Field-winding fault detection in synchronous machines with static excitation through frequency response analysis

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A B S T R A C T

Frequency Response Analysis is a well-known technique for the diagnosis of power transformers. Currently, this technique is under research for its application in rotary electrical machines. This paper presents significant results on the application of Frequency Response Analysis to fault detection in field winding of synchronous machines with static excitation. First, the influence of the rotor position on the frequency response is evaluated. Secondly, some relevant test results are shown regarding ground fault and inter-turn fault detection in field windings at standstill condition. The influence of the fault resistance value is also taken into account. This paper also studies the applicability of Frequency Response Analysis in fault detection in field windings while rotating. This represents an important feature because some defects only appear with the machine rated speed. Several laboratory test results show the applicability of this fault detection technique in field windings at full speed with no excitation current.

Keywords:

Frequency response analysis
Impedance measurement
Fault diagnosis
Fault detection
Rotating machines
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Introduction

Diagnosis and protective techniques are nowadays priorities for achieving the reliability of power generators and transformers. Detecting and locating any type of defect are primary concerns in order to minimize the damage to these electrical machines.

Frequency Response Analysis (FRA) is a well-known technique developed to detect winding deformations and displacements in power transformers [1,2]. These defects can appear as a result of shocks during transportation or electromagnetic forces that occur during short-circuit.

This technique has been remarkably developed in power transformers since its appearance [3] more than twenty years ago, until the development of standards of application as [4]. It is based on the analysis of the equivalent impedance of the winding under test, in the frequency domain. The winding equivalent circuit is composed by resistances, capacitors and inductances. As the equivalent circuit of a winding is unique, so the evaluation of the frequency response of a winding has to be always the same. So the test result in healthy conditions it is considered as a fingerprint of the winding [4]. The response at healthy conditions, generally obtained in the factory just after the manufacturing process. If any type of variation of the winding characteristics occurs, the frequency response is appreciably different and the event can be

detected [5]. The winding variation in power transformers may be caused by a ground fault, an inter-turn fault [6], an isolation failure at its early stage or even a geometric variation caused by shocks during transportation [7–9].

Despite the great development of this diagnosis technique in power transformers [10], and other special applications [11,12], FRA is rarely used in rotary machines. Currently, it is under study for its application to the diagnosis of rotary electrical machines. This paper focuses on the application of FRA for fault detection in field windings of synchronous machine with static excitation.

Currently, the interest in detecting any failure in rotary machines is remarkable, especially in induction motors [13–16]. In this type of machines, the detection of broken bars [17–19], the detection of rotor asymmetries [20], the detection of rotor fault [21] and inter-turn faults [22], are very active research topics.

In the case of the synchronous machines, new techniques detect rotor winding anomalies based on the measurement of different parameters. Some of them are based on the analysis of stator induced currents [23], while other techniques of monitoring systems are based on the flux measurement [24], and are implemented in commercial monitoring systems [25]. Novel ground fault detection methods without using voltage injection have also been proposed recently for static excited generators [26,27]. Currently, some contributions have been published related to the diagnosis of eccentric rotor in synchronous machines [28,29].

Regarding the application of FRA technique to rotary machines, some authors have proposed using it for the characterization of

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Nomenclature

FRA	frequency response analysis	C_s	stator winding series capacitance
C	series capacitance	L_s	stator voltage series inductance
L	series inductance	C_{g3}	stator winding capacitance to stator core
C_p	shunt capacitance to ground	C_{g4}	stator winding capacitance to rotor core
V_1	input voltage (equipment injection)	$x0$	negative terminal of the field winding (0%)
V_2	output voltage (equipment measurement)	$x1$	connection tap (25% of the field winding)
H_{dB}	FRA gain [dB]	$x2$	connection tap (50% of the field winding)
Φ_o	FRA phase [deg]	$x3$	connection tap (75% of the field winding)
n	number of "pi" equivalents	$x4$	positive terminal of the field winding (100%)
C_f	field winding series capacitance	C_g	shunt capacitance to ground ($C_{g1} + C_{g2}$)
L_f	field voltage series inductance	R_f	fault resistance
C_{g1}	field winding capacitance to rotor core	α	rotor position angle
C_{g2}	field winding capacitance to stator core		

synchronous machine stator windings according to the insulation type [30]. Current studies describe the possibility of detecting or even locating faults in synchronous machine stator windings using this technique [31]. The interest in the application of FRA to the fault detection in field winding is due to the following advantages; first, both ground faults and turn-to-turn faults may be detected, just as in power transformers. Second, the FRA technique may be applied while the rotor is turning at full speed (but unexcited). In this way the faults that occur while spinning due to the centrifugal forces may also be detected. Faults produced by temperature effect may also be detected at rated field winding temperature using this test after the disconnection of the rotor excitation at rated speed. There are other methods included in [32], as pole drop test, which can only be performed at standstill, or impedance test, which does not provide so much information as it is carried out at a fixed frequency.

Therefore, in this work the applicability of FRA to the fault detection in synchronous machines is evaluated. Firstly, the influence of the rotor position in the frequency response of the rotor and stator winding is analyzed. Secondly, the results of detection of ground faults and inter-turn faults in the field winding at standstill operating condition are described. Then, the frequency response of the field winding at healthy condition, while rotating, is presented and proposed as reference test. Finally, the detection of ground faults and inter-turn faults in the field winding while rotating is evaluated.

FRA operating principle

It is well known that transformer windings can be represented as an equivalent circuit, composed by n "pi" equivalents with resistances, inductances and capacitors, in series or parallel connection [8], as shown in Fig. 1. Where $L \cdot n$ is the leakage inductance, C/n the series capacitance, $C_p \cdot 2n$ the shunt capacitance and Z is the equipment impedance (typically 50 Ω for FRA equipment metering stage).

The FRA technique is based on the application of an input sinusoidal voltage signal (V_1) of variable frequency to any of the terminals of the winding, and the measurement of the voltage in the free terminal (V_2). The gain of the frequency response is obtained using (1). This gain is commonly expressed in dB units (2). The phase diagram is obtained by applying (3).

The FRA equipment used in this work, is an Omicron FRAnalyzer, whose data is shown in Table 1.

$$\vec{H}(j\omega) = \frac{\vec{V}_2}{\vec{V}_1} \quad (1)$$

$$H_{dB} = 20 \cdot \log_{10} |\vec{H}(j\omega)| \quad (2)$$

$$\Phi_o = \frac{180}{\pi} \cdot \arg(\vec{H}(j\omega)) \quad (3)$$

The Omicron equipment generates a sinusoidal 2.88 V_{pp} signal, whose frequency grows from 10 Hz to 20 MHz. This input signal (V_1) is applied to the terminal A of the winding, and the output voltage (V_2) signal is measured by the same equipment at the terminal B (Fig. 1). A computer, connected to the FRA equipment, registers the frequency response.

Theoretical approach of FRA applied to synchronous machines

A rotary machine represents particular conditions for the application of FRA to its windings, because although the stator winding is static, the field winding is rotating during normal operation. In Fig. 2 the stator winding and the field winding of a salient-pole synchronous generator are represented while rotating. Each pole is in different location as position angle α changes. This fact makes that the frequency response of stator and rotor windings are affected in a different way.

First of all, the field winding can be studied as a distributed circuit composed by n "pi" equivalents in series connection (see Fig. 3), where $L_f \cdot n$ is the leakage inductance, C_f/n the series capacitance, $C_{g1} \cdot 2n$ is the capacitance to the rotor core, which is normally connected to ground in the shaft at the drive end of the machine. $C_{g2} \cdot 2n$ represents the capacitance to the stator core, which is grounded as well.

On the other hand, the equivalent circuit of the stator winding is composed again by n "pi" equivalents in series connection (see Fig. 4), where $L_s \cdot n$ is the leakage inductance, C_s/n the series capacitance, $C_{g3} \cdot 2n$ is the capacitance to the stator core. $C_{g4} \cdot 2n$ represents the capacitance to the rotor core.

Due to the geometry of the system, the parameters of each equivalent vary differently while rotating. The machine is considered at full speed, the field winding unexcited and the stator winding with no current.

Fig. 1. Schematic quadrupole representation of any winding of a power transformer during FRA test.

Table 1

Characteristics of FRA equipment used in the experiment.

Frequency range	10 Hz–20 MHz
FRA method	Sweep frequency
Output impedance	50 Ω
Input impedance	50 Ω
Accuracy (down to –80 dB)	<0.1 dB
Accuracy (down to –100 dB)	<0.3 dB

In the case of the stator winding, while the value of L_s , C_s and C_{g3} remain constant, the capacitance to the rotor core (C_{g4}) vary as the poles is rotating (Fig. 2).

In the case of the rotor winding, the situation is different. While rotating, the values of the field winding parameters are different than the value in standstill condition, because of the effect of the centrifugal forces. However, they are constant, which make the frequency response repeatable. Finally, the value of C_{g2} will have an average value constant while rotating, as the field winding “sees” each instant the same stator winding due to the geometry of the system (Fig. 2).

FRA results assessment

The frequency response of a new winding is unique, so it can be used as a fingerprint of this winding. And it is considered as the reference test. Comparing to this reference test, the faults or displacements in the winding can be detected. The physical explanation is the change of winding impedance at several frequencies when a fault or an incipient fault occurs.

One of the main advantages of the FRA technique is that knowing the equivalent circuit that represents the winding under test is not necessary, due to its comparison principle.

In power transformers, where a lot of experience in FRA test is accumulated nowadays, it is possible to distinguish the different defaults just by the frequency range where the changes between the frequency response and the reference test are detected [4].

Standstill FRA test synchronous machine rotor winding with static excitation

This section presents some results of FRA test in a static excited synchronous machine at standstill conditions.

Experimental setup

The tests have been performed in a laboratory 4 salient-pole 5 kVA 400 V synchronous machine (Fig. 5). The technical data of this machine are listed in Table 2, in the Appendix. The field winding of the aforementioned machine was specially manufactured in order to have three taps available, corresponding to the inter-pole connection.

In Fig. 5, a schematic of the described field winding is shown, where the taps x1, x2 and x3 correspond to the 25%, 50% and 75%

Fig. 3. Quadripole representation of the field winding of a synchronous machine during FRA test.

of the field winding. In this figure, the experimental setup is shown.

Influence of rotor position

In case of salient-pole synchronous machines, the position of the rotor is a parameter that must be taken into account when testing stator windings [14]. This phenomenon causes the frequency response of the stator windings to be different depending on the rotor position angle (see Fig. 6). Since this technique is based on the qualitative comparison of the present FRA test of the field winding, and the reference test, knowing the influence of the rotor position in the field winding frequency response is a primary concern.

The first test is considered the reference response and, after that, six tests were conducted at different rotor angles (0–360° electrical degrees). Once all the results were registered, the frequency responses were represented in the same plot, and there was found to be no difference between them (Fig. 7). This phenomenon allows concluding that the rotor position has no effect on the FRA of the field winding as expected.

In conclusion, the rotor position has an influence on the frequency response of the stator windings, but not on the results of the FRA tests of the rotor windings. For this reason the diagnosis of salient-pole synchronous machines through FRA technique can be performed while rotating in the field winding, but it is not possible in the stator winding. As described, testing the field winding while turning is a great advantage since the defects that only appear in this operating condition may be detected.

Ground fault detection

If an insulation failure occurs at any point of the winding, the equivalent resistant from this point to ground decreases. The equivalent circuit changes and the frequency response become different than the reference test. Therefore, in order to test the detectability of the ground faults by using FRA technique in field windings, several values of fault resistance were connected to the

Fig. 2. Schematic representation of the field winding and the stator winding of a salient-pole synchronous machine.

Fig. 4. Quadripole representation of the stator winding of a synchronous machine during FRA test.

taps x0 to x4. In Fig. 8(a), a ground fault in tap x1 is represented as an example, for the salient-pole synchronous generator under test, where $4 \cdot L_f$ is the leakage inductance, $C_f/4$ is the series capacitance, and $8 \cdot C_g$ is the addition of $8 \cdot C_{g1}$ and $8 \cdot C_{g2}$. In this case, the equivalent circuit is modified, since the fault resistance divide the

winding into two parts, with different values of equivalent parameters. Depending of the value of the fault resistance, the frequency response will be different, where the most detectable case is the solid ground fault ($R_F = 0 \Omega$).

Once again, a large number of tests were conducted in order to ensure the veracity and repeatability of the frequency responses.

- (1) *Zero-resistance ground faults:* The results of the zero-resistance ground fault on taps x1, x2 and x3 are compared to the reference test (Fig. 9). In the 10–100 kHz frequency interval, the frequency responses of each fault are identified. It is clear that because of the symmetry of the equivalent circuit in the cases of ground fault in tap x1 and tap x3, both responses are very similar. Ground faults can be clearly detected in both the gain diagram and the phase diagram.
- (2) *Variable resistance ground faults:* With the aim of verifying the detection of an incipient ground fault, different values of fault resistances were tested at each tap. The results of the ground fault in tap x1 with 1 Ω , 10 Ω and 100 Ω are

Fig. 5. FRA diagnosis for 5 kVA salient-pole laboratory synchronous machine field winding. Layout of the laboratory machine with taps in the field winding. (1: FRA test equipment, 2: synchronous machine, 3: prime mover).

Fig. 6. Results of standstill FRA of the stator winding at different rotor position (0–360° electrical degrees).

Fig. 7. Results of standstill FRA of the healthy field winding at six different rotor position (0–360° electrical degrees). Reference test.

Fig. 8. Equivalent circuit of the field winding for (a) ground fault in tap x1; (b) fault between taps x1 and x2.

compared to the reference test response and shown in Fig. 10. As observed, the effect of the resistance value has influence only in the low frequency range: the greater the value of the fault resistance is, the closer to the reference test the frequency response will be in this frequency range.

Turn-to-turn fault detection

In Fig. 8(b), a fault between tap x1 and x2 is shown as an example. This defect modifies the equivalent circuit and makes the frequency response to be different to the reference test. In this case the defect divides the field winding in three parts, as observed in the mentioned figure.

Several tests were conducted using the three taps and the two brushes available in the described synchronous machine.

- (1) *Zero-resistance turn-to-turn faults:* Turn-to-turn faults were tested using the four possible combinations, which represent a short-circuit on 25% of the winding turns. A great number of tests of each fault were conducted in order to ensure the repeatability of the results. The test results of the four fault types were compared to the reference test and these are presented in Fig. 11. The frequency response in case of fault is quite different from the reference test result. As expected the frequency responses of Fault x0–x1 and Fault x3–x4 are quite similar, because of the symmetry of the equivalent winding during both faults. The same conclusion can be made from the results of Fault x1–x2 and Fault x2–x3. Every fault can be clearly detected in the frequency range close to the absolute minimum gain frequency.
- (2) *Variable resistance turn-to-turn faults:* Additional fault tests were conducted to test the sensibility of the detection to the fault resistance value. Different resistance values were used in the case of a fault between taps x1 and x2. The results of faults with 1 Ω , 10 Ω and 100 Ω were compared to the reference test response (Fig. 12). As shown, the effect of fault resistance is significant only in the low frequency zone, where the offset between the fault response and reference response disappears as the resistance value grows.

Although turn-to-turn faults which involve so many turns do not occur in real generators, the constructive setup of the laboratory synchronous machine only allows performing faults between taps. However the result of the tests shown that the inter-turn defects can be clearly detected using FRA technique. In further studies, FRA technique should be tested on a high power generator in which, turn-to-turn faults corresponding to smaller portion of the winding can be performed.

Fig. 9. Result of standstill FRA for different ground zero resistance faults.

Fig. 10. Result of standstill FRA of ground fault in x1 for different fault resistance values.

Full speed FRA test in rotor winding of synchronous machine with static excitation in unexcited operating condition

This section presents the results of FRA diagnosis in rotor windings of a synchronous machine with static excitation while rotating. As aforementioned, the application of this fault detection method while the rotor is turning may be quite interesting for industry in order to detect faults that occur only when the rotor is rotating, because of the effect of the centrifugal forces.

Other important advantage is that this test can be performed with the rotor at rated temperature, which is important to detect some defaults that are caused by the thermal stress. The results of

this section extend the application of FRA diagnosis to synchronous machine rotor windings, which are rotating but not excited.

Experimental setup

The salient-pole synchronous machine under test was the same special manufactured rotary machine used in the standstill tests. For these tests, the rotor of the machine was rotated at its rated speed, driven by an asynchronous machine coupled in the same shaft. FRA equipment was connected to the field winding by the same procedure as in the previous tests. The excitation system should be disconnected, by opening the generator field breaker.

Fig. 11. Result of standstill FRA for different turn-to-turn zero resistance faults.

Fig. 12. Result of standstill FRA for inter-turn fault between x1-x2 for different fault resistance values.

In these conditions, zero-resistance faults and variable resistance inter-turn and ground faults were tested.

Influence of rotor speed

As described previously, the field winding equivalent circuit presents frequency response, which is not affected by the rotor position. However, when the field winding is turning, the centrifugal forces cause small changes in the physical disposition of the winding. This fact changes the value of the parameters of the equivalent circuit.

Nonetheless, the new equivalent circuit is constant while rotating, and this allows having an exactly repeatable frequency response, which is considered the reference test in this operating condition.

In Fig. 13, the standstill reference test (Ref) is compared to the frequency response at several rotating speeds: 500, 750, 1000 and 1500 rpm. As observed, even though the appearance of the noise in the low-frequency range, the reference profile at different rotation speeds are similar. Therefore, while rotating, the frequency responses of the field winding must be compared to the reference frequency response obtained from the healthy machine at full speed, "Ref_fs" (Fig. 13(d)).

Full speed ground fault detection

Zero resistance ground faults and variable resistance ground faults were tested using taps x1, x2 and x3 of the field winding. Once more, a large amount of tests of each fault were conducted in order to ensure the repeatability of the frequency responses.

Fig. 13. Comparison of static reference test (Ref) and the reference test while rotating at different speeds; (a) 500 rpm (Ref_500 rpm); (b) 750 rpm (Ref_750 rpm); (c) 1000 rpm (Ref_1000 rpm); (d) 1500 rpm (Ref_fs).

Fig. 14. FRA results for different zero resistance ground faults at full speed conditions.

- (1) *Zero-resistance ground faults:* Results of the zero resistance ground faults were conducted using taps x1, x2 and x3, and compared to the rotating reference test (Fig. 14). In the aforementioned figure the responses of each fault are identified. It can be seen that in this case there is no offset between the responses in the low frequency range, but the results nevertheless show that the fault can be clearly detected.
- (2) *Variable resistance ground faults:* The effect of the resistance value has been tested. Responses of the ground fault in tap x1 with 0 Ω , 10 Ω , 1000 Ω and 5600 Ω are compared

(Fig. 15). As shown, the resistance value has again an influence only in the 10–100 kHz frequency range, and the defaults are easily detected.

Full speed turn-to-turn fault detection

Turn-to-turn tests were conducted while rotating using the five taps available. Once more, zero resistance faults and variable resistance faults were tested.

Fig. 15. FRA results for different ground fault resistances fault in tap x1 at full speed conditions.

Fig. 16. FRA results for different turn-to-turn zero resistance faults at full speed conditions.

(1) *Zero-Resistance Turn-to-Turn Faults*: The results of the zero-resistance inter-turn fault using taps x1, x2 and x3 are compared to the rotating reference test response (Fig. 16). In the 10–100 kHz frequency interval, the frequency responses of each test are identified. In both the low frequency range and the minimum response frequency zone, the fault can be clearly detected. It is remarkable that both fault responses are very similar because of the symmetry of the equivalent circuits that remains during both faults.

Despite the fact of the rotor speed, this method is useful to detect turn-to-turn faults.

(2) *Variable Resistance Turn-to-Turn Faults*: In order to verify that faults can be detected for different values of resistance, more tests have been carried out. The results of the fault x1–x2, with 0.2 Ω, 1 Ω, 10 Ω and 800 Ω, are compared (Fig. 17). As presented, the resistance value has influence only in the low frequency range, but has no influence on a wide range of resistance values in the 10–100 kHz frequency interval.

Fig. 17. FRA results in x1-x2 fault case for different fault resistance values at full speed conditions.

Table 2
Characteristics of synchronous machine used in the experiment.

Rated apparent power	5 kVA
Rated voltage ($\pm 5\%$)	400 V
Frequency	50 Hz
Pole pairs	2
Rated speed	1500 rpm
Rated power factor	0.8
Number of slots	36
Stator winding turns per pole and phase	63
Parallel branches	1
Rotor turns per pole	490
Excitation system resistance	11.03 Ω
Excitation system inductance	248.3 mH

So, despite the resistance value is not easy to distinguish, inter-turn faults may be plainly detected.

Conclusions

In this paper, the Frequency Response Analysis technique is evaluated for the diagnosis of the field winding of synchronous machines. A great number of tests have been performed in the field winding of a laboratory salient-pole synchronous machine at standstill and at different speeds. In these tests turn to turn and ground faults with several fault resistances have been performed and compared to the reference test (healthy condition).

The main contributions of this work are described as follows.

First, the frequency response of the field winding while rotating is repeatable and it does not depend on the rotor position. The test result under healthy condition can be used as a reference test.

Second, the frequency responses of the field winding while rotating and in standstill condition are different due to the fact that the equivalent winding impedance changes because of the centrifugal forces. This fact does not reduce the applicability of this method as the test result while turning is exactly repeatable.

Third, ground faults and inter-turn faults have a significant influence on the FRA test results. So they may be detected in both standstill and rotating operating conditions by comparison to the reference test.

Finally, although the results presented in this paper are the first approach, they provide promising expectation to the use of this method as a diagnosis tools for synchronous machines. As in the case of power transformers, in the future after lots of tests with extensive experience, the FRA test could be used to detect and even to locate turn to turn and ground fault in rotating electrical machines and specially in field windings.

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Appendix A

See Table 2.

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