Electrical Power and Energy Systems 73 (2015) 229–239

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

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

F.R. Blánquez, C.A. Platero *, E. Rebollo, F. Blázquez

Department of Electrical Engineering, ETSI Industriales, Universidad Politécnica de Madrid, C/José Gutiérrez Abascal, 2, 28006 Madrid, Spain

ARTICLE INFO

Article history:
Received 3 August 2014
Received in revised form 4 May 2015
Accepted 5 May 2015
Available online 19 May 2015

Keywords:
Frequency response analysis
Impedance measurement
Fault diagnosis
Fault detection
Rotating machines
Generators

ABSTRACT

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.

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

* Corresponding author. Tel.: +34 91 336 31 29; fax: +34 91 336 30 08.
E-mail address: carlosantonio.platero@upm.es (C.A. Platero).

http://dx.doi.org/10.1016/j.ijepes.2015.05.005
0142-0615/

Nomenclature

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

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 FRAnalizer, whose data is shown in Table 1.

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

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

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

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.

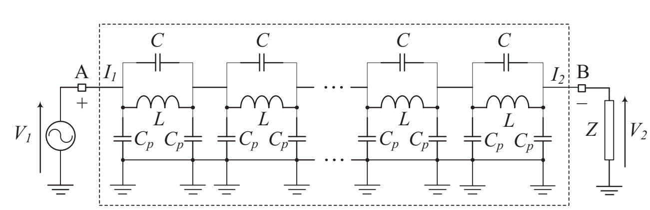

Fig. 1. Schematic quadripole representation of any winding of a power transformer during FRA test.