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Identification of sensitive feature in the stray magnetic field to detect rotor short-circuit fault in synchronous generators

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Abstract—This paper presents an application of the external magnetic field measured in the vicinity of a synchronous generator in a hydroelectric powerplant for the detection of a rotor short circuit fault. The measurement of the external magnetic field was performed using a flux sensor and the analysis of the signal is done in a quantitative and qualitative way by considering the spectral evolution of the signal but also its temporal variation. The presented results are obtained analyzing several operating conditions of a 55 MW generator in healthy and fault case. We notice the interest of using the reduced values in percentage to better compare the different state of the machines. A vibration study is also presented at the end of the paper to complete the analysis.

Keywords—Stray flux, synchronous generators, rotor short circuit fault

I. INTRODUCTION

In the context of pressure on energy resources, associated with an increasing demand for electrical energy due to the electrification of uses (such as electric vehicles), the availability of electric power plants is becoming a major issue. A way to increase the availability is to improve the maintenance plan of the electric generators by surveying incipient degradation of the machine components to avoid an undesirable shutdown. This requires monitoring the machines with invasive or non-invasive sensors, but depending on the age of the machine, its rated power, or its position in the energy delivery plan of the grid manager, machines are more or less equipped with sensors. In France, most of the medium power hydroelectric plants have fewer instrumented machines. The usual faults that can occur on these machines are mainly eccentricity or rotor inter-turn short-circuit fault. Stator winding faults rarely appear because the insulation is generally re-enforced, which limits its degradation. Rotor inter-turn short circuit fault and eccentricity do not generally lead to sudden shut down and they do not prevent the machine to operate normally. Hydroelectric generators have a high number of poles and having a weaker pole due to inter-turn fault in the field winding is not a great concern. However, in these faulty conditions, the vibratory level of the machine increases and in the extreme case, the operating conditions in the (P, Q) diagram may have a limited area. The inter-turn fault in the field winding can be evaluated with an offline test that consists in verifying the voltage equipotentiality over all the poles when all the winding poles, put in series, are flowed the same AC or DC current, but this test can be done only during maintenance periods. For online detection, in absence

of specific instrumentation, the use of an external flux sensor can be a good alternative. The exploitation of the external stray flux has proven to be efficient for fault detection in electrical machines [1]. It has been shown that stator inter-turn short circuit can be better detected with the stray flux than with line current, especially by using several sensors placed around the machine [2]. This is true for both induction and synchronous machine. Stray flux sensors can also be used to detect broken rotor bars in induction machines [3][4], eccentricity [5], or demagnetized magnet in synchronous machines [6]. Bearing faults [7-10] but also other mechanical faults [11-13] have also a significative influence on the stray flux. Concerning large electric generators, [14] deals with winding field diode monitoring with stray flux, [15] uses classification method to detect field winding inter-turn fault, [16] show enhances the correlation between winding faults and vibration. [17] combines finite element simulation and experimental to detect winding field inter-turn fault in hydroelectric generators using an external flux sensor. However, all the papers about detection of rotor field winding inter-turn faults with stray flux sensor do not consider the influence of the machine operating condition.

This study presents an experimental comparison of two 55 MW synchronous real hydroelectric generators. One is assumed to be healthy and the other one has a rotor inter-turn short circuit. Especially designed stray flux sensors have been installed on the machines, and the aim is to highlight what are the signal parameters that are sensitive to a rotor inter-turn short-circuit. The analysis focuses on the spectrum but also the time signal delivered by the sensor for different operating conditions as far as active and reactive power are concerned. A vibratory analysis also brings complementary information.

The paper is organized as follows: section II gives theoretical issues about the external magnetic field and the sensitive spectral lines tied to usual faults, section III presents the machines, the experimental environment with sensor and data acquisition system and the test protocol, section IV deals with results analysis taking into account the operating condition at different active and reactive power. In the last section, a conclusion highlights the main findings of the paper.

II. THEORETICAL ISSUES

A. External magnetic field

The external magnetic field can be classified according to its direction; thus, the notions of axial and radial fields are used. The axial magnetic field is geometrically oriented in a longitudinal direction, parallel to the axis of the machine, and

is rather sensitive to the currents in the stator and rotor end windings. The radial magnetic field is in a plane perpendicular to the longitudinal axis and is the image of the air gap induction which is attenuated by the stator laminations but also by the external frame of the machine. The radial magnetic field has 2 components, a normal direction, and a tangential direction. Therefore, the external magnetic field has three components that can be distinguished experimentally by an appropriate choice of a flux sensor position as shown in Fig. 1.

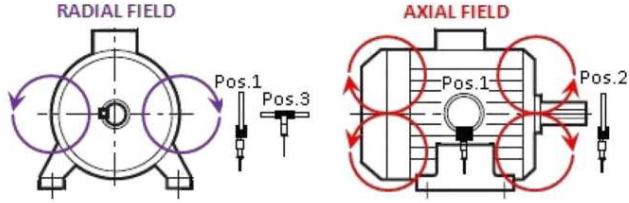


Fig. 1. Radial and axial flux decomposition

B. Sensitive components

An Analytical modelling based on airgap permeance and magneto motive force generated by stator and rotor armature is very convenient to describe precisely the harmonic content of airgap flux density in terms of time or space harmonics. Such an approach has a lack of accuracy concerning the magnitude of the airgap flux density harmonic component, but it enables us to define the change of the harmonic content of the airgap flux density in faulty conditions and to highlight frequencies of sensitive harmonic components. In [16], analytical modelling of electrical machines with stator and rotor inter-turn short circuit, eccentricity leads to define the following sensitive frequencies:

$$\text{For a rotor inter-turn short circuit} \\ f_{cr} = 2k_r f + h f_r \quad (1)$$

$$\text{For a stator inter-turn short-circuit} \\ f_{cs} = 2k_s f + f \quad (2)$$

$$\text{For dynamic eccentricity} \\ f_{exc} = f \pm h f_r \quad (3)$$

k_r varies from $-\infty$ to $+\infty$ and h is a positive integer, f is the supply frequency, f_r is the rotating frequency of the machine. After attenuation by the stator lamination and the external frame, these sensitive components will be found in stray flux.

III. EXPERIMENTAL SETUP

A. Machine presentation

Hydraulic synchronous machines are low speed machines and present a high number of poles. This high number of pole require to manufacture the rotor with salient poles, wound as shown in Fig. 2. Due to winding ageing, inter-turn short-circuit can occur, which make some pole weaker than others, leading to decrease the whole phase flux linkage at given rotor currents. Due to the rotor rotating, the three phases of the machine are affected similarly and the machine stays balanced. Therefore, the rotor fault does not influence the stator electric variable but as the rotor flux reduction has to be compensated by a rotor current increase, some operating conditions where high rotor currents are needed could be excluded. Moreover, due to an irregular force repartition

between rotor poles and stator core along the airgap, the level of vibration may increase.

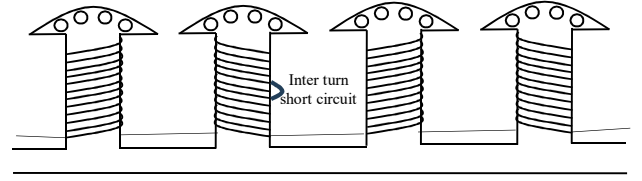


Fig. 2. Salient pole rotor with inter-turn short circuit

The power plant that has been investigated in this study is composed of three synchronous generators which main characteristics are presented in Table I. From the knowledge of the power plant manager, it is known that two of these machines are healthy and one machine have a rotor inter-turn short-circuit in at least one pole. However, the fault severity is unknown. This paper will investigate the faulty, and one healthy machine. The sensors have been instated on the tested machines and it was possible to set up any operating conditions in terms of active power P , and reactive power Q .

TABLE I. MACHINE CHARACTERISTICS

Rated active power	$P_n=55$ MW
Rated reactive power	$Q_n=35$ MVAR
Number of pole	30
Rotational speed	200 rpm
Supply voltage	10000V
Frequency	50Hz
Rated stator current	3700 A

B. The sensor

The used sensor is a tri-axial wound flux sensor (Fig. 3) specially sized to be adapted for high power machines. It is composed of 3 windings of axis NOR, AXI, and TAN. It has 4 tabs with magnets so that it can be easily installed against the external frame of the machines. This sensor has the advantage to be directly connected to a data acquisition system without any filter or amplifier.

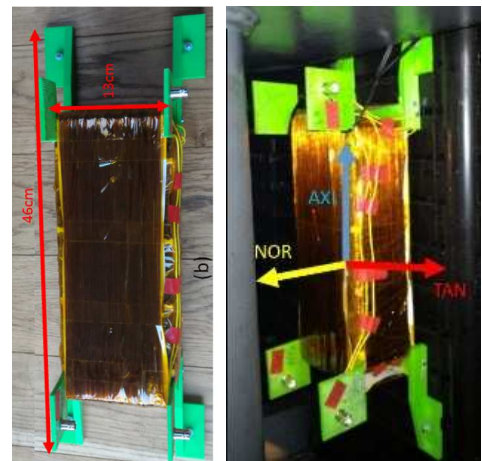


Fig. 3. The tri-axial stray flux sensor

In this study, we consider only the signal from the TAN axis, equivalent to position pos.3 in Fig. 1. In this position, the sensor is supposed to be insensitive to the axial field generated by the current flowing through the end windings of the machines. The obtained signal is an image of the airgap flux

density whose spectral content includes faulty frequencies given by (1), (2), (3) but with a derivative action. An accelerometer is also used to provide a complementary information about the machine's state. It is placed on the external frame of the machine, near the flux sensor.

C. Data acquisition

For both investigated machines, 15 operating points are be considered: three points for the active power (0%, 50%, 100% of P_n), combined with five points for the reactive power (-100%, -50%, 0%, 50%, 100% of Q_n). For each operating point, we pick up the flux sensor signal and the accelerometer signal on two acquisition systems: A pulse system from Bruel & Kjaer that compute directly the FFT of the signals and a PXI data acquisition system with LabVIEW that records the signal. The acquisition duration is 5s with a sampling frequency at 20 khz. Therefore, the recorded length is 10000 points. Fig. 4 shows a picture of the whole acquisition system.

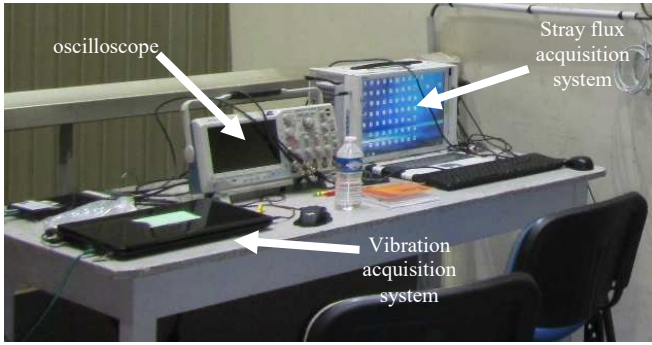


Fig. 4. Data acquisition system

IV. RESULTS ANALYSIS

Four types of analysis will be performed on the recorded signals. For the stray flux signal, a spectral qualitative analysis, a spectral quantitative analysis, and a time domain analysis will be performed. The vibration measured with the accelerometer will just be used to confirm the presence of the fault with a spectral analysis.

A. Qualitative analysis

Fig. 5 shows the spectra over the 0-100 Hz frequency range of the signal measured by the flux sensors at the operating point $P=100\%$, $Q=100\%$ for the healthy and the faulty machine. We can clearly see the fundamental at 50 Hz, and the presence of spectral lines every 3.33 Hz, corresponding to the rotation frequency of the machine. Therefore, there are 15 lines between 0 and 50Hz, and 15 others between 50 Hz and 100 Hz. All these spectral lines are related to sensitive frequencies given by (1) and (2) relative to the rotor faults and dynamic eccentricity. The lines at 3.33 Hz, 6.66 Hz, and 10 Hz ($kr=0$, $h=1,2,3$ in (1)) can be accounted for the rotor short-circuit fault, and the lines at 47.66 Hz, 43.33 Hz, and 40 Hz ($h=-1, -2, -3$ in (3)) to eccentricity. As a first observation, we can see that the sensitive spectral lines appear even for the healthy machine and the difference between the healthy and the faulty machine is quite small. In real machines, there is always minor imperfection due to tolerances in the manufacturing process. Therefore, a pure healthy machine is not a reality.

However, further information can be highlighted if we compare the first rank of the rotor fault-sensitive components at 3.33 Hz, ($kr=0$, $h=1$, in (1)) and the second rank at 6.66 Hz

($kr=0$, $h=2$, in (1)). Table II and Table III gives the magnitudes of the 3,33 Hz and the 6,66 Hz spectral lines for the 15 operating points for the Healthy and for the faulty machine and the variation direction between both frequencies. For the healthy machine, we can see that the variation is mainly positive (14 ↗ and 1 ↘) and for the faulty machine, the variation is mainly negative (11 ↘ and 4 ↗). This is a logical result. Indeed, when the machine has a short circuit fault, the main sensitive spectral line at 3.33 Hz characteristic of the fault (rank $kr=0$, $h=1$, in (1)) is higher than the second rank at 6.66 Hz ($kr=0$, $h=2$, in (1)), so we have a downward trend. On the other hand, in absence of fault, the main sensitive line at 3.33 Hz is lower than the second one 6,66 Hz. The main reason of this property is that the main rank harmonic has generally a higher magnitude than the second rank one.

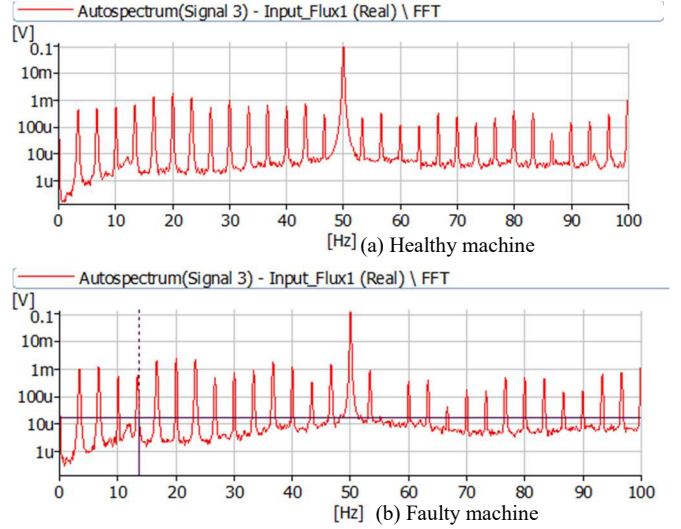


Fig. 5. Stray flux spectrum for the healthy (a), and the faulty machine (b)

TABLE II. MAGNITUDE, IN μV OF THE 3.33 HZ AND THE 6.66 HZ SPECTRAL COMPONENT. HEALTHY MACHINE

		3.33 Hz (μV)	6.66 Hz (μV)	Variation
P=0%	Q=-100%	165	260	↗
	Q=-50%	246	410	↗
	Q=0	321	506	↗
	Q=50%	467	540	↗
	Q=100%	595	586	↘
P=50%	Q=-100%	234	278	↗
	Q=-50%	281	365	↗
	Q=0	323	454	↗
	Q=50%	512	607	↗
	Q=100%	539	693	↗
P=100%	Q=-100%	281	322	↗
	Q=-50%	300	372	↗
	Q=0	342	450	↗
	Q=50%	443	514	↗
	Q=100%	448	515	↗

TABLE III. MAGNITUDE, IN μV OF THE 3.33 HZ AND THE 6.66 HZ SPECTRAL COMPONENT. FAULTY MACHINE

		3.33Hz (μV)	6.66Hz (μV)	Variation
P=0%	Q=-100%	553	532	↘
	Q=-50%	594	515	↘
	Q=0	811	290	↘
	Q=50%	1017	611	↘
	Q=100%	1340	1470	↗
P=50%	Q=-100%	453	275	↘
	Q=-50%	614	258	↘
	Q=0	807	367	↘
	Q=50%	1110	977	↘
	Q=100%	1261	1368	↗
P=100%	Q=-100%	602	453	↘
	Q=-50%	654	465	↘
	Q=0	814	674	↘
	Q=50%	1053	1178	↗
	Q=100%	1086	1247	↗

B. Quantitative analysis

The quantitative analysis focuses on the main rank harmonic at 3.33 Hz. Moreover, the real magnitude may be not a convenient feature when two machines are compared. Therefore, we will consider here the relative magnitude in the percentage of the fundamental. Tables IV and V gives these relative magnitudes for the healthy and the faulty machine for the 15 operating points.

According to Table IV and Table V, it can be observed that for each operating point, the relative magnitude of the faulty machine is roughly twice the magnitude of the healthy one. Tables III and IV also highlight the need of considering the operating point in the analysis, because independently of the operating point we can find magnitudes for the healthy machine higher than those for the faulty machine. It can also be observed that the operating points at maximum active and reactive power correspond to the cases where the relative amplitudes are the highest, similarly as in Tables I and II for the real magnitude. In these operating conditions, the rotor excitation current is maximum and then the effect of the magnetic unbalance generated by a rotor fault is maximum, which leads to enhancing the spectral lines sensitive to the fault. Therefore, based on these matters, it can be recommended to consider the operating conditions at high active and reactive power.

C. Time domain analysis

For a healthy machine, all the rotor poles produce the same magnetic effect that will be found outside of the machine too. Therefore, the linkage flux of the sensor will present a similar waveform for each pole-pass over one rotation of the machine. In the case of a rotor inter-turn short

circuit, a pole will become weaker than the others and there will be a change in the magnitude of the sensor linkage flux when the faulty pole will come in front of the sensor. In this section, the flux signal is used to check these time domain properties.

TABLE IV. RELATIVE MAGNITUDE (IN %) OF THE 3.33HZ SPECTRAL COMPONENT. HEALTHY MACHINE

		P		
		10%	50%	100%
Q	-100%	0,13	0,19	0,27
	-50%	0,18	0,23	0,30
	0%	0,25	0,28	0,38
	50%	0,41	0,42	0,45
	100%	0,61	0,55	0,44

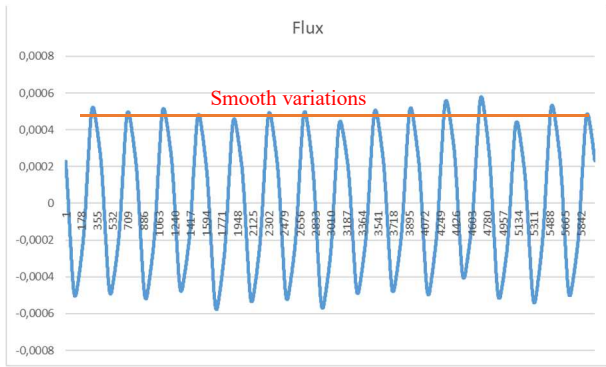
TABLE V. RELATIVE MAGNITUDE (IN %) OF THE 3.33 HZ SPECTRAL COMPONENT. FAULTY MACHINE

		P		
		10%	50%	100%
Q	-100%	0,30	0,24	0,36
	-50%	0,32	0,34	0,39
	0%	0,47	0,48	0,54
	50%	0,66	0,83	0,81
	100%	1,17	1,09	0,86

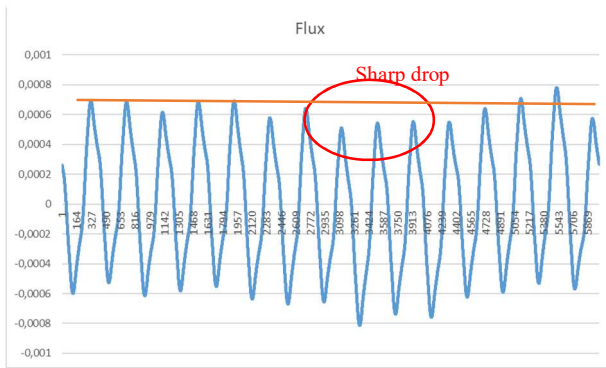
Fig. 6 shows the linkage flux of the sensor for one revolution of the healthy and faulty machines. The flux is obtained by integration of the voltage signal delivered by the flux sensor. In both flux signal, one can find 15 positive poles (north pole) and 15 negative poles (south pole), but it can be observed that the flux magnitude are different for each pole-pass even for the healthy machine, which means that this machine is probably not perfectly health. This is in accordance with section IV.A about the frequency domain qualitative analysis where the presence of eccentricity was also mentioned. Actually, both eccentricity and rotor fault may cause a change in the magnetic effect of one rotor pole, but it can be expected that the eccentricity produces a smooth change of the flux magnitude over one rotation whereas shorted turns produce a sharp drop of the linkage flux of the sensor as shown in [17]. In addition to eccentricity and rotor shorted turn, another phenomenon may cause flux magnitude variations. Actually, due to manufacturing a positioning imperfection of the rotor poles, the airgap between the rotor pole and stator may be not perfectly constant which can make some magnitude variation of the airgap flux density and also magnitude variation of the sensor flux linkage.

In Fig. 6 it can be seen that the flux magnitude presents regular smooth change that may be caused by the eccentricity or manufacturing tolerances for the healthy machine (Fig. 7.a) whereas a sharp drop appears for the machine with rotor shorted turns (Fig. 6.b). Therefore, time domain analysis can be complementary to the frequency domain analysis to detect

rotor faults, even if this analysis is not so easy as the spectral analysis.



(a) Healthy machine

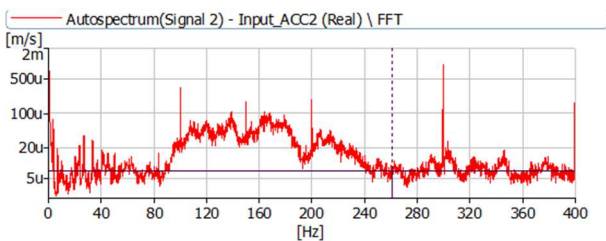


(b) Faulty machine

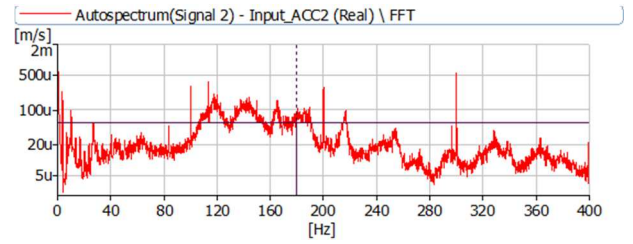
Fig. 6. Time domain signal, healthy machine (a), faulty machine (b)

D. Vibratory analysis

The vibratory analysis is not at the heart of the paper, but in this section, we can try to evaluate the consequence of rotor shorted turns on the mechanical behaviour of the machine. The accelerometer is placed on the external frame of the machine, close to the flux sensor. Fig 7 shows the spectrum of vibration (speed information) for both machines in a 0-400 Hz frequency range. Firstly, it can be observed that the spectra are roughly similar. The spectral lines at 100 Hz, 200 Hz, and 300 Hz which originate from electrical excitation of the stator frame clearly appear. They are due to radial forces between the stator and the rotor. In a very low part of the spectrum, the main finding concerns the spectral line at 3.33 Hz that goes from $78\mu\text{m/s}$ for the healthy machine up to $366\mu\text{m/s}$ for the faulty machine, for an operating condition with $P=100\%$, $Q=100\%$. A deeper analysis should be taken with care because of the complex mechanical structure of the machine.



(a) Healthy machine $78\mu\text{m/s}$ à 3.33 Hz



(b) Faulty machine, $366\mu\text{m/s}$ à 3.33 Hz

Fig. 7. Vibratory spectrum

V. CONCLUSION

The presented study has highlighted the interest in the use of the external field to evaluate the health state of an electrical machine, more particularly to detect rotor short-circuit fault in synchronous machines. The flux sensor is simple, cheap, non-invasive and easy to install, even on operating machines. It can be an interesting alternative for the monitoring of non-instrumented machines. The analysis focuses on one healthy and one faulty machines of 55 MW in a hydroelectric power-plant. We were able to appreciate the consequences of the fault on various parameters obtained from real measurements. The originality consists in the possibility to analyze the behavior of the external magnetic field for different operating points characterized by different powers P and Q. The analysis allows us to state that it is better to work with the values reduced in percentage to be able to compare the healthy state of different machines. The obtained results are surely not enough sufficient to give general conclusions, but they allow us to give trends to define analysis and diagnosis procedures that will help to improve the maintenance and thus to increase the life-time of hydroelectric machines. In future work, we will be interested in estimating the severity of the fault. A finite element analysis will be used for that. We can also use the sensors to evaluate operating conditions.

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