Electric Power Systems Research 133 (2016) 71–78

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Influence of rotor position on the repeatability of frequency response analysis measurements on rotating machines and a statistical approach for more meaningful diagnostics

Wilson Cesar Sant'Ana[a,b,*], Germano Lambert-Torres[b], Luiz Eduardo Borges da Silva[a], Erik Leandro Bonaldi[b], Levy Ely de Lacerda de Oliveira[b], Camila Paes Salomon[a,b], Jonas Guedes Borges da Silva[a,b]

[a] Universidade Federal de Itajuba, Av. BPS, 1303, Itajuba, MG 37500-903, Brazil
[b] Instituto Gnarus, rua Cel, Francisco Braz, 185, sl. 307, Itajuba, MG 37500-052, Brazil

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 13 October 2015
Accepted 28 November 2015
Available online 5 January 2016

Keywords:
AC machines
Condition monitoring
Frequency response analysis
Rotating machine insulation testing

ABSTRACT

This work presents an investigation on the influence of rotor position on the Frequency Response Analysis (FRA) of electric machines. Different types of machines have been analyzed. Contrary to common belief, not only the salient-pole machine suffered from rotor position influence on the FRA. This can have severe impact on the repeatability of the tests and, consequently, their ability to identify early damage in the insulation system of the machine. This paper is intended to warn practitioners of FRA that care should be taken while analyzing the results, in order to avoid false positives in their measurements. Recommendations are made aiming to avoid the influence of rotor position on the results. Also, the use of statistical techniques is proposed, in order to improve the diagnosis, even when there is some lack of repeatability.

1. Introduction

Early fault detection and diagnosis of AC electrical machines have been gaining increasing importance due to the criticality that these equipment represents to the industries and to the electrical power system. When faults are identified in an incipient stage, maintenance actions can be performed in a timely basis, avoiding breakdowns and the consequential losses. Among the common faults on AC machines, stator winding insulation failures are of particular importance. These failures are responsible for a great part of AC machines breakdowns and can severely compromise the machine life span. An international survey carried out by CIGRE [1,2] shows that 56% of hydro-generator failures were caused by insulation damage. Concerning induction motors, this rate of failure drops to something between 26% and 40% [3,4]. A complete list of conventional diagnostics for insulation failures (including guidelines) is found in [5]. Recently, a lot of research has been being done on on-line methods (that do not require the machine to be shutdown to perform the diagnosis), such as MCSA (Motor Current Signature Analysis) and ZSVC (Zero-Sequence Voltage Component) [6,7]. According to US patents [8] and [9], conventional insulation assessment methods are not able to detect early insulation failures. The argument presented in [8] and [9] is that conventional methods can only detect if a failure is already installed or not, but are not able to inform if a failure is developing. These patents propose the injection of high frequency into the stator winding of the machine and the computation of the machine's impedance spectrum. The evolution of some characteristics in the spectrum (when compared with historical data) indicates the onset of a failure. Perisse et al. [10] also use high frequency injection and impedance spectrum analysis (with focus on changes in the winding capacitance) to evaluate turn-to-turn insulation of an AC machine. A very similar technique to those proposed in [8,9] and [10], known as Frequency Response Analysis – FRA, has been widely used for diagnostics of transformers [11]. All these techniques [8–11] rely on comparisons of a given spectrum with its historical data. Thus, good repeatability on the measurements is essential for an accurate diagnostic.

Studies reported in Reykherdt and Davydov [12] and Bagheri et al. [13] show that temperature and moisture content have some influence on the repeatability of FRA results on transformers. Specifically to rotating machines, there is also another factor that can lead to an inaccurate diagnostic: the angular position of the rotor of the machine. To avoid the rotor influence on FRA

* Corresponding author at: Universidade Federal de Itajuba, Av. BPS, 1303, Itajuba, MG 37500-903, Brazil. Tel.: +55 35984511211.
E-mail address: wilson_santana@ieee.org (W.C. Sant'Ana).

http://dx.doi.org/10.1016/j.epsr.2015.11.044
0378-7796/

measurements of hydrogenerators, Lamarre and Picher [14] performed their tests with rotors removed. Also Florkowski and Furgal [15] applied FRA to detect insulation failures on an induction motor and, again, the tests were performed without the rotor (although the reason is not explicit in the text). Platero et al. [16] explicitly discussed about the influence of rotor position on FRA measurements on salient-pole synchronous machines. According to [16], the measurements are dependent on the ratio between the air and the iron and vary depending on the position of the poles. Also according to [16], squirrel-cage machines would not suffer influence of rotor position, as they have a constant air gap. However, this current work shows that this is not always true.

This current work has analyzed FRA results of three different machines of different construction types: a salient-rotor synchronous machine, a round-rotor synchronous machine and a squirrel-cage induction machine. It is shown that, contrary to common belief, not only the salient pole machines suffer influence of rotor position. This can have severe impact on the interpretation of FRA results and its use on early detection of insulation problems. It is also shown that the rotor position only influences the inductive regions of the spectra.

The first contribution of this work is to warn practitioners of FRA on rotating machines that care should be taken while analyzing the results in order to avoid false positives/negatives. The second contribution is the proposal of the use of statistical indexes in order to obtain a more meaningful diagnosis on the machine condition, even when there are variations in the measurements.

Section 2 presents an overview of the FRA technique. Section 3 discusses the influence of rotor position on FRA measurements. Section 4 proposes a statistical approach to mitigate the rotor position influence on the measurements. Section 5 presents the experimental results, confirming that the use of statistical techniques can improve the diagnostics.

2. Frequency response analysis (FRA) method

Ryder [17] presented a didactic description of the FRA method. Basically, it consists in the injection of a high frequency signal at the machine windings and the calculation of the winding impedance over a wide range of frequencies. The resulting impedance spectrum is, then, compared against a reference set (called baseline – which is a previous known condition of the machine). Differences between the spectra can indicate problems with the machine, either electrical or mechanical.

This technique has been widely used on transformers and its application is standardized through IEEE standard C57.149-2012 [11]. Recently Pramanik and Satish [18] proposed a modification on the concept of resonance that is used on this standard.

Based on the pattern of the deviation from the baseline, a specialist is able to identify several types of failures. IEEE standard C57.149-2012 [11] and Abu-Siada et al. [19] listed some of the failures that can be identified using FRA on a transformer, based on the frequency region where the differences from the baseline are located. Modelling of failures is also very advanced in case of transformers – among these works it can be highlighted Florkowski and Furgal [20] and Lei et al. [21].

Concerning rotating machines, there is still no guideline to differentiate a specific failure from another. US patents [8] and [9] have identified four patterns of insulation failure (cut winding, moisture, percolation and thermal ionization) on rotating machines, but no scientific paper has been found in the literature confirming these patterns. According with Blanquez et al. [22], despite the advances of FRA in transformers, it is rarely used in rotating machines. Platero et al. [23] explained the reasons for this, refering to the stator division into slots and the existence of a rotor winding. The reported influence of rotor on the measurements is analyzed in Section 3 of this current paper and a mitigation method is proposed in Section 4.

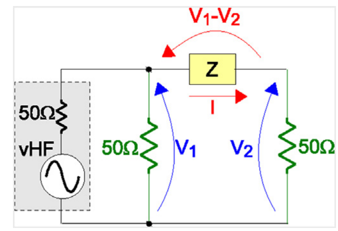

Fig. 1. Measurement circuit of gain/phase analyzer.

2.1. FRA classification according to type of signal injection

Basically, there are two types of FRA tests, that differ on the way the high frequency signal is injected on the windings:

- Impulse-FRA (IFRA): injects a broadband pulse signal and the spectra are calculated via FFT (Fast Fourier Transform) [24].
- Sweep-FRA (SFRA): injects sinusoidal signals of variable frequencies and the spectra is calculated directly, with no further signal processing [24].

According with [17], the advantage of IFRA over SFRA is the shorter measurement time; however SFRA is preferred because of its better signal to noise ratio, equal accuracy on the whole measurement range and the wider range of frequencies that are injected. The results presented in this current paper are obtained by using the SFRA method.

2.2. FRA classification according to measurement circuit

Lamarre and Picher [14] listed two measurement circuits that are used to obtain an impedance spectrum:

- gain/phase analyzer (Fig. 1): used in commercial FRA equipment. The output impedance and input channels impedance are 50Ω to match the coaxial cables characteristic impedance and avoid reflected waves. Usually, the spectrum obtained with these kind of equipment is in the form of a gain (in dB) over frequency, according to Eq. (1). This is the form of spectra that appear in [11–13,16,17,19] and [24]. To obtain a impedance spectrum with the circuit of Fig. 1, Eq. (2) has to be applied. This form of spectrum appears in [14].

$$H_{\mathrm{dB}} = 20 \cdot \log_{10}\left|\frac{\vec{V}_2}{\vec{V}_1}\right| \tag{1}$$

$$\vec{Z} = \frac{\vec{V}_1 - \vec{V}_2}{\vec{I}} = \frac{\vec{V}_1 - \vec{V}_2}{\vec{V}_2/50} = \frac{50}{\vec{V}_2/\vec{V}_1} - 50 \tag{2}$$

- impedance analyzer (Fig. 2): used in general purpose impedance analyzers. The input impedances of channels V_1 and V_2 are usually very high (in case of the prototype described in Section 5.1, 1MΩ) in relation to the impedances connected in parallel to them, thus they can be disconsidered in Fig. 2. Eq. (3) gives the impedance spectrum obtained with this circuit. This is the form of spectra that appear in [8–10] and [14] and is the form adopted in this current work.

$$\vec{Z} = \frac{\vec{V}_2}{\vec{I}} = \frac{\vec{V}_2}{\frac{\vec{V}_1 - \vec{V}_2}{R_{sh}}} = R_{sh} \cdot \frac{\vec{V}_2}{\vec{V}_1 - \vec{V}_2} \tag{3}$$