online modal analysis of the end winding vibration signals [7]. The Siemens system provides online evaluation and visualization of the standstill and rotating vibration modes separately. The respective changes in these vibration modes during operation are trended to detect possible changes in the structure mechanical behaviour of the generator end winding. This kind of diagnostics calls for detailed knowledge of the generator design in order to define potential measures.
5.3 Examples of EWV

![Fig. 11: Typical examples of EWV](image)

In most cases, end winding vibration is indicated by friction dust (Fig. 11) caused by relative movement of various end winding components (bandings, blocking elements, etc.). Permanent mechanical stressing of individual bars can lead to fatigue cracking of strands. The heat produced in cracked bars due to the cyclically interrupted current causes perforation and discoloration of the bar insulation.

6 Rotor Interturn Short Circuit (ISC) Detection

Rotor interturn short circuits are one of the most commonly encountered issues affecting the rotor of a turbogenerator. Possible reasons are:

- relative movement of bars inside the slots, resulting in abrasion of the insulation and displacement of insulation layers
- distortion of coils in the end winding area caused by centrifugal forces, resulting in abrasion of the insulation between top bars and the rotor retaining ring
- displacement of blocking elements in the end winding area
- foreign particles such as conductive dust
- oxidation due to humidity in the cooling gas

Common electrical and thermal aging can result in turn-to-turn, coil-to-coil shorts and coil/turn-to-earth shorts. In the event of a shorted turn or coil, a higher exciter current is needed to compensate the reduced magnetic field, leading to diminished efficiency. Shorted turns can cause hotspots and can result in thermal asymmetry, which is usually the reason for increased shaft vibration. Especially in 4-pole rotors, magnetic asymmetry leads to increased
vibration. The more turns are shorted, the lower the impedance of the short and the closer the short to the top of the slot, the better is the possibility of detecting shorted turns.

6.1 ISC Sensors – Flux Probes

To detect shorted turns, a sensor must be installed in the air gap between the rotor and the stator to measure the magnetic flux. The sensor is typically installed at the 3 o’clock or 9 o’clock position and is fastened on top of a stator slot wedge near the turbine end of the generator (see Fig. 12).

![Fig. 12: Installation of air gap sensor at stator winding slot wedge](image)

The monitoring system continuously analyses the magnetic flux during the unit’s operation by detecting changes in the rotor slot leakage flux signal provided by the sensor. It detects most of the shorted turns which can occur in a generator rotor and issues an alarm if a shorted turn is found. It is also possible to identify the affected slot in the rotor.

6.2 ISC Analysis

The measured magnetic flux does not cross the air gap to reach the stator windings. Its magnitude is proportional to the current flowing through the active turns in each slot. This fact is used for diagnosing shorted turns (see Fig. 13).
The sensitivity for detecting shorted turns in the coils depends on the load point. This makes it necessary to use a highly sensitive data acquisition system. To detect even the smallest changes in magnitude, the Siemens system uses a sampling frequency of 100 kHz and a resolution of 24 bit. This high resolution eliminates the need to approach different load points between no-load and full-load (flux density zero crossing). Pole-to-pole comparison of the heights of the flux probe waveform peaks makes it possible to detect the decrease in the number of active turns in the affected pole.

Fig. 13: Magnetic flux distribution around a two-pole generator

Trending the data emanating from a short makes it possible to detect potential growth of rotor winding defects at an early stage and facilitates planning of the next maintenance outage to minimize loss of revenue.

Fig. 14: Screenshot of SIEMON\textsubscript{plus} ISC monitoring software
6.3 Examples of ISC

Typical reasons for rotor interturn short circuits are, for example, end-turn distortions or copper chloride contamination. End-turn distortions are usually the result of aging due to relative movement of the rotor turns. The ensuing misalignment of the insulation layers causes breakdown of the turn-to-turn insulation. Copper chloride contamination can lead to conductive bridges between the turns (Fig. 15).

**Fig. 15: Typical ISC examples**

7 Conclusion

Successful diagnosis of the generator condition depends on the availability of information reflecting the health state of the generator. Knowing that health state can help to reduce maintenance cost and the risk of unexpected shutdowns. Monitoring can help to optimize outages by enabling early recommendations based on the condition of the generator. This minimizes outage times, because all necessary repair measures can be planned in advance and all spare parts are available when needed.

Another goal of generator monitoring is to extend the intervals between maintenance outages based on empirical analysis of operating conditions, machine characteristics, maintenance history and online diagnostics. Last but not least, the lifetime of generator components such as stator or rotor windings, bushings or circuit rings can be extended by facilitating the maintenance and overhaul of these components.

With SIEMON\textsubscript{plus}, Siemens offers operators a modular online monitoring system which enables integral monitoring of partial discharge, stator end winding vibration and rotor interturn short circuits during generator power operation. SIEMON\textsubscript{plus} systems can be retrofitted for all generator models.
8 References


9 Disclaimer

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