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Online SFRA characterization of a batch of induction motors for predictive maintenance.

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***Abstract* – Asynchronous motors represent a large percentage of motors used in industry. Implementing predictive maintenance techniques can be justified in the case of engines that are of critical importance in the processes despite being of low cost. In these cases, the continuous monitoring of the motors requires non-invasive and online techniques, which allow the monitoring of motor characteristics over time to highlight potential trends that tend toward the condition of catastrophic failure. Online SFRA may be of interest in this scenario. In this article, this technique has been applied to a set of new asynchronous motors. They have been characterized under different load conditions. The results were used to determine transfer functions (TFs) with which it is possible to compare the TFs acquired by an engine to be monitored. The test system and the first experimental results are presented.**

I. INTRODUCTION

The role of electric motors in the industrial sector is increasingly central if we consider the current increase in the use of electric systems for efficiency and the development of intelligent systems. Although the purchase cost of mains-powered asynchronous motors is low compared to the cost of the energy they consume during their life, it is nevertheless of interest to investigate their state of health during normal operating conditions [1-5]. It is possible to use online techniques based on the injection of test signals on the stator windings and carry out the frequency response processing, with different methodologies as, for example, the online SFRA (Sweep Frequency Response Analysis). It can avoid the costly and challenging decommissioning of motors that can power complex and critical processes [6-9].

These techniques have numerous advantages, including the low cost of the measuring equipment; however, these techniques are based on evaluating the variations of the characteristic curves of an engine. These variations can occur over time due to normal aging and wear or as an initial symptom of impending failures as a result of conditions such as overload, bearing damage, and the effects of improperly performed maintenance.

Therefore, it is necessary to acquire information on a sufficient number of new motors in different operating conditions to identify reference curves for the processing of deviations and identify normal operating conditions from that symptom of a possible initial failure.

For this purpose, ten new induction motors were acquired from the same production batch and were connected to a dynamometer for nominal and variable load tests. The characteristics were achieved with a mains power supply, without the interposition of transformers or other systems, to reproduce the normal operating conditions of mains-powered asynchronous motors. Moreover, the dynamometer itself is of the passive type, without energy recovery, so as not to disturb the power supply network during the tests.

II. THE TESTING SYSTEM

The measurement technique used is the SFRA[10], in online mode. SFRA is based on injecting a sinusoidal signal with a typical amplitude of a few volts, with frequencies ranging from a few Hz to 2 MHz, between the two terminals of an electrical winding, both in rotating electrical machines in transformers. The traditional SFRA is used on non-powered devices, which requires them to be put out of service; for online monitoring, it is necessary to carry out measurements without interruption of operation and without the stimulus signals interfering with the normal functioning of the equipment.

Previous works [10-12] have carried out various experimental measurement campaigns on different devices, and ad hoc systems have been developed for standard SFRA and online.

The SFRA online was developed for this need, with the adoption of coupling filters with the electrical network, suitably designed to operate as a band-pass in the 2 kHz - 1.5 MHz range to stop the fundamental component at 50. Hz and voltage harmonics up to the 40^{th} and allow the application of the stimulus signal.

The SFRA signal generation and the acquisition were performed with the Digilent Analog Discovery 2 NI

Edition board with BNC Adapter [10], controlled by a PC running the testing software designed in the NI LabVIEW Environment. This device is a two-channel oscilloscope with differential inputs, 14-bit resolution, ±25 V input range, 30-MHz bandwidth, and 100 MSample/s sampling frequency, equipped with a two-channel arbitrary function generator with ±5 V output range, 20-MHz bandwidth, and 100 MSample/s sampling frequency.

The overall cost of the whole testing system, including the coupling filters and cables, is less than €400, to which the software development cost is to be added.

The measurement software has been developed to evolve the version proposed in [10], implemented in the NI LabVIEW environment. The S/N reduction was the most critical objective during the design of the proposed system due to the high electromagnetic noise generated by the motor under test, which can lead to different SFRA measurement problems.

The measurement procedure is based on the following steps: 1) simultaneous acquisition of input Vin and output Vout signals; 2) application of Hanning window to both the signals; 3) Fast Fourier Transform (FFT) processing of Vin and identification of its amplitude and frequency (bin position) in the spectrum; and iv) FFT processing of Vout and the identification of the component having the same bin position of Vin.

The test bench used must reproduce the actual operating conditions of a mains-powered asynchronous motor, without an inverter, without energy recovery systems introducing disturbances on the power supply line that would make the test results unacceptable.

The load has been carried out adopting the Magtrol HD 815 hysteresis brake dynamometer equipped with a Magtrol TM 108 torque and speed transducer. In addition, the brake has been controlled with a Magtrol DSP 6001 unit that also performed the acquisition of torque and rotational speed (Figs. 1 and 2)

III. EXPERIMENTAL RESULTS

The experimental tests have been performed on a set of 10 new three-phase induction motors model BE 90 LA4 produced by Bonfiglioli; the rated features @50 Hz are the following: i) voltage 230/400 V Δ/Y, ii) current 6.1/3.5 A Δ/Y; iii) power 1.5 kW; iii) speed 1430 rpm; iv) power factor 0.74; v) efficiency 82.5% at 100% load, complying IE2 according to IEC EN 60034; vi) insulation class F, IP 55.

The motor under test can be considered parallel connected to the network, composed of cables, power transformer, and power mains; the input signal is applied to both the motor under test and the supply system.

Therefore, a diagnostic system must separate the effects of the motor from those external to it.

To this aim, we first applied the SFRA to the supply system with the motor circuit breaker open (Fig. 3).

The line-to-line terminals selected for further acquisitions are wu because of only one resonance peak in the range 800-1500 kHz.

In Fig. 4, the SFRA TF for motor #1, at various load percentages after 1 hour of full load service, are shown; no effects of the motors are appreciable below 100 kHz. Therefore, the following figures will refer to the band 100 kHz, 1.5 MHz. 5 TFs were acquired for each motor, for mechanical load varying from 100% to 0%, after one hour of operation at full load.

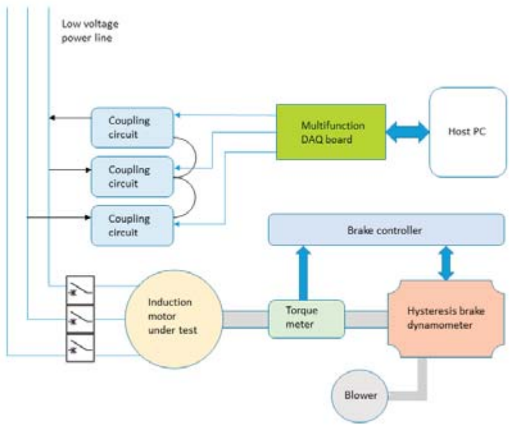

Fig.1 – Block diagram of the experimental setup

Fig. 2. The testing bench.

The reference curves have been processed by considering firstly. The definition of the reference curves was first performed considering the TFs corresponding to the same working point, and the envelope TFs in figures 5 to 9 were obtained. In each one, there are: i) the TF of the envelope of the maximum values, ii) the mean TF, iii) the envelope TF of the minimum values, iv) the TF obtained as the mean plus the standard deviation, v) the TF obtained as the mean minus the standard deviation. This choice allows for identifying different degrees of deviation of a subsequent experimental TF. For example, the standard deviation allows defining a region that includes 68 percent of all the data points around the mean TF. In Fig.10, the total reference TFs, obtained with the dataset of 50 acquisitions, are reported in the complete range of 3 kHz - 1500 kHz and in detail in the range of interest 100 - 1500 kHz. It is observed that below 100 kHz, the TFs remain almost similar, confirming that the effect of the presence of the motor is not relevant in this band.

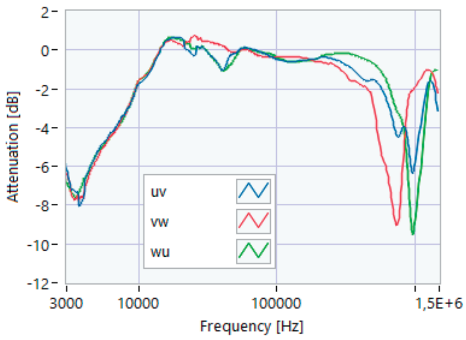

Fig.3 - SFRA online TF of the supply system only, measured on terminals line to line.

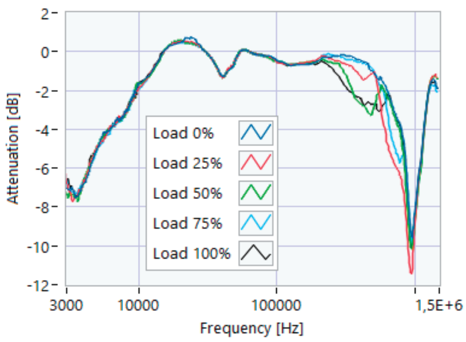

Fig.4 - SFRA online motor #1, at various load percentages after 1 hour of full load service.

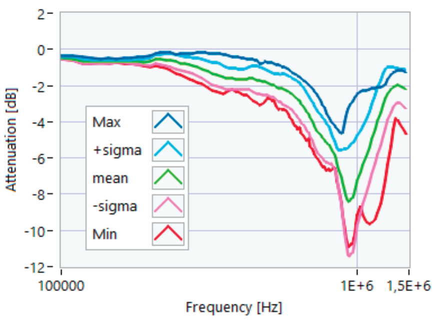

Fig. 5 - Reference TF processed at 0 % load

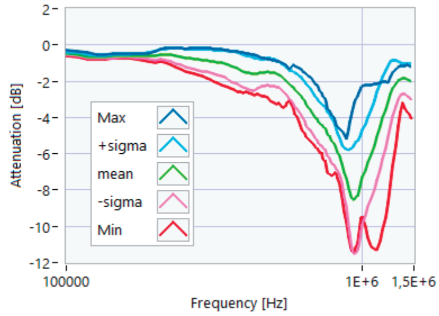

Fig. 6 - Reference TF processed at 25 % load

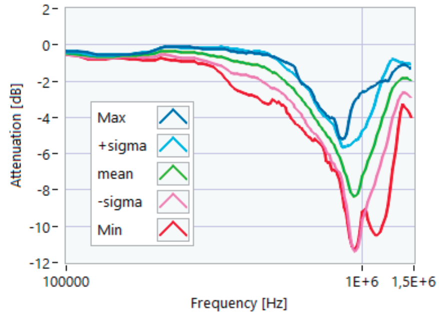

Fig. 7 - Reference TF processed at 50 % load

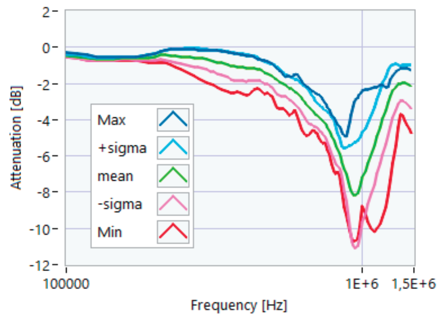

Fig. 8 - Reference TF processed at 75 % load

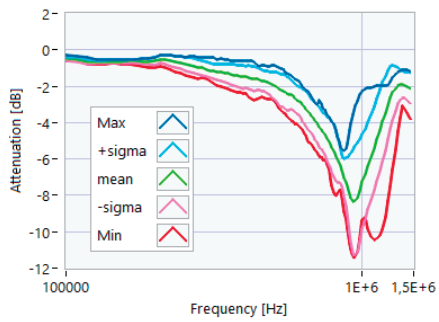

Fig. 9 - Reference TF processed at 100 % load

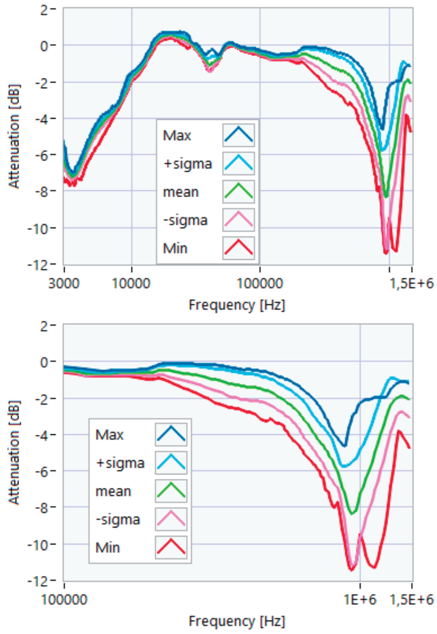

Fig. 8 – Overall reference TFs processed with the whole dataset

IV. DATA ANALYSIS: A PROPOSAL

The evaluation of the data obtained with the SFRA technique is usually carried out with a qualitative approach by displaying the reference TFs compared to the current TF, with the support of numerical indicators, which can be of a statistical type. It is generally possible to use the correlation methods on the whole extension of the TF and subsections deemed significant. In this article, two correlation indices have been considered; the first index is Pearson's correlation ρ:

$$\rho = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2}} \quad (1)$$

where n is the number of TF values, x_i and y_i are the values of the X and Y TFs (for ith sample). The Pearson's correlation is the most commonly used in the SFRA contest.

The second is Spearman's rank r correlation coefficient; it is helpful if the compared TFs make the Pearson's correlation coefficient undesirable or misleading. Spearman's correlation measures the strength and direction of monotonic association between the two TF, according to the equation:

$$r = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \quad (2)$$

where d_i is the difference in paired ranks and n = the number of values. Kendall's τ and other correlation coefficients have been neglected as they cannot provide further information than these two. The coefficient evaluation procedure is based on the qualitative observation that the motor effect is not significant for frequencies lower than 100 kHz. Therefore, it is possible to carry out correlation tests with ρ and r in the 3 -100 kHz band to mainly observe variations in the supply network impedance in the motor connection node.

The correlation test can start from the following observation: in the range 100 kHz - 1.5 MHz, there may be more resonance peaks; in the case of the motor considered, only one is present at about 950 kHz, if we consider the mean TF of the motors set. To use Spearman r correctly, monotonous, increasing, and decreasing sections of TF must be isolated. Therefore, an algorithm was implemented that can divide the TF into monotonous sections and then perform the calculation of the ρ and r coefficients in the identified sections. The appearance of additional peaks or the shift of the primary resonance peak is detected concurrently by ρ and r. Five reference TFs are available, respectively, envelope TF of the maxima, mean TF plus one standard deviation, mean TF, mean TF minus one standard deviation, and TF envelope TF of the minima. We suggest calculating the ρ and r of the TF acquired for all TFs, to identify the best similarity.

As a preliminary test, a reversible malfunction condition was implemented by inserting in series on one of the motors a power resistor of 1 ohm in series with one of the line conductors. According to the rated values of the motor, the average phase impedance is about 38 ohm; the inserted resistance involves a variation on a phase of 2.6% of impedance. The acquired TF is in black in Figs. 9 - 12; the correlation factors obtained compared with the reference TFS are in Tables 1-4.

The results in Table I refer to the whole frequency range 3 kHz-1.5 MHz; the correlation with all five curves is high, with higher values for both indices relative to the mean TF. In reality, the engine is apparently functioning normally, even if there is a fault in the connection. The correlation across the range does not seem capable of providing helpful information.

The results in Table II relate to the 3-100 kHz band; the correlation with all five curves is very high; therefore, there are no variations in the characteristics of the power supply network during the test.

Table III shows the correlation results in the frequency range lower than the resonant frequency at 950 kHz. A better correlation is observed with the envelope TF of the maxima, considering both the values of p and r. This may suggest an anomalous condition, even if within the limits of regular operation. Table IV shows the correlation values for the frequency range higher than the resonance peak. In this interval, the considered TF realigns itself with the mean TF.

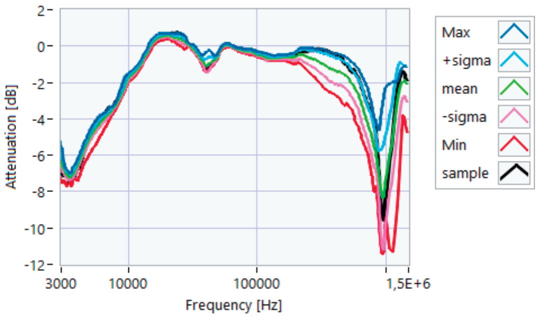

Fig. 9- TF of a motor with a 1-ohm resistance in series on a phase conductor: comparison with the reference TFs on the whole bandwidth

Table 1. Correlation factors on the whole TF range.

Reference TF	Pearson's ρ	Spearman r
Max	0.8863	0.9466
+ sigma	0.9619	0.9869
mean	0.9843	0.9883
-sigma	0.9699	0.9782
Min	0.9332	0.9592

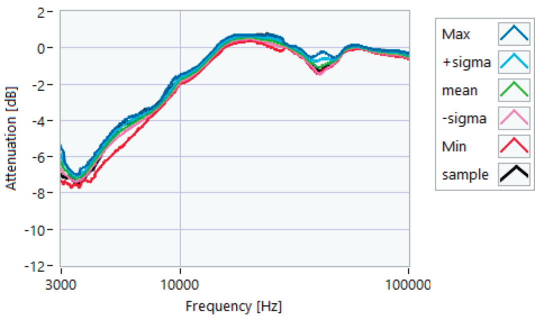

Fig. 10- TF of a motor with a 1-ohm resistance in series on a phase conductor: comparison with the reference TFs in the range 3-100 kHz

Table 2. Correlation factors in the range 3-100 kHz.

Reference TF	Pearson's ρ	Spearman r
Max	0.9443	0,9599
+ sigma	0.9820	0.9908
mean	0.9922	0.9971
-sigma	0.9964	0.9987
Min	0.9915	0.9968

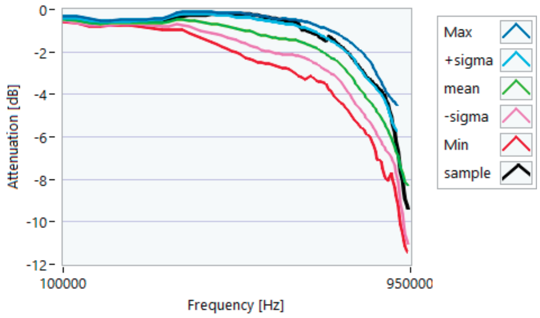

Fig. 11- TF of a motor with a 1-ohm resistance in series on a phase conductor: comparison with the reference TFs in the range 100-950 kHz

Table 2. Correlation factors in the range 100-950 kHz.

Reference TF	Pearson's ρ	Spearman r
Max	0.9885	0.9861
+ sigma	0.9947	0.9695
mean	0.9769	0.9146
-sigma	0.9772	0.8974
Min	0.9582	0.8939

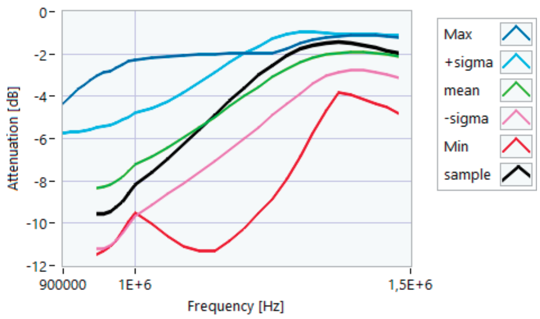

Fig. 10- TF of a motor with a 1-ohm resistance in series on a phase conductor: comparison with the reference TFs in the range 950-1500 kHz

Table 2. Correlation factors in the range 950-1500 kHz.

Reference TF	Pearson's ρ	Spearman r
Max	0.7771	0.8687
+ sigma	0.9795	0.8693
mean	0.9973	0.9795
-sigma	0.9914	0.9754
Min	0.8023	0.8544

V. CONCLUSIONS

In this article, the characterization of a batch of new asynchronous motors was carried out using the SFRA online technique. The goal is to identify a predictive diagnostic technique for mains-powered motors, capable of recognizing possible deviations from regular operation characteristics before catastrophic failures occur. With the aid of correlation indices determined in specific areas of the TFs, it is proposed to support the qualitative analysis of the TFs with data to be included in predictive diagnostic algorithms. In the future, reversible and non-reversible damages will be implemented on the same motors, and the new TFS will be compared with the reference TFs obtained.

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