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Equipment for Monitoring Synchronous Generators Condition through External Magnetic Field Waveforms

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***Abstract*— This paper presents an equipment for monitoring synchronous generators condition through characteristics of the time derivative of the external magnetic field. The developed monitoring methodology allows the identification of established or incipient faults, by detecting changes in the magnetic signature of the synchronous generator. In this methodology, the measurement of signals outside the machine gives this equipment a non-invasive characteristic, allowing its monitoring without interfering or disturbing its operation. The developed system includes the specification of magnetic field sensors, signal measurement and processing equipment, as well as software for analysis and monitoring. The validation of the methodology used in this system was carried out through the analysis of experimental data, presenting efficient results in the detection of electrical and mechanical faults in synchronous generators of an experimental test bench and a hydroelectric power plant. As a result, the commercial specification of this equipment was obtained and two units were implemented in a hydroelectric power plant to monitor 305 MVA synchronous generators.**

***Index Terms*—** external magnetic field, fault detection, machine condition monitoring, synchronous generator.

I. INTRODUCTION

Condition Monitoring of synchronous generators (SGs) is a predictive maintenance strategy of great interest among electric power generation companies, as it allows the optimized scheduling of maintenance outages, leading to technical, financial and operational advantages. SGs, mainly used in hydroelectric and thermoelectric power plants, can operate for decades, and monitoring their condition over time increases the reliability and availability of the generation plant. The condition diagnosis of SGs can be performed mainly by monitoring electrical, magnetic and mechanical variables [1], [2].

Magnetic field monitoring is an efficient strategy for condition monitoring of SGs, since this

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quantity reflects the constructive and operating characteristics of the machine [3]–[6]. It can be performed inside the machine by measuring the field in the air gap region, or outside the generator by measuring the leakage magnetic field around the machine. Internal magnetic field monitoring is an efficient strategy for fault detection, but it has an invasive characteristic, since it is necessary to stop the generating unit for the installation or maintenance of the sensors in the air gap region [7]–[9].

The external magnetic field monitoring in SGs is still an uncommon strategy in the industrial context, although its application is being explored in several theoretical and experimental studies [10]. This monitoring class is indicated as a trend in the faults diagnosis in electrical machines [11], mainly because it allows the development of non-invasive systems, that is, the sensors can be installed outside the machine without interrupting or disturbing its operation. This fault detection strategy is found mainly in applications involving induction motors [6], [12]–[15], although recent studies show that this application is also being investigated for synchronous machines [5], [16]–[18].

The investigation of the external magnetic field characteristics for fault detection purposes in synchronous machines started from the observation of changes in the frequency spectrum of the external magnetic field when faults occur [16]. In later work, the investigation of the frequency spectrum of electrical and magnetic quantities have shown the presence of a spectral component corresponding to the mechanical rotation frequency of the synchronous machine and its harmonics, whose amplitude was sensitized when faults occurred [19], [20]. This research topic was outlined and complemented by theoretical and experimental studies that proved the existence of these spectral components from analytical models of the air gap magnetic induction, which showed the presence of these components due to the small asymmetries between the poles in real machines [18], [21]. The evaluation of the frequency spectrum of external magnetic field measurements on SGs for fault detection has been reported in several theoretical and experimental investigations in recent years [22]–[25], although no standard or commercial equipment for this end have been established.

The methodology used for fault detection in the equipment proposed in this paper is based on the frequency spectrum monitoring of external magnetic field time derivative obtained through the electromotive force induced in induction coil sensors. Through the frequency analysis of these signals, the harmonic components amplitudes of the mechanical rotation frequency of the SG are monitored, which reflect constructive and operational characteristics and allow the monitoring of the machine condition. This monitoring system methodology is innovative and has generated a patent, filed in 2015 and granted in 2020 [17].

One of the main positive aspects of the proposed system is its ability to detect incipient or established faults of electrical nature, in the stator or rotor, or mechanical nature in synchronous machines. Furthermore, due to its non-invasive nature, the system does not interfere with the structure or operation of the SG, simplifying the installation and maintenance of the equipment that, technically, can be performed with the SG in operation.

Currently, in terms of condition monitoring of synchronous machines through magnetic field characteristics, only the magnetic flux in the air gap is monitored by commercial equipment, such as the *FluxTracII-S* and *GuardII+* from Iris Power company [26]. This class of equipment has proven to be effective in detecting faults in synchronous machines, with the disadvantage of being invasive systems, due to the need to install sensors in the air gap. Its installation involves stopping the SG operation and, eventually, disassembling the stator and rotor structures in order to place the sensors. In this scenario, the equipment proposed in this paper presents itself as a non-invasive and easy-to-install alternative, which also monitors the SG condition through the characteristics of magnetic quantities.

This paper presents the development, specification and application of a pioneer equipment called MagAnalyzer that monitors the condition of SGs based on measured waveforms related to the time derivative of the external magnetic field. Validation tests of the methodology employed for fault detection are also addressed, with positive results in an experimental test bench and in a SG of a hydroelectric power plant where an initial prototype is installed. The development of the presented equipment results from a cooperation between the Federal University of Santa Catarina, responsible for the theoretical and experimental validation of the monitoring technique employed as well as the initial hardware and software specification, the AQTech Engenharia e Instrumentação company, responsible for the final hardware and software specification of the equipment for a commercial version, and the ENGIE Brasil Energia and Itá Energética companies, which collaborated with the specification and installation strategies.

II. Operating Principle

A. Basic system architecture

The operating principle of this equipment is based on monitoring signals proportional to the time derivative of the external magnetic field around the SG. Based on the frequency spectra of these signals, periodic storage of the amplitudes of the multiple components of the mechanical rotational frequency allows its magnetic signature monitoring. The mechanical rotational frequency (f_m) is defined by the ratio between the electrical operating frequency and the number of pole pairs of the SG. The magnetic signature is associated with structural and operational characteristics of the SG, so that its monitoring throughout the operation of the SG allows the detection of incipient faults, as well changes in the machine operation.

The basic architecture of the monitoring system is shown in Fig. 1. Induction coil sensors are used to measure the external magnetic field in a non-invasive way. These signals allow monitoring of the SG magnetic signature history. With this, anomaly detection methods can be employed to detect changes in the magnetic signature that are related to a fault. In this way, this monitoring system can generate fault alerts and diagnoses, allowing maintenance teams to assess events and act before an incipient fault evolves into a failure or unscheduled outage.

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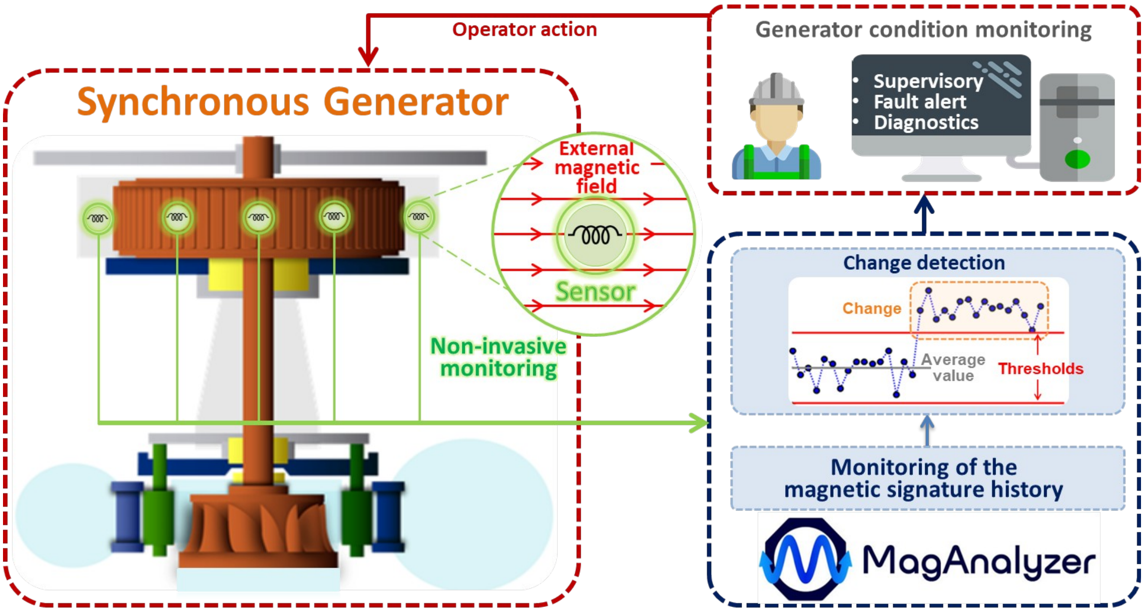

Fig. 1. Generic architecture of MagAnalyzer monitoring system.

The use of several sensors around the SG, as shown in Fig. 1 for a SG with vertical axis in a hydroelectric power plant, allows monitoring the magnetic signature in different regions of the machine, assisting in fault location.

B. Measurement of the external magnetic field

The magnetic signature reflects physical and constructive characteristics of each machine, in addition to being associated with its operating condition [18]. These characteristics influence the machine internal magnetic field, of which the external field is a reflection. To extract these characteristics, the strategy established in this methodology is the measurement of the electromotive force at the terminals of an induction coil sensor, induced by the stray magnetic field outside the machine. The sensors are positioned so that they preferentially concatenate the tangential component of the stray magnetic field, avoiding end winding regions. This component is conserved in the magnetic field transition between the metallic structure of the SG and the air [27]. It presents the order of magnitude of the field values inside the stator core when the sensor is next to the stator frame. Fig. 2 shows the general architecture of the electromotive force $v(t)$ measurement, where μ_0 is the air magnetic permeability, N is the number of coil turns, S is the sensor cross section, and H_{tan} and H_{nor} are the tangential and normal components, respectively, of the stray magnetic field $\boldsymbol{H}$.

When the sensor is not close to the stator frame, the intensity of the leakage field tends to be very low, inducing voltages in the order of millivolts or even microvolts in the induction field sensors, mainly due to the attenuation of the high frequency components by the stator frame. This fact leads to the need for analog conditioning steps, composed of amplification and filtering stages, to ensure a good signal-to-noise ratio and increase the signal amplitude for the analog-to-digital conversion step [18]. From the digitized signal, the external magnetic field time derivative can be obtained, as indicated in Fig. 2, which is the signal monitored by the system proposed here.

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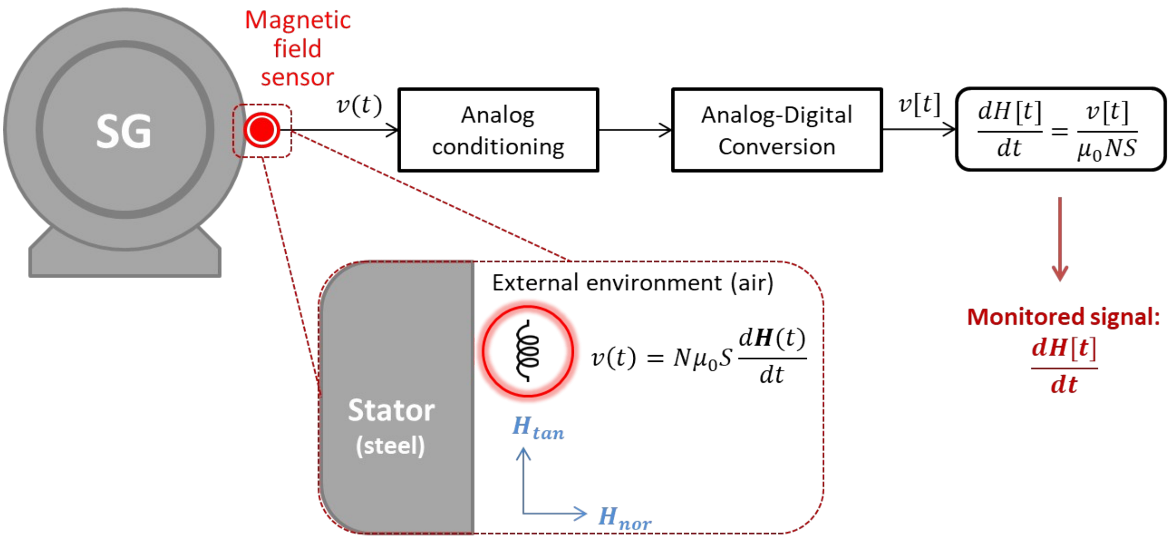

Fig. 2. General architecture for measuring the external magnetic field time derivative.

The magnetic field time derivative is used to monitor the SG magnetic signature because it naturally amplifies the high frequency components of the signal, which are useful in the process of monitoring and detecting faults in the machine. This specification was motivated by theoretical and experimental findings that indicate the possibility of finding features of interest in high frequency regions of the spectrum (>100 Hz).

The magnetic induction in the air gap *B(t)* can be modelled through analytical functions [5], [18], [28]. A simplified model for *B(t)* is given by (1), where *mmf(t)* is the function representing the magnetomotive force from the rotor and *P(t)* is the function characterizing the magnetic permeance along the air gap. The function *P(t)* is composed of a constant part associated with the average length of the air gap and a variable part depending on the number of slots in the machine.

$$B(t) = mmf(t)P(t) \quad (1)$$

The product of these two functions in the time domain is the equivalent to a convolution in the frequency domain and describes an amplitude modulation, where the waveform of the function *P(t)* is the carrier signal and the waveform of the function *mmf(t)* is the modulating signal. Some features of the spectrum at low frequency can be translated along the spectrum. For fault detection purposes, there have been reports of changes in harmonic components of the mechanical rotation frequency up to frequencies above 2 kHz in experimental tests with imposition of faults in SG, mainly in the evaluation of stator faults. Therefore, it is recommended to monitor the harmonic components of the mechanical frequency rotation of the machine up to approximately 4 kHz, in order to enable the detection of different types of faults. In this scenario, monitoring the external magnetic field time derivative has the advantage of amplifying the high-frequency components of the monitored signal, which favors the identification of the harmonic components of the machine rotation frequency at high frequency.

C. Magnetic signature extraction

From the *dH/dt* digitized signal, data processing steps are employed to perform the signal frequency analysis and update the SG magnetic signature history. This process is presented in a simplified way in Fig. 3.

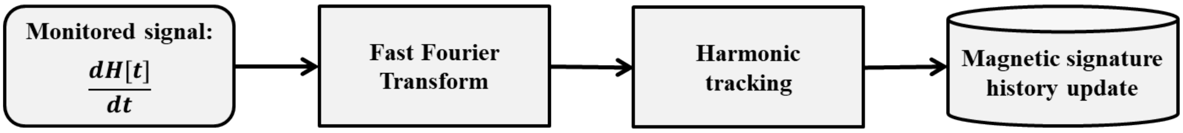

Fig. 3. Data processing for magnetic signature update.

The frequency spectrum can be obtained by applying the Fast Fourier Transform (FFT) on the measured signal. After this procedure, an automatic tracking step of the actual rotational frequency of the machine and its harmonics is applied over the frequency spectrum of the signal, to identify precisely the position of the components of interest in the amplitude spectrum and store their amplitudes. The rotation frequency harmonics can be identified based on (2), where f_e is the electrical operating frequency of the SG, p is the number of pole pairs, k is the order of the harmonic, and f_h is the frequency associated with the identified k-order harmonic [19]. For $k=1$, f_h equals f_m.

$$f_h = k\frac{f_e}{p} \tag{2}$$

After tracking the harmonics of interest, their amplitudes are stored in time series that can be evaluated to detect faults or changes in the generator operation. In this way, the so-called SG magnetic signature is manipulated as a set of time series where the amplitude history of each harmonic component of the machine rotation frequency is periodically updated.

This process is evaluated by processing data from experimental tests on an 8-pole SG operating at 60 Hz, which has a f_m of 15 Hz. Fig. 4 shows a few cycles of the digitized signal corresponding to the external magnetic field time derivative and a range of its frequency spectrum, where the presence of f_m and its harmonics is evident. The automatic harmonic tracking process identifies the amplitude of the f_m harmonics and updates the time series containing the amplitude history that characterize the machine magnetic signature. The process shown in Fig. 4 is periodically repeated to update the magnetic signature, allowing online condition monitoring of the SG throughout its operation.

D. Fault detection method

Since the time series that characterize the magnetic signature are sensitive to the SG operating point, the analyses of these series for fault detection purposes should be performed within operating ranges where the SG can be considered operating close to a steady state condition. Under these conditions, the magnetic signature is expected to be stationary, so that significant changes in the time series can be associated with structural changes due to faults.

The analytical technique of 3σ control charts was used to develop a tool to analyze and detect changes in the magnetic signature. A change is detected when the trend or mean value of the monitored variable leaves its normal range defined by upper and lower control thresholds. These limits are calculated based on the mean and standard deviation of the series in a reference region where the time series is stationary [29].

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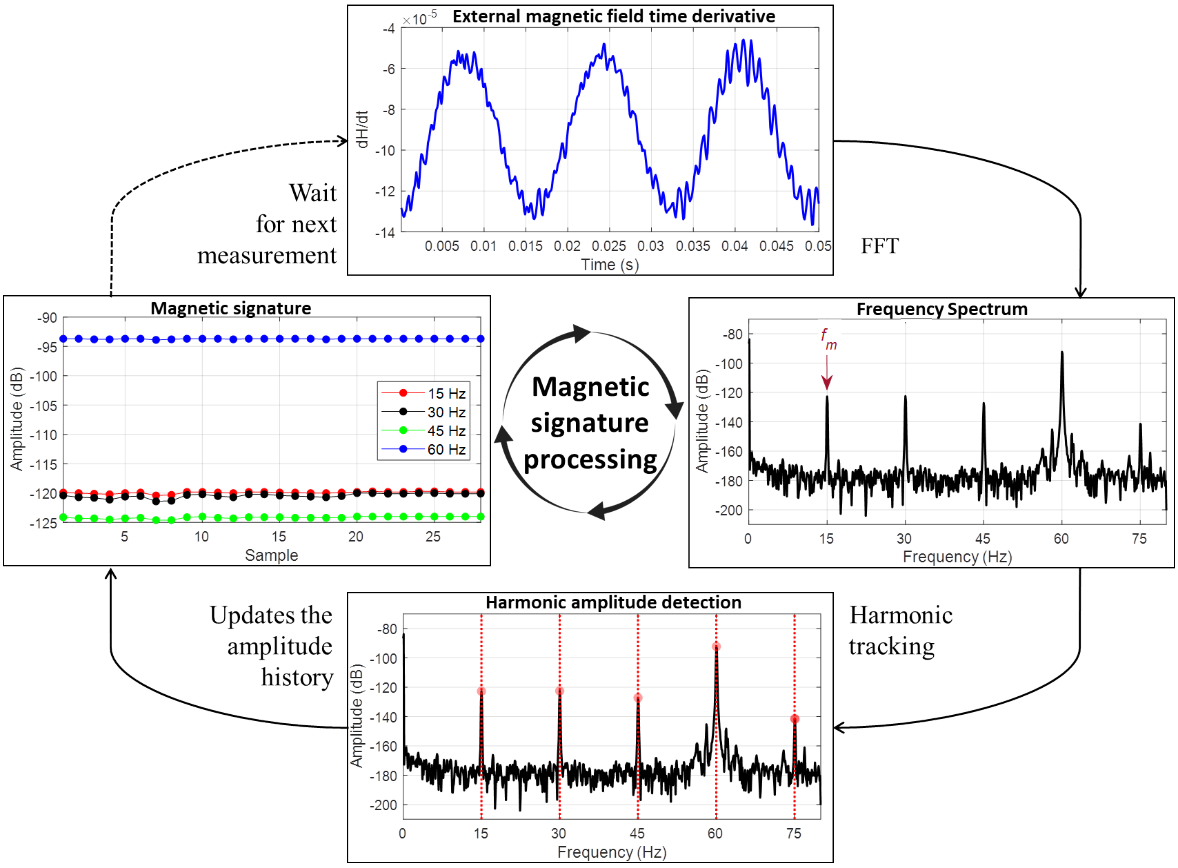

Fig. 4. Magnetic signature processing for a 8-pole synchronous generator operating at 60 Hz.

For a reference region of the time series x composed of n samples, the control thresholds (CT) can be defined by (3), where k is set according to the amplitude of the desired change to be detected. This technique is suitable for detecting changes greater than three standard deviations (3σ) based on the selected reference region.

$$CT = \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right) \pm k\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left[x_i - \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)\right]^2} \tag{3}$$

For application in the MagAnalyzer analysis software, the reference region must be selected where the SG supposedly operates in a healthy condition (without established or incipient faults), which expresses the expected characteristics of the machine external magnetic field. The change in the mean value of the series, or change in its trend, is detected from the persistent violation of one of the control thresholds, indicating a permanent change in the magnetic signature. Fig. 5 shows the application of this technique in the detection of a fault due to the removal of a stator pole turns. In this figure, the time series is the amplitude history of a harmonic of the SG mechanical rotation frequency.

It is noticed that after the fault occurrence, the amplitude history has its average value altered, violating one of the control thresholds and leaving the initially specified normality region. In this way, the fault can be detected and the monitoring software can issue abnormality alerts.

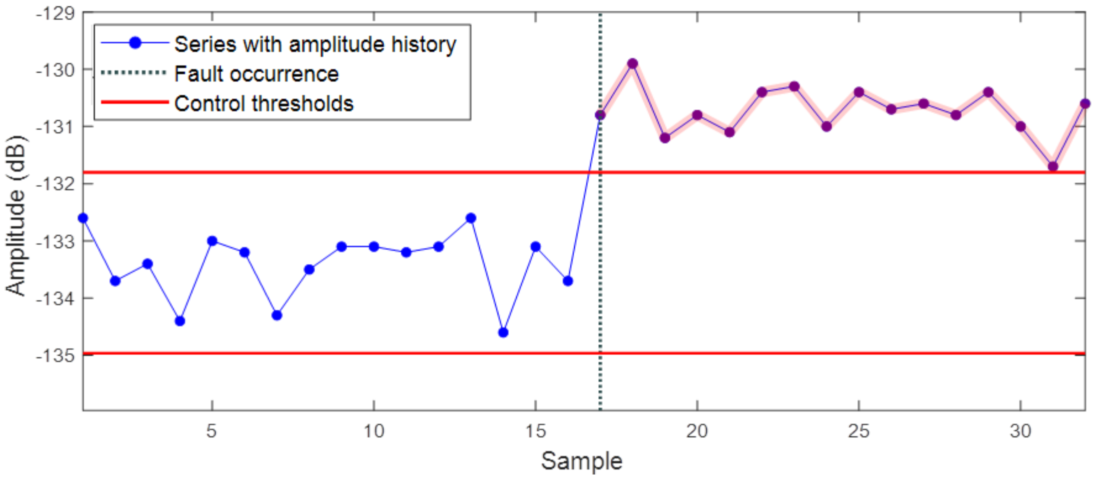

Fig. 5. Application of the control chart method in the detection of magnetic signature changes.

E. Methodology validation tests

The proposed architecture for the magnetic signature monitoring system presents good results in fault detection on SGs implemented on a laboratory test bench [5], [18]. For the development of this equipment, additional evaluations were carried out with experimental tests, evaluating the frequency spectrum up to 4 kHz and investigating different types of faults. Additionally, the analysis of a mechanical fault occurrence in a 305 MVA SG of a hydroelectric power plant, recorded by a prototype of this equipment, corroborated the practical validation of the efficiency of this methodology.

A 10 kVA, 8-pole salient SG, depicted on the right end of the experimental test bench shown in Fig. 6, was used for the evaluation of the influence of fault occurrence on the machine magnetic signature. The primary machine is a DC motor located on the center. The test bench has a control panel that allows the synchronization of the SG with the electrical grid, as well as adjustments of the speed of the primary machine and of the field excitation, enabling manual control of the operating point during synchronized operation.

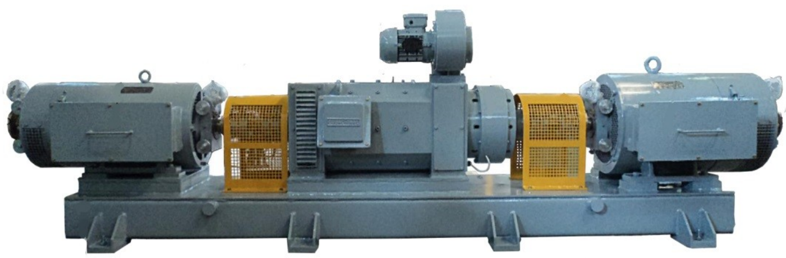

Fig. 6. Experimental test bench with a 10 kVA, 8-pole synchronous generator.

This experimental test bench was customized to allow controlled fault imposition. The tests were performed with the SG synchronized to the electrical grid at 60 Hz (commercial frequency in Brazil), keeping the operating point approximately constant to evaluate only the influence of the imposition of faults on the magnetic signature of this SG. For this test, two types of electrical faults were imposed on the stator (removal of 17% active turns from a stator pole and short-circuit between stator core sheets) and one type of electrical fault imposed on the rotor (removal of 20% active turns from a rotor pole) were evaluated. In addition, a test was evaluated with the imposition of a dynamic unbalance (vibration) fault, which is mechanical in nature.

A prototype developed according to the premises of this methodology was used to perform the measurements and store the magnetic signature [18]. For the 8-pole SG operating at 60 Hz, the frequency f_m is 15 Hz, as already mentioned. The harmonics of this frequency were stored up to the 267th order, comprising the spectrum from 15 to 4005 Hz.

For all four types of faults evaluated, the magnetic signature was altered, as can be noticed from the amplitude change in specific harmonics in each test. Fig. 7 presents some harmonic components sensitized by each type of fault, which demonstrate the change in the machine magnetic signature when each fault occurs.

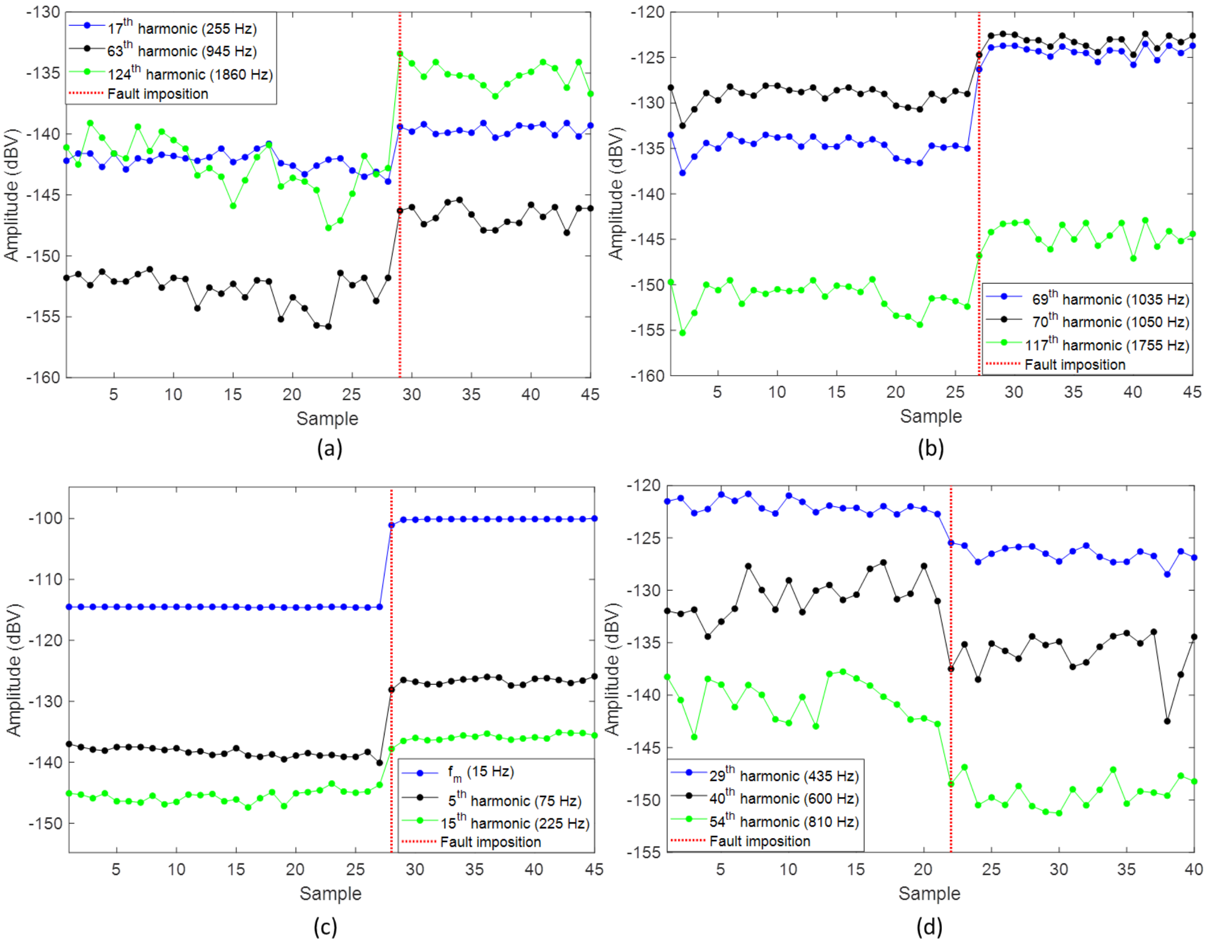

Fig. 7. Tests with controlled fault imposition on the experimental test bench: (a) removal of turns from one pole of the stator, (b) short-circuit between stator core sheets, (c) removal of turns from one pole of the rotor, (d) dynamic unbalance (mechanical vibration).

It is observed that stator faults due to the removal of turns of a stator pole (Fig. 7 (a)) and stator core sheets short circuit (Fig. 7 (b)), sensitized high-order harmonic components at frequencies above 1 kHz. Thus, monitoring the spectrum at high frequency may favor the detection of these types of faults. The removal of turns in a rotor pole caused changes in harmonic components at low frequency, including the mechanical rotation frequency (f_m), as shown in Fig. 7(c). The dynamic unbalance caused changes in harmonic components at frequencies mainly below 1 kHz, as shown in Fig. 7 (d).

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These experimental results demonstrate the efficiency of the proposed system for fault detection, both for electrical/magnetic and mechanical origin.

The behavior of the magnetic signature of a 305 MVA 56-pole SG in a hydroelectric power plant was also evaluated in the event of an incipient fault of mechanical nature. The magnetic signature of this SG was monitored during the period of occurrence of this fault by a prototype of the equipment proposed in this paper. This prototype employs six sensors located around the SG [18]. The evaluated event was the occurrence of a mechanical vibration fault in the generator shaft, also detected by a commercial vibration monitoring system and verified by the power plant maintenance team in a predictive maintenance stop [30]. The external magnetic field monitored during the evolution of this fault shows the change in the magnetic signature by changing the amplitude pattern of some harmonic components of the mechanical rotation frequency (approximately 2.14 Hz for the 56-pole SG operating at 60 Hz). Fig. 8 shows the history of amplitudes of the 141st harmonic of f_m for six sensors, where the evolution of the fault can be observed clearly.

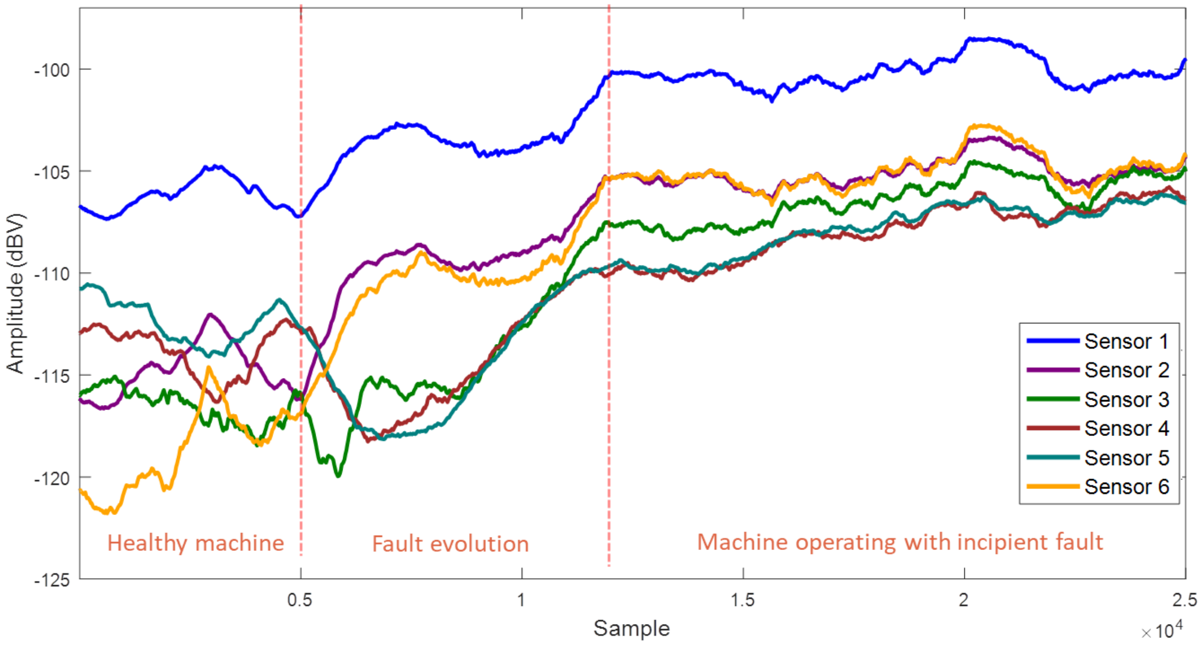

Fig. 8. Amplitude history of the 141st harmonic of the mechanical rotation frequency during the fault evolution.

This pattern alteration, also observed in other harmonic components of f_m, allowed the fault detection in a non-invasive way through the external magnetic field, corroborating the validation of this monitoring methodology and contributing to the development of the equipment presented in this paper.

Currently, the fault analysis and detection method used in the proposed equipment allows the distinction between stator and rotor faults and indicates the probable type of fault. Guidelines for fault typification and results will be presented in other papers because of the extent and complexity of these topics.

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III. System Architecture

A. Main elements and topology

The developed system was specified with three main parts: the Processing Unit (PU), the Monitoring Units (MU) and the server/monitoring software. The system architecture is shown in Fig. 9. The MUs, strategically positioned around the SG to capture the external magnetic field, are connected to the PU in a star topology, through a PoE (Power over Ethernet) switch. This switch enables to carry both data and power over the same Ethernet cable in an isolated manner. The data stored in the PU are transferred to a server, where the SG magnetic signature history is processed and stored. The monitoring software runs in the server and allows the visualization and analysis of results through the use of an interactive interface and statistical tools.

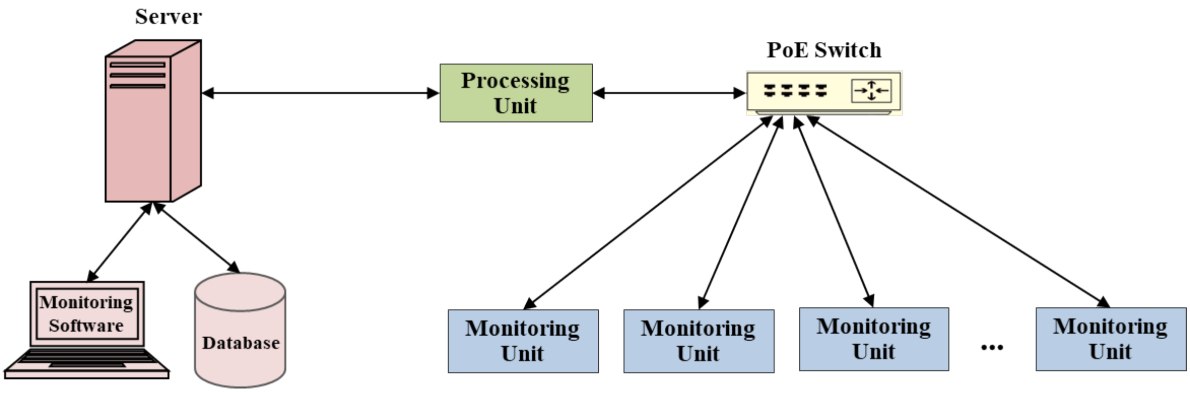


Fig. 9. MagAnalyzer system architecture.

The system, in its commercial specification, is composed of a PU that can hold up to eight MUs. Regarding sensing strategies, in addition to induction magnetic field sensors, a Rogowski coil can be used to monitor the signal of the SG neutral current derivative, also used in fault detection. The signal measured by the Rogowski coil is conditioned and digitized by the same hardware of the MUs with induction field sensors. In addition, this signal is processed in the same way as the magnetic field sensor signals, allowing the extraction of a current signature to track the SG condition. In this way, it is possible to choose to monitor, in a non-invasive way, both the magnetic signature of the SG, through induction magnetic field sensors, and the signature of the neutral current time derivative waveforms, with a Rogowski coil sensor.

B. Monitoring Units - MUs

The MUs function is to measure waveforms proportional to the external magnetic field time derivative. This equipment is composed of an induction field sensor, shown in Fig. 10 (a), optimized for large generator applications, coupled to a signal conditioner and digitization board, shown in Fig. 10 (b). For application in an industrial environment, this circuit is contained in a plastic enclosure, shown in Fig. 10 (c), which does not interfere in the measurement of the magnetic field. The signal conditioning circuit consists of filtering and amplification stages, which are necessary to raise the signal level, with an adequate signal-to-noise ratio, before the digitization stage. Since the MUs are installed in different positions and are subject to magnetic fields of different intensities depending on their position, the gain of the amplifiers used in this equipment is set automatically to ensure flexibility and to optimize the use of the analog-to-digital converter scale.

(a) (b) (c)

Fig. 10. Monitoring unit: (a) induction field sensor, (b) MU circuit board, (c) MU cabinet.

This equipment delivers the measured signal in digital form to the PU in response to acquisition commands sent periodically.

C. Processing Unit - PU

The PU has the function of sending acquisition commands periodically to the MUs and receiving the digitized signals, in a synchronized way. In addition, the PU controls the amplifier gains of each MU, forwards the collected signals to the server and provides local indications through digital outputs and LEDs. In this equipment, FPGA technology was used for acquisition control, and an ARM processor was used to enable processing at the Linux operating system level. Fig. 11 shows the circuit board of this equipment and its cabinet for industrial application.

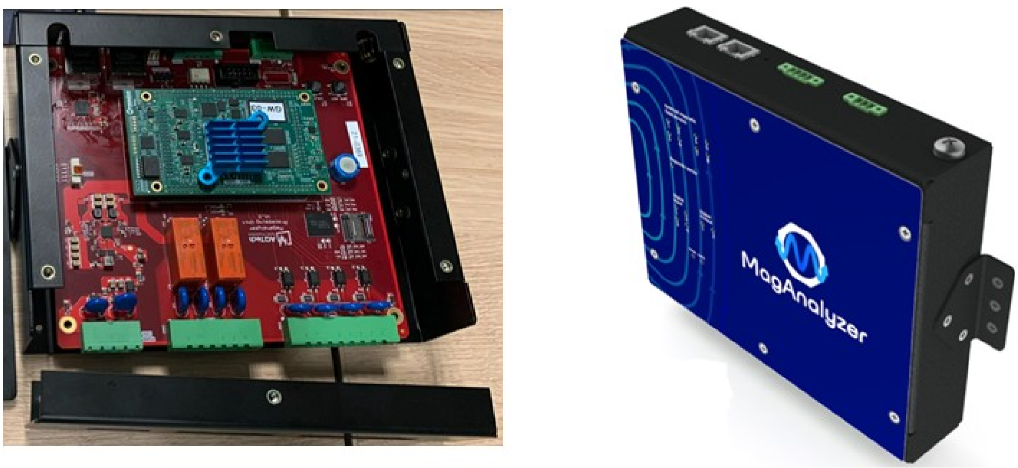


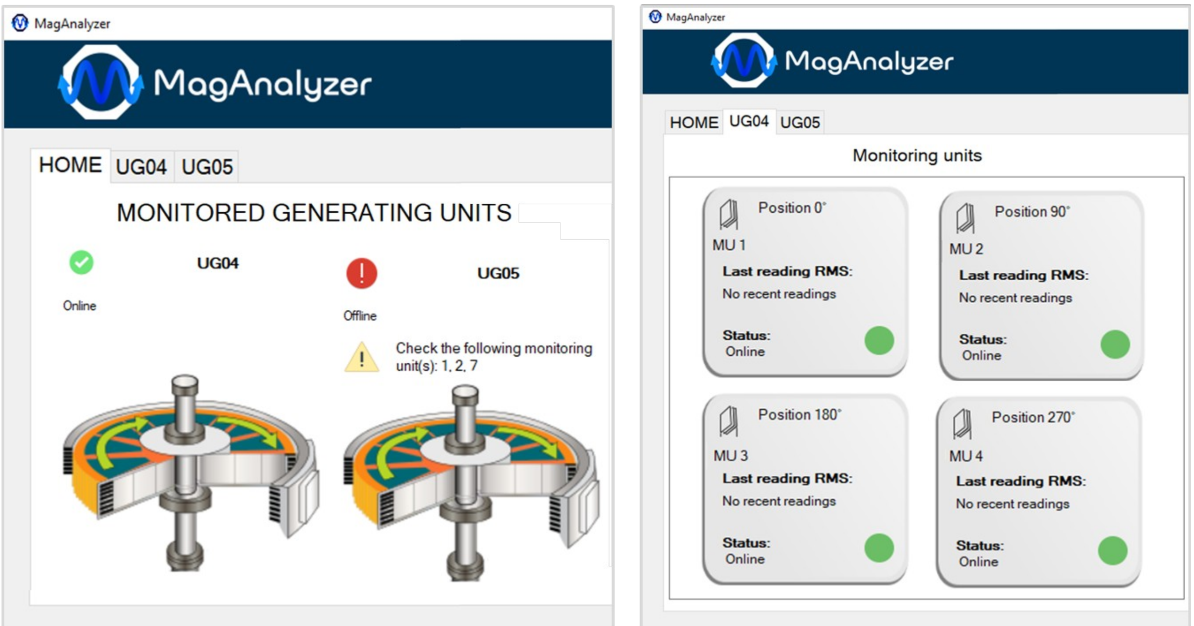
Fig. 11. Processing unit circuit and cabinet.

D. Server and monitoring software

An external server is used for advanced processing, data storage and execution of dedicated software for monitoring the SG magnetic signature.

The processing performed on the server includes calculating the FFT of the digitized signals received by the PU, tracking the harmonic components of the SG mechanical rotational frequency and storing the amplitudes of these harmonics, updating the amplitude histories that characterize the machine magnetic signature. In addition, the server is responsible for integrating, in a synchronized way, the amplitude history with time series of SG electrical measurements, such as terminal voltage and power, which characterize its operating point. This allows the magnetic signature to be analyzed in correlation with the operating point, as well as to monitor the magnetic signature within narrow operating ranges to avoid false alarms in the fault detection process resulting from variations in the operating point.

The monitoring software that runs in the server was developed with a graphical interface that centralizes the control of several MagAnalyzer systems installed in a generation plant to monitor several generators and indicates the status of the MU sensors. Fig. 12 (a) shows the main window of the software where the monitored SGs in a generation plant are registered and the operating status of the MagAnalyzer system in each generator is indicated. Fig. 12 (b) presents the interface for checking the status of each MU of a MagAnalyzer system, showing its installation position, its operating condition and the effective value of the signal measured at the last acquisition performed by the MU.



(a) (b)

Fig. 12. (a) Main window of the monitoring software, (b) control window of the monitoring units.

An interactive graphical interface has been developed to allow visualization of the time series of the SG magnetic signature history. In this interface, it is possible to configure the data visualization period, to select specific time series for visualization and to use statistical tools to detect anomalies in the magnetic signature. Fig. 13 shows one of the windows for viewing and analyzing the magnetic signature, where it is possible to select a time series for the analysis and to configure the control chart method for detecting changes in the mean value or trend. Resources were included to specify the reference region and to adjust the detection threshold, in order to allow the investigation of changes in different scenarios.

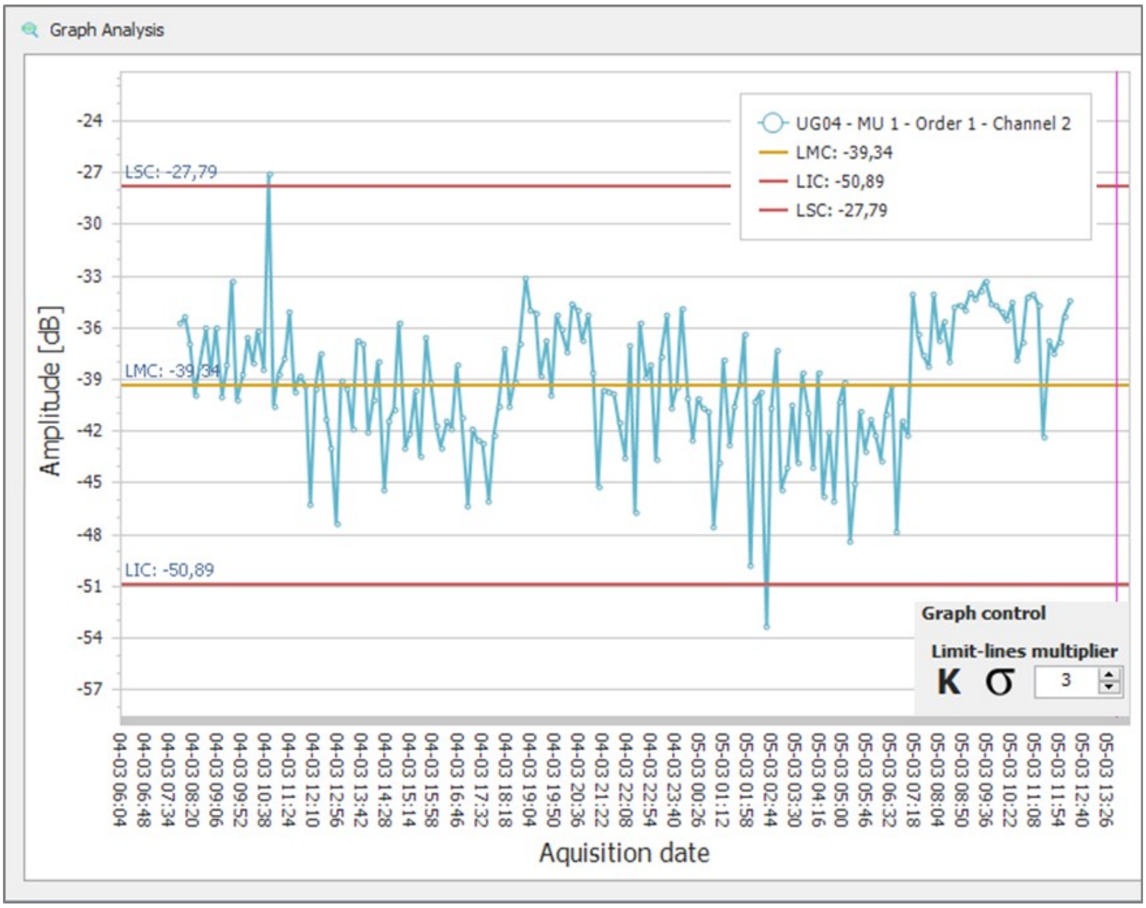


Fig. 13. SG magnetic signature viewing and analysis window in the monitoring software.

IV. Installation of the Equipment in a Hydroelectric Power plant

The MagAnalyzer system was installed in two 305 MVA SGs of the Itá Hydroelectric Power Plant, located in the south region of Brazil. The SGs have 56 salient poles, vertical axis and a Francis hydraulic turbine as primary machine. Its electrical operating frequency is 60 Hz and the mechanical rotational frequency is approximately 2.14 Hz for the SG operating in synchronous mode with the electrical system. The installed MagAnalyzer systems were configured to perform periodic signal acquisitions every ten minutes to form series with the machine magnetic signature. The duration of each acquisition is 20 seconds at a sampling rate of 20 kHz. This enables the investigation of the frequency spectrum up to 10 kHz with a spectral resolution of 0.05 Hz, which is sufficient to identify the harmonic components of the mechanical rotational frequency of the SG.

A. System Installation on a SG

The positioning of the MagAnalyzer system elements around the SG is shown in Fig. 14. The MUs numbered from 1 to 7 contain induction magnetic field sensors and are positioned on the inner wall of the SG housing. Fig. 15 (a) shows the internal view of one of these MUs and its position in relation to the stator frame. The magnetic axis of the field sensor is horizontal in order to preferentially capture

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the tangential component of the magnetic field externalized by the SG, as indicated in section II. The sensor of the MU 8 is a Rogowski coil positioned in the neutral cable of the SG, to monitor signals proportional to the neutral current time derivative. The PU is positioned on the outer wall of the SG housing. Fig. 15 (b) shows the PoE switch, which connects the eight MUs to the PU via Ethernet cables, as well as the panel that houses these two elements.

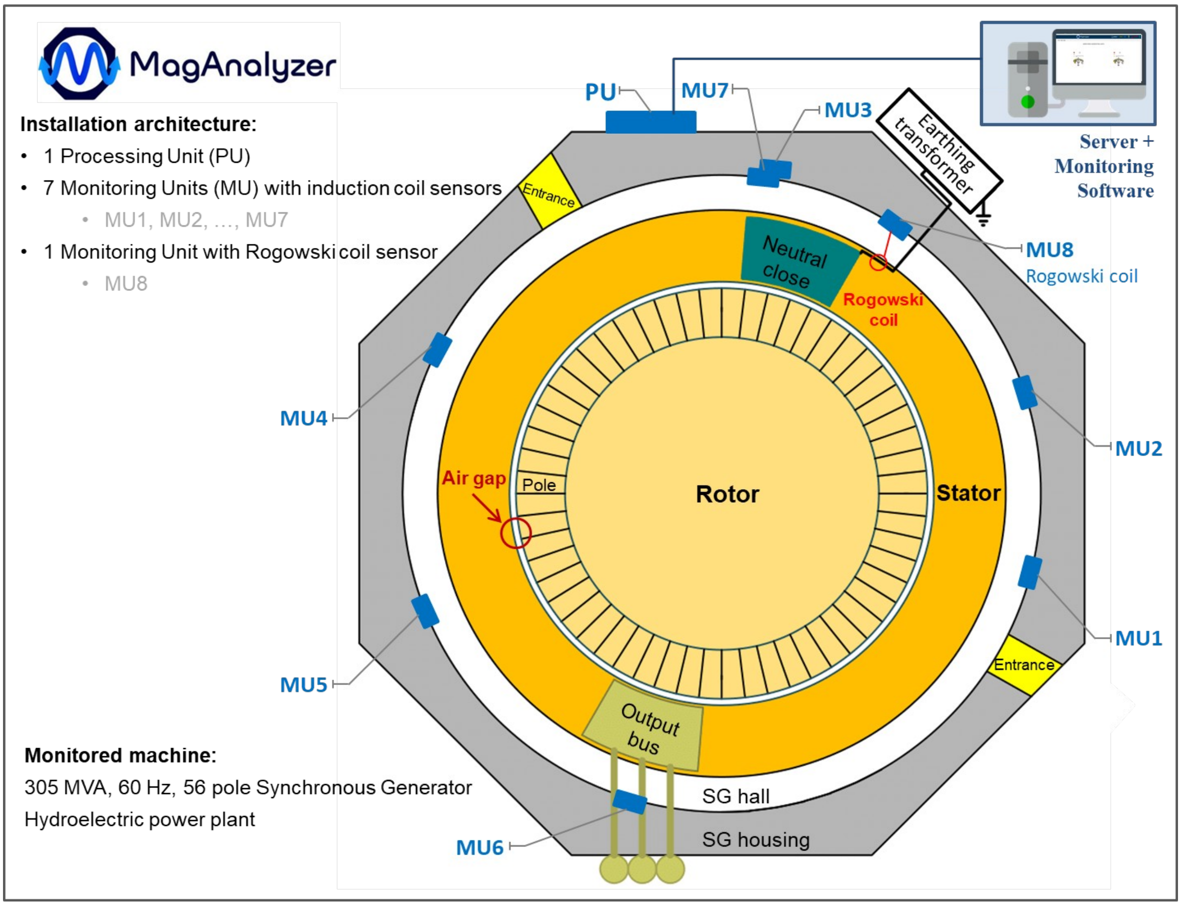

Fig. 14. Positioning of the MagAnalyzer elements installed in a 305 MVA SG of a hydroelectric power plant.

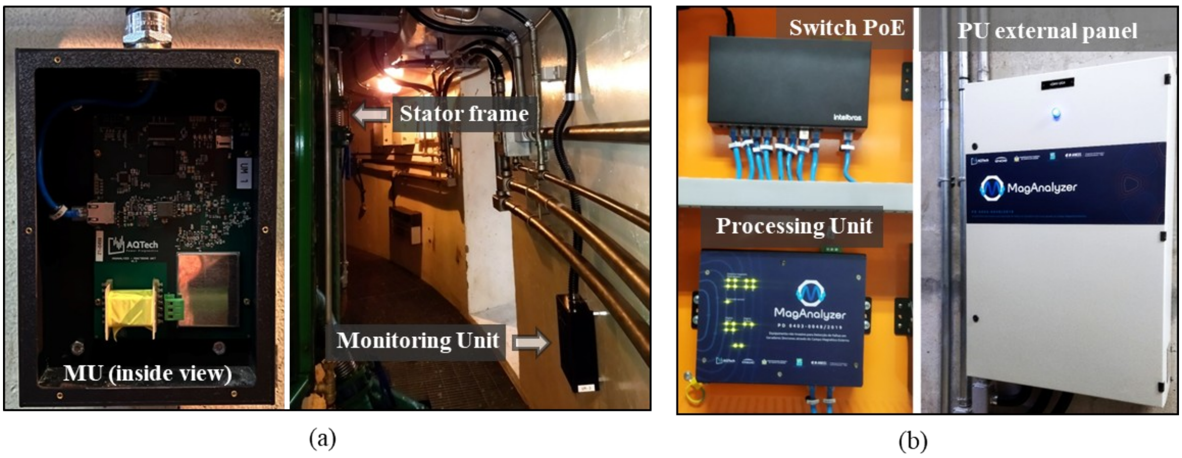

Fig. 15. Equipment installation: (a) monitoring unit, (b) processing unit and PoE switch on the external panel.

The position of the MUs within the SG housing is defined by the following guidelines: i) The MUs must be distributed along the circumference of the housing to monitor different regions of the machine; ii) The installation of MUs should be avoided in locations close to energized auxiliary

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equipment existing in the SG hall, such as radiators, heaters or other monitoring equipment, that may interfere on the external magnetic field measurement of SG; iii) The MUs should be positioned near the center of the stator stack length, so that the sensors are sensitized, preferably, by the magnetic field leakage through the stator frame. One particularity of the equipment installation shown in Fig. 14 is that the MU3 and MU7 were installed in the same angular position, but at different heights. This configuration was defined to assess the effect of the installation height on the measurements.

A preliminary configuration of the equipment is required for the installation of the MagAnalyzer system in each SG. This configuration is performed by the monitoring software, where the parameters of the monitored SG, such as the electrical operating frequency, the number of poles and the number of SG stator slots, must be set. In addition, system measurement and processing parameters, such as sampling frequency, logging interval and the number of monitored harmonics, can be adjusted for each particular SG.

The preliminary configuration of the equipment with the SG parameters, the installation of the MUs following the positioning guidelines presented previously, and the automatic adjustment of the amplifier gains on the signal conditioning stages, presented in section III, enable the use of the MagAnalyzer system in different SGs. This set of attributes and guidelines has been specified to monitor the external magnetic field in different environments, minimizing interference from environmental magnetic noise and measuring the signals of interest with a quality suitable for monitoring each SG, without the need for additional equipment adjustments.

B. Commissioning of the MagAnalyzer system and evaluation of the measured signals

After installation, verification tests are carried out to validate the system operation, especially with regard to the equipment operation and communication between the units. The MUs and the communication system are assessed by acquiring and evaluating signals with the SG in operation. Fig. 16 (a) shows some cycles of the waveform of the external magnetic field time derivative measured by a MU. The waveform is dominated by the SG electrical frequency. The frequency spectrum of this signal, shown in Fig. 16 (b), emphasizes the electrical frequency as the component with the preponderant amplitude of the signal. In addition, the SG mechanical rotation frequency (f_m), which is approximately 2.14 Hz, and its harmonics ($2f_m$, $3f_m$, ...) are observed. These results verify the correct function of the system in measuring the external magnetic field characteristics required for monitoring the machine condition.

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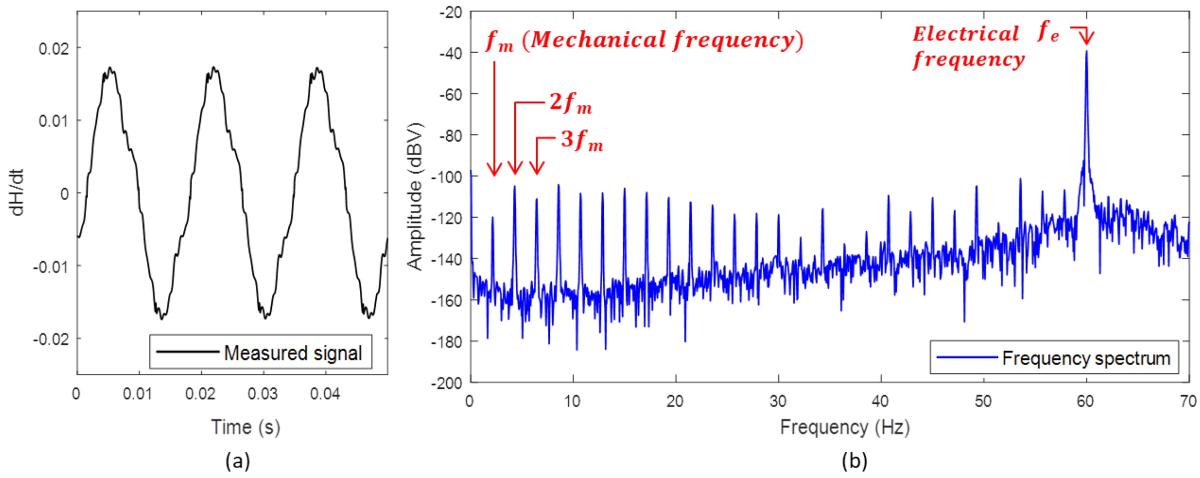

Fig. 16. (a) Waveform of the external magnetic field time derivative, (b) frequency spectrum of the signal.

The evaluation of the frequency spectrum under different load conditions also highlights the influence of the operating point on the amplitude of some f_m harmonics. Fig. 17 shows the frequency spectrum of the signal measured by the same MU for the SG operating in synchronized mode in two conditions: at no load and at close to rated load. It can be observed that at no-load condition the mechanical rotation frequency and its harmonics are already present in the spectrum. The load increment up to the rated condition causes an increase or decrease in the amplitude of these components, independently of each other.

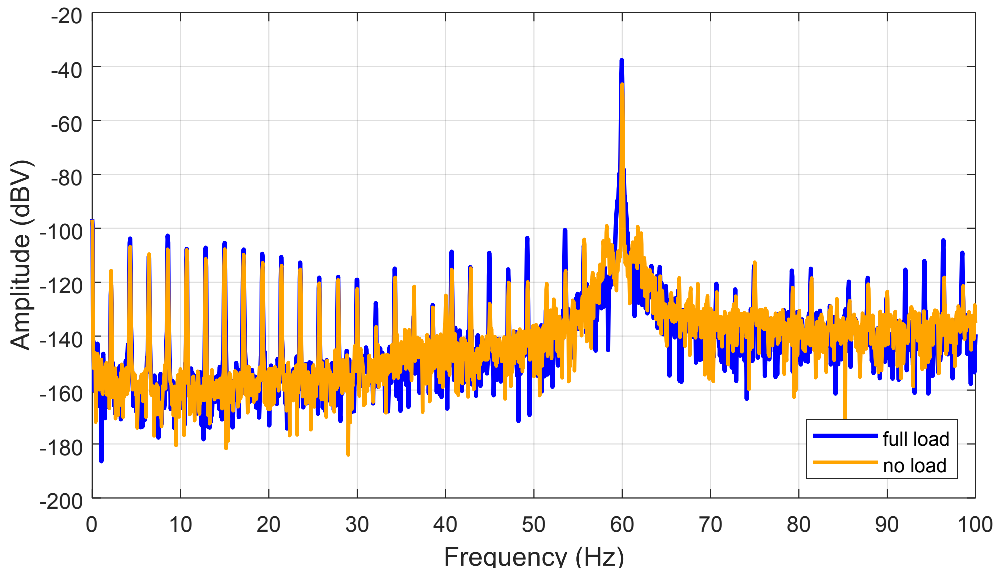

Fig. 17. Change of the frequency spectrum with increasing load on the SG.

This finding evidences the sensitivity of the amplitudes to operating point changes and the need to evaluate the magnetic signature in limited operating regions for incipient fault detection.

C. Supervisory system results

After installation and commissioning, the equipment remained in operation monitoring the SG condition. The monitoring software allows visualization of the time series of the magnetic signature of each machine for evaluation and anomaly detection. Fig. 18 presents the selection and visualization

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window of the MagAnalyzer software, where the amplitude history of the mechanical rotation frequency (2.14 Hz) and its 10th harmonic for a MU are presented. The amplitude changes observed in this period are caused by the variation in the generator operating point.

Fig. 18. Magnetic signature history visualization window.

Control chart statistical tools can be used to detect anomalies or changes in trends interactively. The stationarity condition of the amplitude history of the mechanical rotation frequency can be verified with 3σ control thresholds in an approximately constant operating region, defined as the reference region. Fig. 19 indicates the upper and lower control thresholds defined based on the specified reference region, in addition to the reference average value. It can be seen that the amplitude samples remain mostly within the region of normality for this analyzed period.

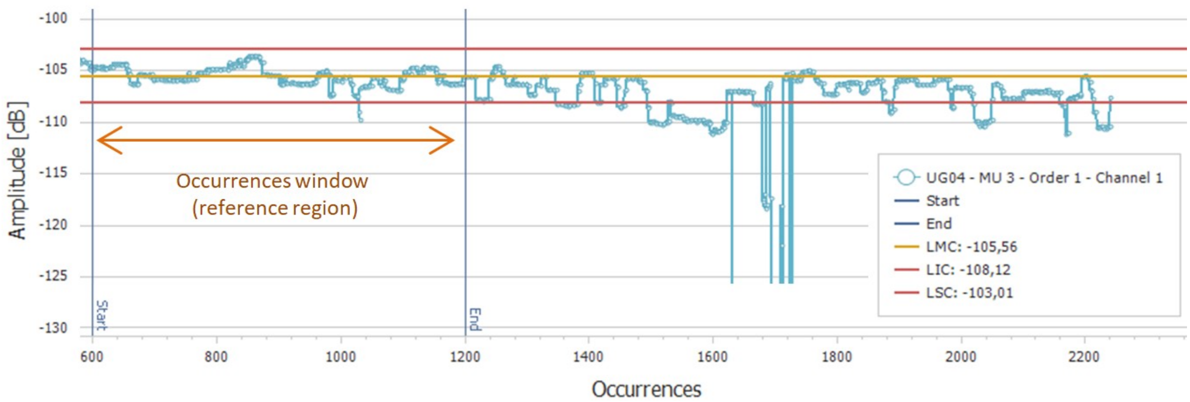

Fig. 19. Applying control charts for detecting trend changes.

D. Testing the MagAnalyzer system in laboratory

The MagAnalyzer system was also tested in laboratory with the experimental test bench presented in section II. The system was adapted in the form of a mobile device for this application, containing the PU and the conditioning and digitizing electronic boards of the MUs in a suitcase and employing an external notebook computer as a server for magnetic signature storage and execution of the monitoring software. A test with controlled removal of 50% of the active turns from a rotor pole was evaluated in an approximately constant operating condition, with the SG operating at around 70% of its rated power synchronized with the electrical grid. In this test, the SG was operated in the healthy condition, in a fault condition, and finally in the healthy condition again. Fig. 20 shows the amplitude history of the mechanical rotational frequency of this SG (15 Hz) at four sensors (MUs) fixed at different positions on the periphery of the stator frame. It is possible to observe that the influence of the fault on this component is clearly significant in all MUs. The amplitude of the f_m component varies according to the position of the sensor, as well as the amplitude variation observed under fault. After the fault is removed, the machine operates again in the healthy condition, presenting small amplitude changes with respect to the initial test condition, due to small changes in the operating point caused by the machine heating and by the procedure of imposing and removing the fault. Fig. 21 shows the application of control charts for change detection in the amplitude history of the second harmonic of f_m in one sensor. Even with thresholds set far from the reference average value, it is possible to detect the fault automatically, since a control threshold is violated. The monitoring software can be configured to detect changes in various amplitude scales. This allows the operator to investigate and locate harmonics with both high and low sensitivity to faults.

Fig. 20. Amplitudes history of the mechanical rotation frequency in 4 MUs face to the fault.

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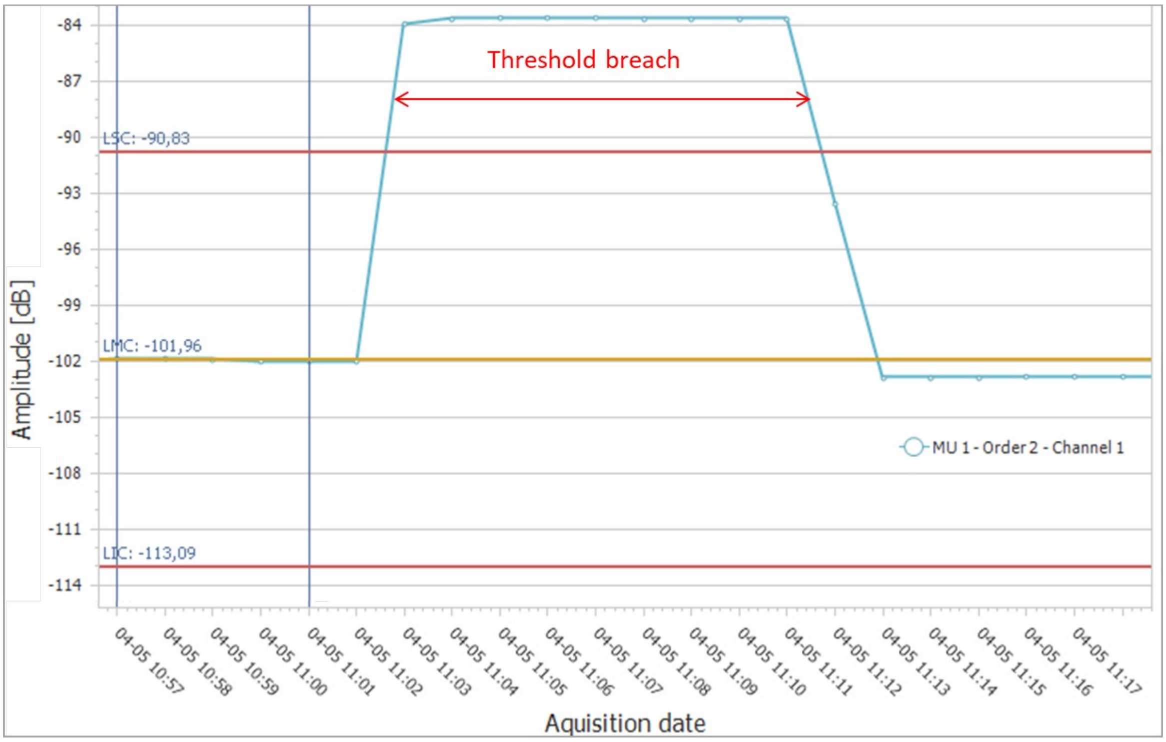

Fig. 21. Application of control charts for fault detection with the MagAnalyzer system monitoring software.

The results of laboratory tests with the commercial version of MagAnalyzer corroborate the results obtained through the initial evaluation of fault detection with a prototype, presented in section II.

V. CONCLUSIONS

The proposed equipment for monitoring the external magnetic field time derivative has innovative features with great potential for application in the predictive maintenance of synchronous generators. The system is easy to install and does not interfere or offer risks to the machine operation. The ability to detect stator or rotor faults, both of electrical/magnetic and mechanical origin, makes the equipment versatile in detecting different types of incipient faults in synchronous machines. The technologies employed in the proposal of this system, including the specification of the magnetic field sensor, the signal conditioning circuits, the data processing techniques and the fault detection methods, culminated in great precision and sensitivity in incipient fault detection. The specification of this equipment, as a whole, is a contribution to the electrical machines monitoring and supervision field, since there is no evidence of a non-invasive monitoring equipment for SGs on the market employing these technologies. The presented results show that the equipment can be used for the continuous monitoring of synchronous generators, being able to generate alerts in real time or serving as analysis tool of the machine condition by a specialist. Theoretical aspects and developments, detailed description of the modulation processes that occur in synchronous machines, guidelines and patterns of magnetic signature changes in relation to the types of faults and the development of artificial intelligence algorithms, used to avoid false alarms due to operation point variation and for the typification and location of the possible incipient fault, will be presented in subsequent papers, due to the complexity inherent to the development of these topics.

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