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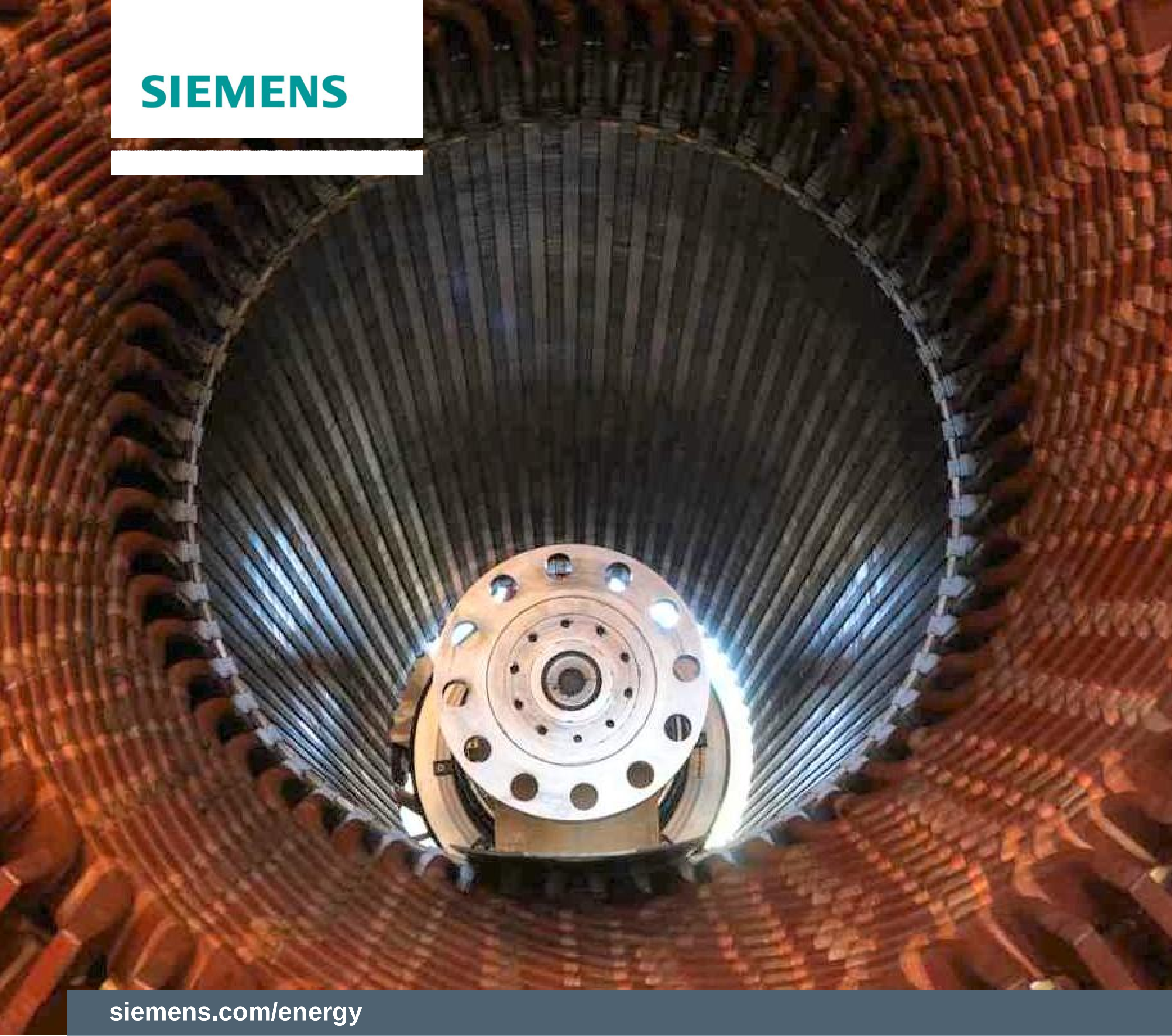

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Online Monitoring - Early detection and diagnosis of initiating damages in turbo generators

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Answers for energy.

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1 Introduction

The influence of renewable energy – especially wind energy – is increasing. This trend results in an increased requirement of medium and peak load operation of fossil power for the stabilization of the electrical grid. Especially for large fossil power plants this medium and peak load operation results in an increased thermo-mechanical stress for the core components like the generator due to the increasing number of load cycles. This typically results in an accelerated aging of the machines and the risk for damages and unexpected failures. As a preventive measure inspections in more frequent intervals offer insight into the condition of the generator, but they cost expensive outage time of the power plant. To minimize loss of revenue, it is helpful to use online condition monitoring and diagnosis systems to receive information about the state of the machine during operation. This will lead to condition based maintenance with extended operating periods in between stand stills.

a) Online monitoring of partial discharges enables the user to detect an abnormal condition in the electrical insulation system of the generator.
b) Online monitoring of stator end winding vibrations yields information about the actual vibrations 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 the above mentioned online monitoring systems in correlation with the operational parameters enables a powerful generator diagnostic.

2 Generator Monitoring Overview

Generators are in service in power plants for many years. Operation and ageing can gradually cause damage to its high-voltage insulation. If early detection of changes in the components is possible through 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 for different parameters are available, but at Siemens the focus is on the monitoring of partial discharges (PD), end winding vibrationss (EWV) and interturn short circuit (ISC). Other systems for shaft voltage/current and fiber optic stator and rotor temperature monitoring are available or in development but not mentioned here.

The typical Siemens generator monitoring concept of the main monitoring systems mentioned above is illustrated in **Figure 1**.

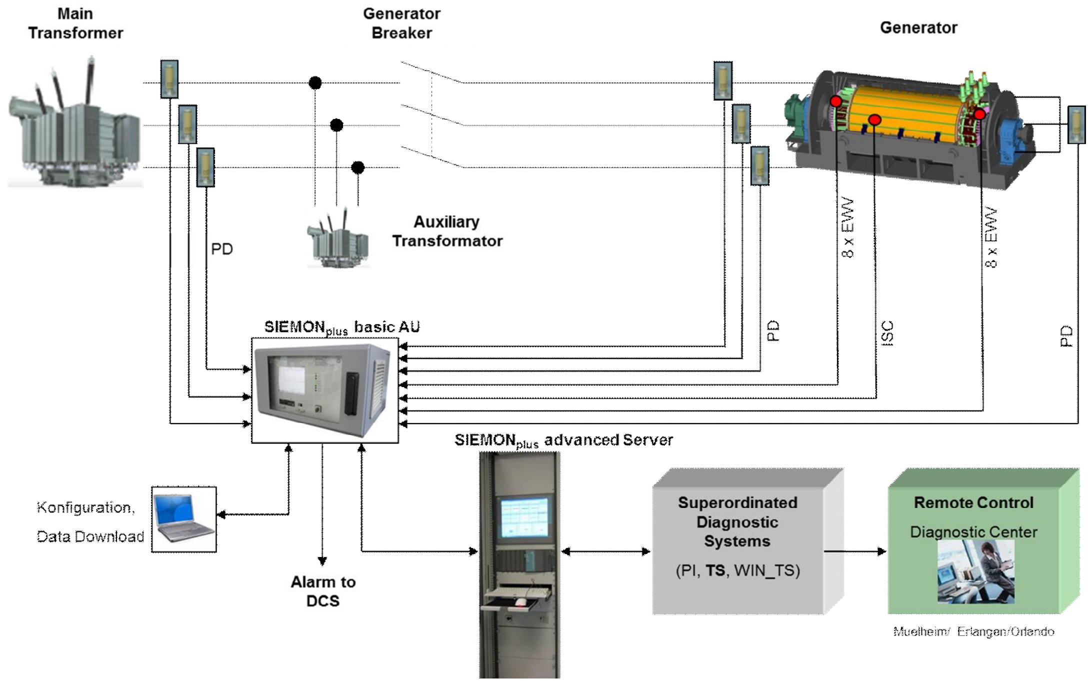


Figure 1: *Overview of SIEMON$_{plus}$ monitoring system*

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 of 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 extending the system by a central server, up to 20 generators can be monitored and the data can be stored, visualized and compared to each other. The server can be easily connected to any I&C systems like plant information (PI) system and T3000 system or to a superordinated Siemens system like the WIN_TS system. Once connected to one of these systems the data can be automatically transferred to one of the Siemens Power Diagnostic Centers, where the data is observed permanently by high sophisticated rule based analyses which includes the automatic comparison of the measured data with all relevant and existing generator parameters. In case of any deviations from the normal behavior the Siemens experts are informed to perform a detailed evaluation of the data and to provide recommendations for the customer.

3 Partial Discharge (PD) Monitoring

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

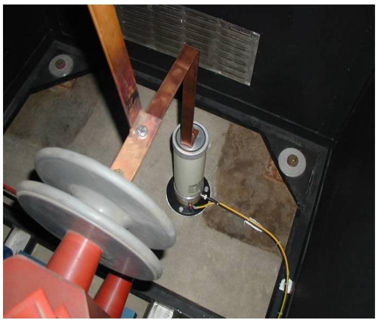
The distribution of the discharges with respect to the phase angle of the generator voltage is characteristic for the cause of discharges and allows for conclusions to the grade of risk for the further operating of the high voltage equipment.

The PD measuring system can be normalized according to IEC/TS 60034-27-2. By transformation of the measured voltage signals to charge units, being a measure for the transferred electrical energy, an estimation of the risk is possible. Although the generator, as the most expensive electrical component, is generally the main target of supervision, the complete high voltage area including the main and auxiliary transformers is being monitored by registration of PD signals.

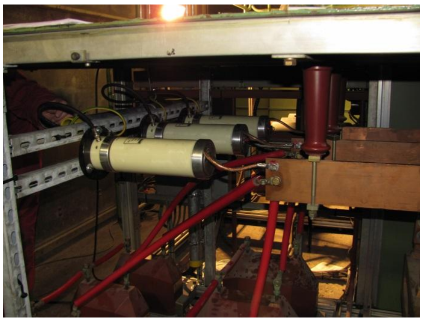
3.1 PD Sensors – Coupling Capacitors (CC)

For the detection of PDs, special coupling capacitors have to be installed in existing voltage transformer cabinets (**Figure 2a**), generator terminal boxes (**Figure 2b**), inside the isolated phase bus (IPB) (**Figure 2c**), inside generator neutral cabinets (**Figure 2d**) or at other suited places in the high voltage area of the power plant [5].

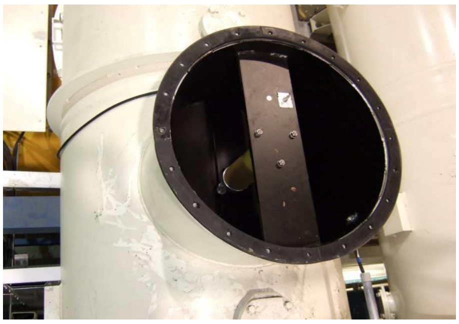
The coupling capacitors are used to pick up the PD signals from the high voltage line. The capacitors usually have a capacity in the range of 1nC to 9nC. Coupling capacitors with lower capacities are not used due to a decreased sensitivity which not fulfills the Siemens requirements. Usually the capacitors are equipped with an integrated over voltage protection and have an insulated signal output to avoid any eddy currents along the cable shields. Possible locations for the installation are shown in **Figure 2**:



a) CC inside voltage transformer cabinet



b) CC inside generator terminal box



c) CC inside IPB

d) CC inside generator neutral cabinet

***Figure 2**: Location of different measuring points within HV area of large power plants*

3.2 PD Analysis Tools

Phase Resolved Partial Discharge (PRPD) Pattern

The most known and powerful tool is the analysis of the PRPD patterns (**Figure 3**).

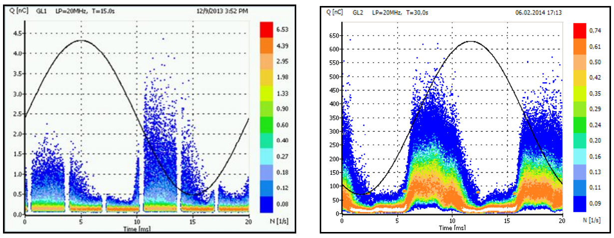


***Figure 3**: Examples of PRPD Patterns*

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. A classification and interpretation of these patterns can be done by using the international pattern catalog (IEC/TS 60034-27-2).

Trending over the lifetime

Usually the monitoring of a generator starts with the fingerprint measurement, which is the first measurement after the monitoring system was commissioned and the generator at base load. The fingerprint measurement is used as a reference for any future analyses. The measurement further serves to identify narrow-band interference and to eliminate these with digital interference suppression in order to improve the measurement sensitivity.

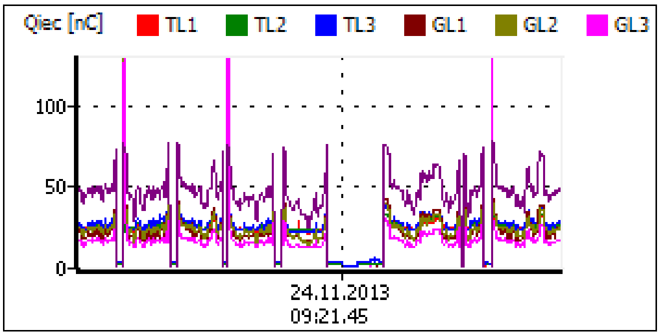


***Figure 4**: Example of PD trends*

Once the fingerprint measurement is done, the trending (**Figure 4**) of the following common PD parameters starts:

- Q_{IEC} [nC] Apparent charge according IEC60270
- Q_{max} [nC] Maximum Charge
- N [1/s] PD rate
- QR [nC²/s] Quadratic charge rate

According to IEC 60027-2 [2], the above mentioned common PD parameters should be correlated with the following generator parameters:

- 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 for localization it becomes important to evaluate high resolved oscillograms (**Figure 5**) taken with a sampling frequency of up 125MS/s 4 channels simultaneously over one AC cycle of the high voltage (50Hz → 20ms).

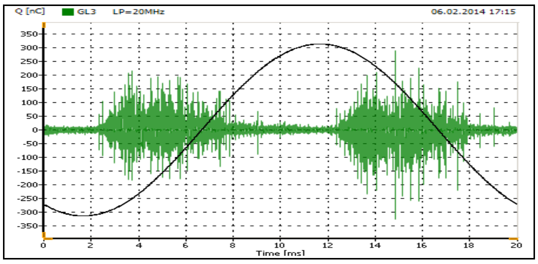


***Figure 5**: Example of an oscillogram*

Furthermore the oscillogramms can be used to determine the slew rates of the PD impulses to get information about the source or the 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 of the PD monitoring systems on the market provide the possibility of performing ToF measurements for fault localization (**Figure 6**).

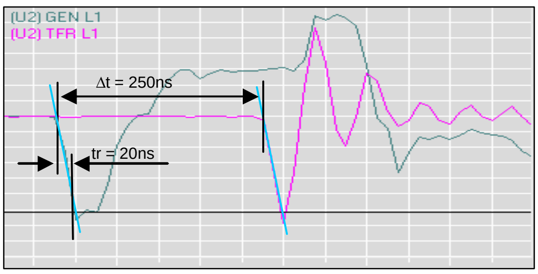


***Figure 6**: Example of a ToF measurement*

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 the comparison for both test points give some knowledge about the discharge source.
The difference of the propagation times of the measured pulses can be determined and the possible region of the corresponding PD activity can be restricted. By this way in first order the travel direction of the pulses can be directly calculated.
If there are well defined signal propagation paths between two test points (e.g. along the IPB), the analysis of the travel time allows the calculation of the distance of the PC source with respect to both test points. For time differences below the calibrated travel time between both test points, the place of the PD source is located between both test points and can be determined with an accuracy depending on the steepness of the pulses and the geometry of the propagation paths.

Suppression of Interferences

In general PD measured in power plants is superimposed by a lot of noise signals, which have to be eliminated prior to any further processing. Those signals can be principally divided in 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 high 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 for operation of generators with static excitation system with slip rings (**Figure 7**).

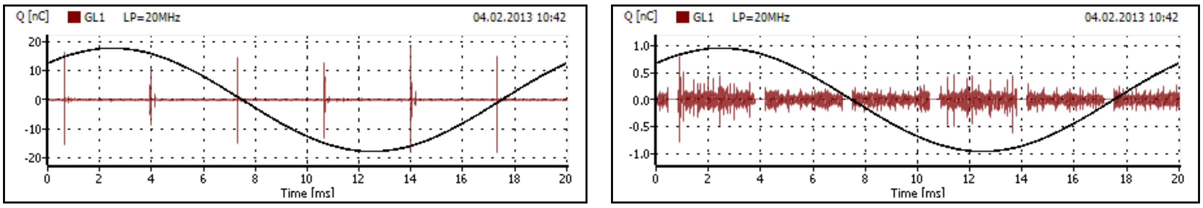


***Figure 7**: Example of an unfiltered (on the left) and filtered signal (on the right)*

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

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

3.3 PD Example – Slot Discharges

Slot discharges typically appear between the outer corona protection (OCP) and the stator core. The typical appearance of slot discharges is an unsymmetrical distribution of the discharges covering the amplitude and number within the two halve waves, which can be clearly seen in the PRPD pattern presented in **Figure 8**.

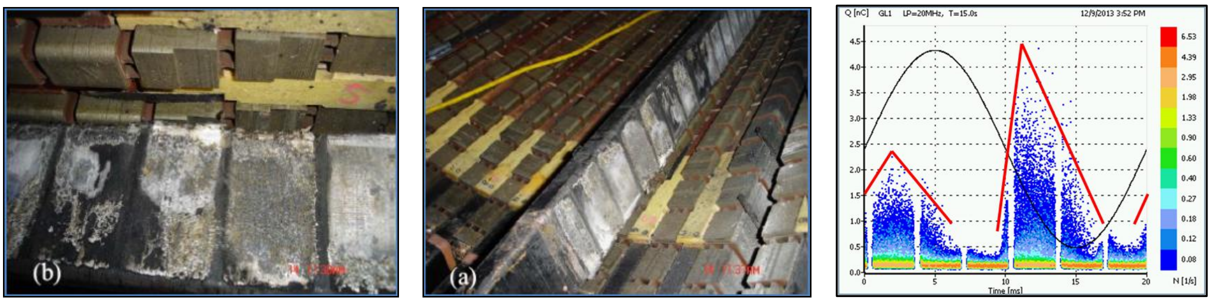


***Figure 8**: Example of PD - slot discharges*

In the negative halve wave higher PDs appear. In both halve 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].

4 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 generator are excited particularly by

1) the core which vibrates at twice the line frequency and

2) current forces and
3) 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 be damaged by such events, it cannot 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 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 that the generator has to be completely re-wound.

End-winding vibration monitoring thus is a useful tool for evaluating the condition of generator end windings and also minimizes the risk of a re-wind.

4.1 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 **Figure 9**) considering 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 even eight, sensors per end winding should be used to allow a reliable data analysis.

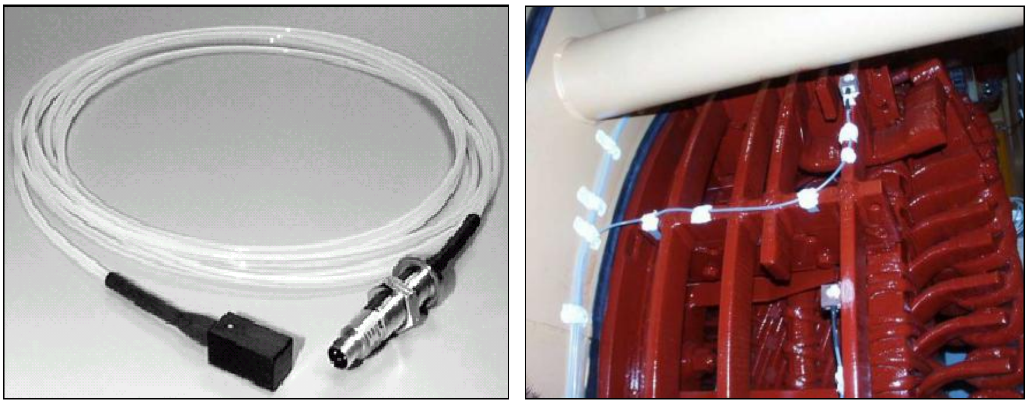


Figure 9: *Application of fiber optic accelerometers inside a stator end winding basket. The fiber optic accelerometers are non-metallic and do not interfere with the electromagnetic field in the end winding area.*

4.2 EWV Analysis Tools

Real time signals are usually used to check the general functionality of the sensors. The signals of the up to 16 fiber optic sensors are acquired with a sampling frequency of 9kS/s simultaneously to enable the possibility to perform online modal analyses.

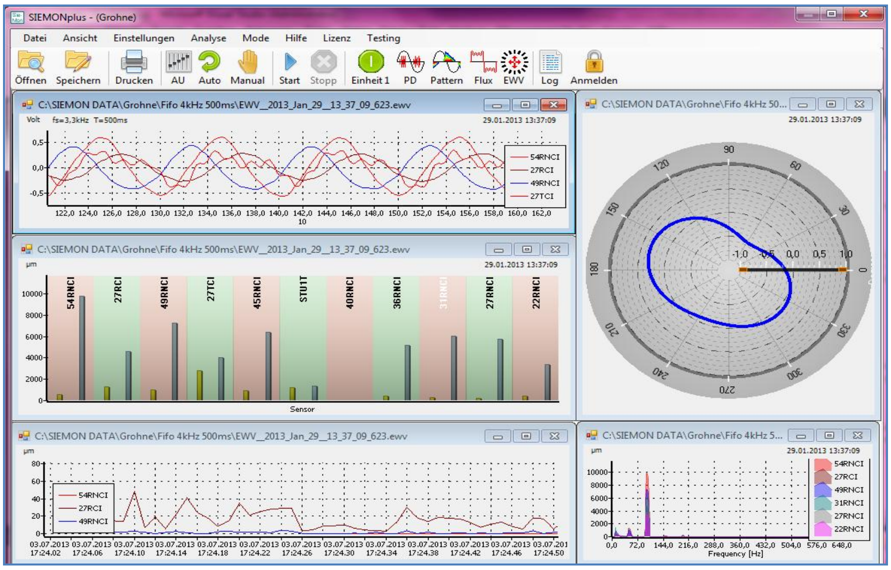


***Figure 10**: Screenshot of SIEMON$_{plus}$ EWV monitoring software*

By using a fast fourier transformation (FFT), the time domain signals are transformed into the frequency domain. Here usually the first and second harmonics of the line voltage are observed and the respective amplitudes, which usually represent the vibration level in [µm], are trended for every sensor signal separately. The trend of the vibration values can be displayed and correlated to operational parameters, for example, active power, reactive power and exciter current, which may have a direct influence to 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 the online evaluation and visualization of the standstill and rotating vibration modes separately. The respective changes of these vibration modes during operation are trended, to be able to detect possible changes of the structure mechanic behavior of the generator end winding. For such kind of diagnostics a detailed knowledge of the generator design is necessary to define potential measures.

4.3 EWV Examples

***Figure 11**: Typical examples of EWV*

In most cases end winding vibrations are indicated by friction dust caused by relative movements of different end winding components (bandings, blocking elements, etc.). The permanent mechanical stresses to single bars can lead to fatigue cracks of single strands. In case of cracked single bars, the produced heat, caused by the cyclic interrupted current, leads to a perforation and discoloration of the bar insulation.

5 Rotor Interturn Short Circuit (ISC) Detection

A major portion of rotor faults are related to some kind of winding faults, such as earth faults, shorted windings, or cracked conductors [1]. Some of the winding faults do not directly lead to a trip of the generator, but may lead to increased shaft vibrations, excessive wear or simply reduced efficiency. Therefore a rotor winding monitor is a useful tool for fault analysis [8].

Different mechanisms can be responsible for shorted rotor turns. Most shorted turns are caused by some kind of relative movement in the rotor turns. This relative movement may lead to misalignment of the insulation layer between individual turns, failure of turn-to-turn insulation, or loosening of blocking elements in the end winding region. Relative movement of rotor winding parts is unavoidable due to the fact that the copper of the windings has a thermal expansion coefficient different from that of the insulation materials and the rotor body. During each start-up and shut-down the copper windings move relative to the rotor slots and the insulating parts. An experienced and reliable rotor winding design takes care of this thermo-mechanical mechanism. Otherwise relative movement leads to increased wear of the insulating materials and ultimately to interturn short circuits. Sometimes even plastic deformation can occur leading to end turn elongation, which in turn may cause the loosening of blocking materials in the end winding region and ultimately to shorted turns.

The effects of such shorted turns depend on the number of shorted turns as well as their location. In the first place, shorted turns require a higher field current than previously to run at a specific load, thereby decreasing the efficiency. Higher field currents result in higher overall field operating temperatures. In the case of a two-pole rotor, shorted turns in one pole lead to increased temperatures on that side of the rotor only. This leads to thermal unbalance in the rotor and increased vibrations due to thermal bowing. Four-pole rotors may suffer from magnetic unbalance in case of shorted turns in one pole. Interturn short circuits or earth faults in the end winding region may produce arcing underneath the retaining ring, leading to retaining ring damage.

5.1 ISC Sensors – Flux Probes

For the detection of shorted turns, a sensor which measures the magnetic flux has to be installed in the air gap between the rotor and the stator. The sensor is typically installed in 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 **Figure 12**).

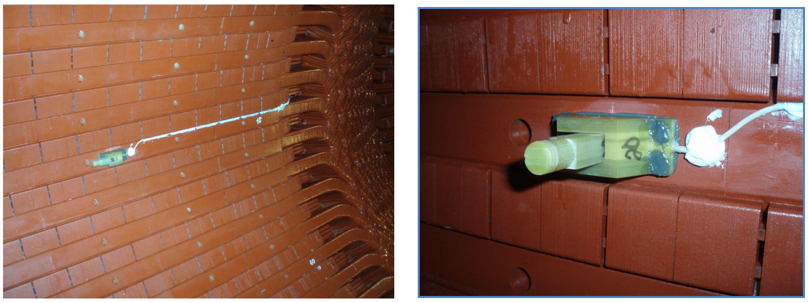


Figure 12*: Installation of air gap sensor at stator winding slot wedge*

The monitoring system analyses the magnetic flux continuously during the unit's operation by detecting changes in the rotor slot leakage flux signal provided by the sensor. It will detect most of the shorted turns which can occur at a generator rotor and issue an alarm if a shorted turn was detected. Also an identification of the affected slot of the rotor is possible.

5.2 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 the diagnostic of shorted turns (see **Figure 13**).

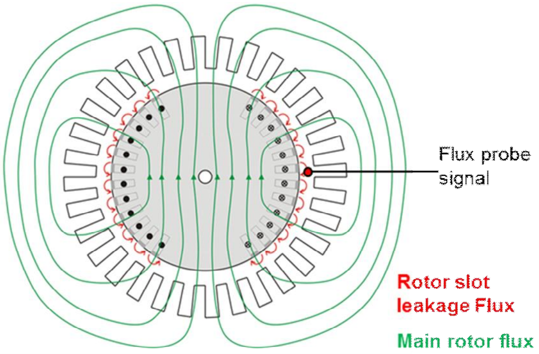


***Figure 13**: Magnetic flux distribution around a two-pole generator*

The sensitivity to detect shorted turns in the coils depends on the load point. Therefore it is necessary to use a very sensitive data acquisition system. To detect even smallest changes in magnitude the Siemens system uses a sampling frequency of 100kHz and a resolution of 24 bit. By using such a high resolution it is not necessary anymore to approach different load points between no-load and full-load (flux density zero crossing). By performing a pole-to-pole comparison of the heights of the flux probe waveform peaks, the decrease in the number of active turns in the affected pole can be detected.

***Figure 14**: Screenshot of SIEMON$_{plus}$ ISC monitoring software*

By trending the data in case of an existing short, possible growing of rotor winding defects can be detected in an early stage and the planning of the next maintenance outage can be supported to minimize loss of revenue.

5.3 ISC Examples

Typical reasons for rotor interturn short circuits are for example end-turn distortions or copper chloride contamination. End-turn distortions appear usually due to aging by relative movements of the rotor turns. The resulting misalignment of the insulation layers causes failures of the turn-to-turn insulation. Copper chloride contamination can lead to conductive bridges between the turns (**Figure 14**).

***Figure 14**: Typical ISC examples*

6 Conclusion

A successful diagnostic of the generator condition is dependent on the information which is available. The more monitoring modules and operational parameters are available the more successful is the diagnostic. As stated before one of the most important benefits of the monitoring of the generator condition is the reduction of maintenance costs and unexpected shut downs. Monitoring can help to optimize outages by early recommendations based on the condition of the generator. This leads to minimized outage times due to the fact that all necessary repair measures are planned in advance and all spare parts are available just in time. Another goal of the generator monitoring is the extension of periods between maintenance outages based on experienced analysis of operational conditions, machine characteristics, maintenance history and online diagnostics. Last but not least a life time extension of generator components, such as stator or rotor windings, bushings or circuit rings can be achieved by assisting the maintenance and overhaul of these components.

7 Forecast

Currently the main focus of Siemens is to establish a modular generator diagnostic platform by integrating other monitoring modules to the existing $\text{SIEMON}_{\text{plus}}$ system such as the permanent fiber optic temperature and strain monitoring. Enabling this possibility, local hot spots can be detected in an early stage during operation independent of any magnetic fields or high voltages. Possible applications are:

- Temperatures at cooling gas exit (direct hydrogen cooled generators)
- Local hot spots at teeth of the core or cooling slots
- Hot spots at front end connections, main leads or generator bushings

The permanent monitoring of these temperatures enables the possibility of trending the temperature behavior in correlation to the operational parameters such as the generator load. Critical overheating, which can leads to damages and unexpected outages can be avoided by changing the load operation.

Further modules like the shaft voltage/current monitoring, which enables the possibility to detect poor insulation of generator bearings and failures of grounding brushes are currently under development and will be available next FY as additional modules for the generator monitoring and diagnostic platform $SIEMON_{plus}$.

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