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Evaluation of the voltage supply unbalance and detection of the short-circuit faults in induction machine through the neighboring magnetic field

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Abstract— This paper presents a new way to use magnetic field analysis for the detection of two electrical dissymmetries which appear in the asynchronous machine. The magnetic field is an interesting variable to exploit for the diagnosis of electrical machines because its measurement is easy, completely non-invasive, and uses inexpensive coil flux sensors. The advantage to use this variable is that it is more sensitive to electrical faults than to current or vibration. In the faulty case or voltage supply unbalance, a magnetic dissymmetry occurs which can be found in the external magnetic field measured near the electrical machine. The sensitive harmonics are extracted from the signals delivered by a pair of flux sensors placed around the machine and the data obtained from several positions are analyzed. The amplitude ratio and the correlation coefficient are the parameters used by the proposed diagnosis method. In practice, the user needs to detect whether there is a fault but also to know its origin. The originality of the proposed method is that can detect and classify the type of fault at the same time. The tests are applied for unbalance voltage and short-circuit faults. Obtained results show that the proposed approach makes it possible to detect and to determine the type of fault and for an easy analysis a graphic interpretation is proposed. Thus, the results presented in this paper pave the way to the better classification of different types of faults that appear in electrical machines and so to ensure safe operation in various technical processes.

Keywords— voltage supply unbalance, magnetic field, correlation coefficient, amplitude ratio, short circuit fault.

I. INTRODUCTION

The motors are used in numerous applications of industrial environments and are becoming more complex and technical, so it is not easy to maintain them at an optimal level of performance [1].

Electric motors encounter a wide range of mechanical problems common to most machines, such as unbalance, misalignment, bearing faults, and resonance [2-4]. Electrical problems that frequently affect industrial installations include voltage dips and spikes, harmonics, transients, voltage, and current imbalances. An unbalanced three-phase system can cause degradation of performance or premature failure of three-phase motors and shortens the life of three-phase motors. This unbalance can impose constraints on each of the phase circuits of a three-phase power system [5]. The unbalance creates an excess of current flow in one or more phases, then increases the operating temperatures, which leads

to the breaking of the insulation. These problems also occur due to short circuits.

Indeed, in electrical machines, as a result of the similarity of the symptoms that result due to these faults, it is difficult to classify the cause of the faults, whether it is due to the unbalance voltage of the source or a short circuit in the stator winding of the machine.

There are many works that study the problems of machines with imbalance [6] and have proven their effectiveness in diagnosing the faults generated by the unbalance of the source, as well as there, are many studies that diagnose the faults of machines resulting from electrical contact. For a decade have appeared new methods that use the external magnetic field measured near the electric machines for fault detection. The leakage field can provide information on the presence of a fault and sometimes its location. These methods are interesting for several reasons: they are completely non-invasive [7], [8] use inexpensive coil flux sensors, can be easily performed "on-line", implemented and the magnetic field is more sensitive to electrical faults than classical methods based on current or vibration measurement. So, monitoring devices based on the information provided by the magnetic flux produced by the imbalances in the magnetic or electrical circuit of the motors can be effectively used in addition to, or as an alternative to the current monitoring more conventionally used. Thus, recent methods used for the diagnosis of electrical machines are based on the analysis of combining measurements of current and magnetic flux, where, based on an evaluation of many tests, the stator current and the external leakage flux were selected as the most practical signals containing the information needed to detect broken bars and short circuit between turns of the stator winding [9], [10].

The proposed paper presents a new analysis method that performs measurements of the external magnetic field at several locations around the machine for the detection and classification of voltage unbalances and short circuit faults. This analysis method is based on two indicators called amplitude ratio (AR) and correlation coefficient (r) [11].

This paper is organized as follows. The second section recalls the case of voltage unbalances. The modeling of the faulty machine is discussed in the third section. The fourth section presents the measurement magnetic field. Extraction of indicators is introduced in the fifth section. Section VI

presents the analysis of results demonstrating the validity of the proposed method.

II. UNBALANCED VOLTAGE

When the voltages (or currents) have a difference in amplitude, there is an imbalance and this can cause problems for three-phase equipment connected to the network. A voltage unbalance can be highlighted by measurement of the voltage differences between the phases of a three-phase system. The voltage unbalanced has negative effects on the performance of three-phase induction motors such as higher losses, a higher temperature rise of the machine, reduction efficiency, and a reduction in developed torque. When there is an equality of the moduli of the three-phase voltages and of their relative phase shifts in a three-phase network the system is said to be symmetrical as shown in Fig.1. Otherwise, the three-phase network is called asymmetric or unbalance as shown in Fig.2. The motors manufactured by the companies' members of the National Electrical Manufacturers Association (NEMA) are designed to tolerate no more than 1% voltage imbalance [12]. As a rule, it should aim to keep voltage imbalance less than 1% and to not exceed 2% and it most important, refrain from operating a motor with a voltage unbalance above 5%. This should make sense as a 5% voltage unbalance equates to a 50% increase in temperature, so for a motor that typically operates above 100° C, this would result in a 150° C. This type of operation leads to overheating and consequently, to the degradation of the electrical insulation with reduced service life.

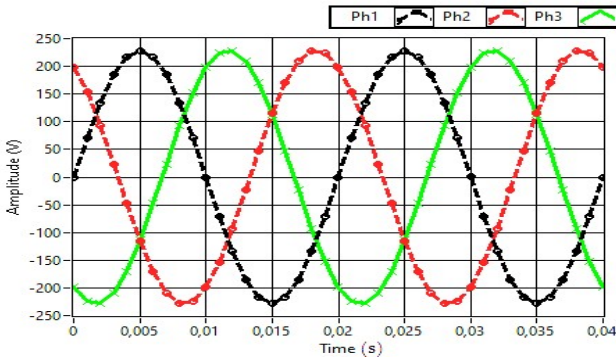


Fig. 1. Balanced voltage measured in the asynchronous machine

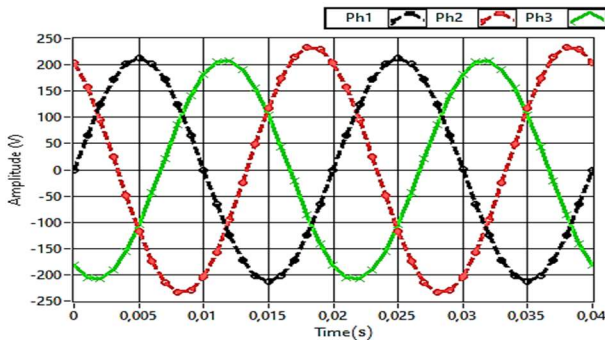


Fig. 2. Unbalanced voltage measured in asynchronous machine

Table I gives the measured values of voltage and current in a three-phase asynchronous machine operating under balanced and unbalanced conditions.

TABLE I VOLTAGE AND CURRENT VALUES FOR ASYNCHRONOUS MACHINE OPERATING UNDER BALANCED AND UNBALANCED CONDITIONS.

	V_{PH1} (V)	V_{PH2} (V)	V_{PH3} (V)	I_{PH1} (I)	I_{PH2} (I)	I_{PH3} (I)
balanced	228.5	229	228.5	4	4	4
unbalanced	213.9	234.5	209.6	3.57	5.44	3.14

From the measurement values presented in Table I, we can find the percentage of voltage imbalance using IEEE Standard 141-1993 [13]. The Line Voltage Unbalance in Percentage (LVUP) coefficient is defined by:

$$LVUP = \frac{\text{maximum deviation from average line voltage}}{\text{average line voltage magnitude}} * 100\% \quad (1)$$

Using (1) [14], we can calculate the ratios of the balanced and unbalanced voltage compared to the voltage source applied at the input of the machine. These ratios are shown in Table II.

TABLE II RATIO OF THE BALANCED AND UNBALANCED VOLTAGE

Supposed case	balanced	unbalanced
Average voltage (v)	228.67	219.33
Maximum deviation (v)	(229-228.67) = 0.33	(234.5-219.33) = 15.17
LVUP	0.14%	6.91%
The decision	balanced	unbalanced

For the considered test, in the second column of Table II, the voltage unbalance is equal to 0.14%, so according to the criterion (NEMA) as this value is less than 2% the voltage source is considered balanced. Measurement presented in the third column gives the voltage unbalance coefficient equal to 6.91%. Therefore, the voltage source is considered unbalanced.

III. MODELING OF A SHORT CIRCUIT FAULT

For modeling the faulty machine, we will consider a three-phase stator winding. It is supposed that 'y' turns from the n^s turns of an elementary section belonging to the phase q ($q=1,2,3$) are short-circuited. If 'y' is small compared with pn^s the total number of turns per phase, then it is possible to consider that the currents flowing in the three phases remain practically unchanged in faulty conditions. This hypothesis can, therefore, characterize the short circuit, thanks to a model that preserves the original structure of the machine. This model assumes that the stator winding in fault is equivalent to the healthy winding, associated with 'y' independent turns in which the short-circuit current flows. It will be assumed that these two circuits are independent. The healthy part of the winding generates, therefore, the same flux density components without fault. Fig. 3 shows the model considered for an elementary section with short-circuit turns in phase q of the machine.

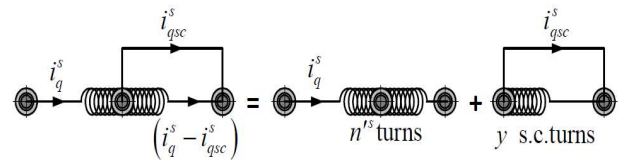


Fig. 3. Considered model for short-circuit fault in phase q of the machine.

In this model, the resulting airgap flux density b^* is equal to the initial airgap flux density b , to which is added the flux density b_{sc} generated by the 'y' turns flowing through by the current i_{qsc}^s : $b^* = b + b_{sc}$.

The flowing short-circuit current is defined by:

$$i_{qsc}^s = I_{SC} \sqrt{2} \cos(\omega t - \varphi_{sc}) \quad (2)$$

where φ_{sc} is the phase lag between the short-circuit current and phase 1.

This short-circuit model can explain the dissymmetry which appears in the magnetic field [7].

IV. MAGNETIC FIELD MEASUREMENT

For measurement two external flux sensors S1 and S2 are placed at 180° around the frame of the electric machine as shown in Fig.4. There are three different measuring positions P1, P2, and P3 used by the sensors around the machine. The emf signals provided by the sensors are acquired by the LABVIEW analyzer, which calculates the FFT of the signal and displays its spectrum.

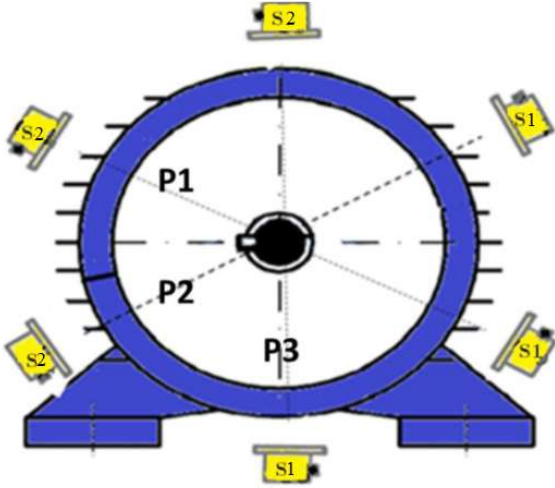


Fig. 4. Position of sensors placed around the asynchronous machine.

In a healthy case, the electromagnetic forces (emf) delivered by the sensors are identical to those illustrated in Fig. 5 which denotes the symmetry of the magnetic field around the machine. In this case, the harmonics are approximately the same amplitude on each side.

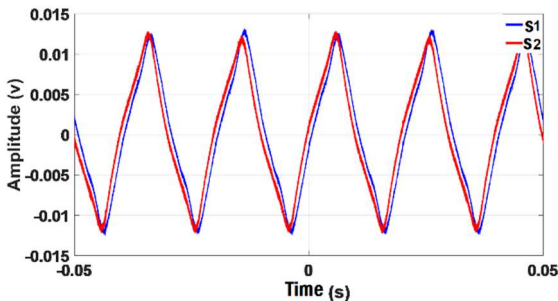


Fig. 5. Electromagnetic force measured for healthy machine

In a faulty case, the current i_{qsc}^s generate a new air-gap flux density which leads to magnetic asymmetry and to a difference between the two electromagnetic forces delivered

by the sensors as shown in Fig. 6 and therefore to an asymmetry between the corresponding harmonics.

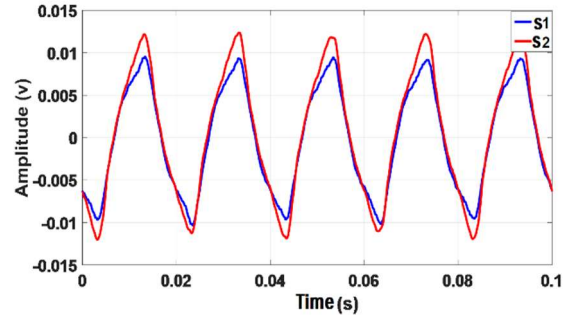


Fig. 6. Electromagnetic force measured in the case of short circuit fault.

V. EXTRACTION OF INDICATORS

Some diagnostic methods have been proposed to detect stator short circuits that rely on the fact that stator asymmetry causes an increase or a decrease in the amplitude of sensitive harmonics generated by the fault [15]. As a consequence, the amplitude of specific harmonics of the air-gap flux density, and thus of the external magnetic field, can be considered useful to obtain reliable results. We must specify here that the difficulty is not the measurement but the interpretation of the measured signals. In the proposed diagnosis model two specific parameters are used for analysis.

A. Ratio Amplitude RA

The ratio amplitude RA_i parameter gives the ratio between the amplitudes of the harmonics measurements $A_{S1,i}$ and $A_{S2,i}$ obtained, respectively, from sensors S1 and S2 in different positions i (with $i = 1, 2, 3$) around the machine. It is calculated by the following equation for different positions but also for different levels of load l with variation between 0 and rated value accepted by the machine:

$$RA_i = \min_{l:0 \rightarrow l_{max}} \frac{\min(A_{S1,i}, A_{S2,i})}{\max(A_{S1,i}, A_{S2,i})} \quad (3)$$

The values of ratio RA_i belong to $[0, 1]$. When RA_i is close to 1, it means that the two measurements are close.

B. Correlation coefficient r

The amplitudes of considered harmonics sensitive to faults are used as inputs to calculate the Pearson correlation coefficient r expressed by (4). These different amplitudes are noted $mes_{1,i}(k)$, and $mes_{2,i}(k)$ for different load conditions k and different sensors positions i .

$$r_i = \frac{\sum_{k=1}^n mes_{1,i}(k) mes_{2,i}(k) - \frac{\sum_{k=1}^n mes_{1,i}(k) \sum_{k=1}^n mes_{2,i}(k)}{n}}{\sqrt{\left(\sum_{k=1}^n mes_{1,i}(k)^2 - \frac{\left(\sum_{k=1}^n mes_{1,i}(k) \right)^2}{n} \right) \left(\sum_{k=1}^n mes_{2,i}(k)^2 - \frac{\left(\sum_{k=1}^n mes_{2,i}(k) \right)^2}{n} \right)}} \quad (4)$$

The following interpretation of the correlation coefficient is applied:

- If r_i is close to 0, it means that the amplitudes of the harmonics do not vary similarly and therefore there is no linear relationship between these variables.
- If r_i is close to -1, this indicates a strong negative

relationship between the variables. The relationship is negative because when one variable increases, the other variable decreases so the amplitudes of the field harmonics vary in opposite directions.

- On the contrary, when r_i is close to 1, it means that the two measurements evolve in the same way according to the variations of the load. This means that the machine may be in good condition, but we do not know for sure because we are not yet aware of other positions [16].

C. Calculation example

The following presentation exposes a calculation example for the proposed approach. For example, we take measurements obtained from the induction machine whose parameters are presented in Table III. Here the sensitive harmonics is the 17th harmonics corresponding to $f=850\text{Hz}$. The amplitude of measured harmonics obtained from sensors 1 and sensors 2 are the μV values and they change with the load condition. The machine can operate without load or under load conditions and for the test, the considered loads were chosen between 0 (without load), 600W, 1200W, 1800W, and 2400W.

The measurements of the amplitudes A_{S1} and A_{S2} for 5 loads given by sensors placed at 180° from each other around the machine are shown in Table III. In this example, the machine has three cases: healthy, voltage unbalanced, and short-circuit fault.

TABLE III. AMPLITUDE OF MEASURED HARMONICS ($f=850\text{ Hz}$) BY SENSORS S1 AND S2 FOR DIFFERENT LOAD LEVELS.

Loads (W)	healthy		unbalanced voltage		short-circuit	
	A_{S1} (μV)	A_{S2} (μV)	A_{S1} (μV)	A_{S2} (μV)	A_{S1} (μV)	A_{S2} (μV)
0	4.40	4.54	144	28.4	336	158
600	11.3	10.4	171	68.7	511	598
1200	23.3	22.7	188	95.1	599	240
1800	33.7	33.6	218	122	585	378
2400	40.0	39.6	223	131	322	461

- Case of the healthy machine :

If the machine is healthy, the field distribution on each side of the machine is uniform. In this case, the signal amplitudes are approximately the same on each side. When the load increases from 0W to 2400W, the measurements from sensor S1 and S2 increases with each load point as shown in Fig. 7.

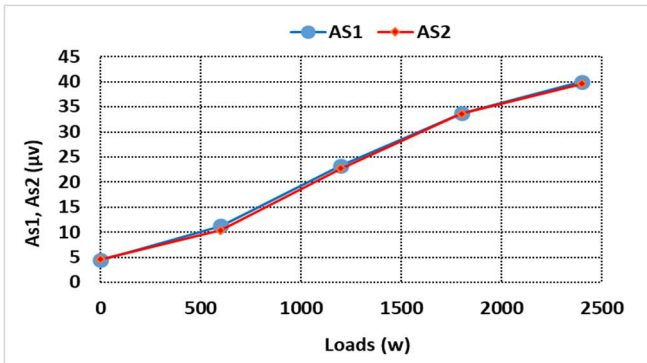


Fig. 7. Variation of 850Hz harmonic amplitude in the healthy case of the asynchronous machine when the load increases.

Thus, it becomes clear that the value of measurements S1 and S2 are very close to each other at all load points, this leads to obtaining a value of RA close to 1 when (3) is used as indicated in Table IV.

When equation (4) is used to calculate the correlation coefficient r it is found equal to 0.9996 (Table IV). This high value indicates that there is a strong relationship between S1 and S2, indicates that the magnetic field around the machine is symmetrical, and confirms the healthy state of the machine.

TABLE IV. VALUES OF PARAMETERS RA AND r OBTAINED FROM THE EXPERIMENTAL MEASUREMENT IN THE CASE OF THE HEALTHY MACHINE

Loads (w)	0	600	1200	1800	2400
A_{S1} (μV)	4.40	11.3	23.3	33.7	40.0
A_{S2} (μV)	4.54	10.4	22.7	33.6	39.6
RA eq (3)	0.9692	0.9204	0.9742	0.9970	0.9900
r eq (4)	0.9996				

- Case of the unbalanced voltage

If the machine is fed by an unbalanced voltage source, that leads to an excess of current flow in one or more phases which creates an unbalance in the magnetic field around the machine. In this case, a dissymmetry appears between the amplitudes of the harmonics extracted from the emf signal issued by the sensors. For the presented experimental test when the load increases from 0W to 2400W, measurements of sensor S1 and S2 increase with each load point, as shown in Fig. 8. This graphical presentation makes it possible to notice the asymmetry created by the unbalanced voltage.

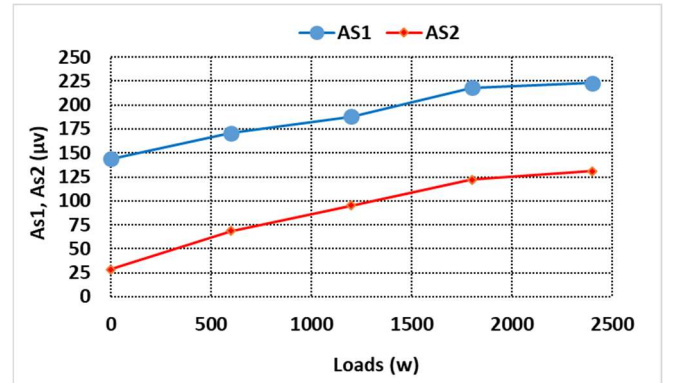


Fig. 8. Variation of 850Hz harmonic amplitude in unbalanced voltage case of the asynchronous machine when the load increases.

Applying (3) to the measured values shown in Table III, it is seen that the values of ratio parameter RA move away from 1 and approach to 0 for the five loads points, these results are presented in Table V. For example, at the load point corresponding to 600 W, we see that the value measured by the sensor S1 is equal to 171V and the value measured by the sensor S2 is equal to 68.7V. Using (3), we see that the value of RA is equal to 0.2489 and calculating the value of the correlation coefficient r with (4), we obtain r equal to 0.9205. This means that the two measurements amplitudes evolve in the same way depending on the load changes while keeping a fixed difference between the two measured values A_{S1} and A_{S2} .

TABLE V. VALUES OF PARAMETERS RA AND r OBTAINED FROM THE EXPERIMENTAL MEASUREMENT IN CASE OF THE UNBALANCED VOLTAGE

Loads (w)	0	600	1200	1800	2400
A_{S1} (μV)	144	171	188	218	223
A_{S2} (μV)	28.4	68.7	95.1	122	131
RA eq (3)	0.5070	0.2489	0.5059	0.5596	0.5874
r eq (4)	0.9205				

- Case of short-circuit fault

In a short-circuit fault condition, the magnetic asymmetry generated by the fault leads to a difference between the signals delivered by sensors S1 and S2. Therefore, the variation of the magnitude A_{S1} and A_{S2} have different values and sometimes in opposite directions. This means that the amplitudes of the harmonics do not vary similarly and therefore there is no linear relationship between these variables when the load is changed. This can be seen in Fig. 9 where 12.5% of elementary turns of phrase ‘‘C’’ are short-circuited.

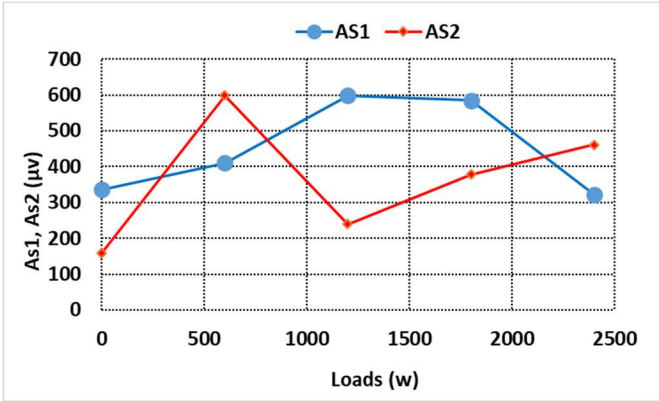


Fig. 9. Harmonic amplitude variation in short circuit case present in the asynchronous machine.

In this case, the RA parameter gives reduced values compared to 1 for the five load points tested, and the Pearson correlation coefficient r takes a negative value as presented in Table VI. It can be noted here that the parameters proposed have different behaviors depending on the type of fault.

TABLE VI. VALUES OF PARAMETERS RA AND r OBTAINED FROM THE EXPERIMENTAL MEASUREMENT IN CASE OF THE SHORT-CIRCUIT FAULT

Loads (w)	0	600	1200	1800	2400
A_{S1} (μV)	336	411	599	585	322
A_{S2} (μV)	158	598	240	378	461
RA	0.4702	0.6873	0.4007	0.6462	0.6985
r	-0.1570				

VI. ANALYSIS OF RESULTS

The experimental tests are carried out using an asynchronous machine operating as a motor and characterized by 4-poles ($p=2$), 50Hz, 11kW, 380/660V, 22.3/13A, 1450 r/min, 48 stator slots ($N_s=48$), and 32 rotor bars ($N_r=32$) which allow us to simulate a damaged coil (short-circuited turns) in each elementary coil (turns in a slot). The machine can operate without load or under load conditions and the load’s increase has been chosen equal to 0 (no-load), 600W, 1200W, 1800W, and 2400W.

For measurement three sensor positions are used around the frame of the machine and several operating configurations as follows:

- 5 tests in the healthy and balanced case.
- 5 tests in unbalanced case create in phase A.
- 5 tests in short circuit case created in phase C (12.5% of elementary turns of phrase C are short-circuited)

All these cases are carried out under five load conditions and this leads to getting 75 values of the amplitude ratio RA and 15 values of the correlation coefficient r for each case as shown in Fig.10.

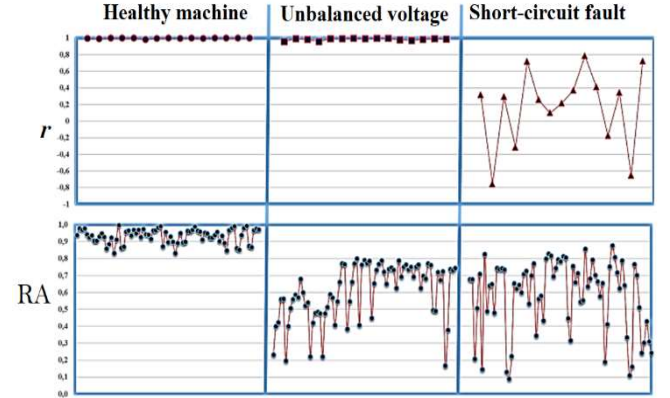


Fig. 10. Representation of global result obtained in the three operating conditions: healthy case, unbalanced voltage and short-circuit stator fault.

Through the results obtained from the healthy machine, we can remark that the value of the correlation coefficient r is close to 1 in all the tests, at the same time we observe that the value of the amplitude ratio RA close to 1 too.

In the case of an unbalanced voltage, the correlation coefficient r is close to 1 in all tests, while the values of the amplitude ratio RA diverge from a value of 1 to a value less than 0.8.

In the case of a short circuit appearing in an elementary coil of the stator windings of the machine, it can be seen that the values of the correlation coefficient r diverge from a value of 1 to a value less than 0.85 in all the tests. Likewise, the values of the amplitude ratio RA diverge from a value of 1 to a value less than 0.8.

So it is found in Fig. 10:

- For the healthy machine, the 15 results give $r > 0.90$, and 75 results give $RA > 0.8$.
- For an unbalanced voltage, the 15 results give $r > 0.90$, and 75 results give $RA < 0.8$.
- For a short-circuit fault, the 15 results give $r < 0.80$, and 67 results give $A < 0.8$.

Taking into account the results presented in Fig. 10 it is possible to define a threshold value of the correlation coefficient r and of the amplitude ratio RA . It is chosen as presented in Fig. 11 which corresponds to 0.9 for r and 0.8 for RA . By this analysis method, a difference between the types of faults can be highlighted.

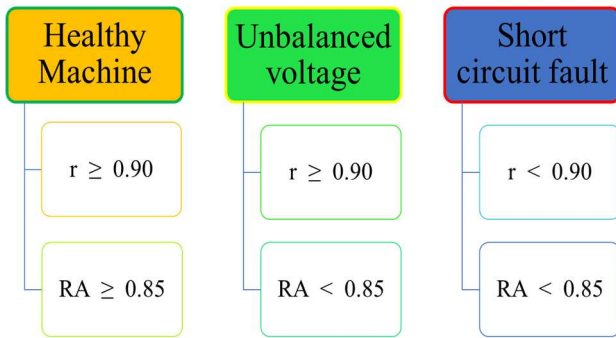


Fig. 11. The choice of the threshold in the asynchronous machine using for diagnosis the information of correlation coefficient (r) and amplitude ratio (RA).

VII. CONCLUSION

This paper uses the external magnetic field for the detection and classification of the short circuit fault and the unbalanced voltage which can appear in the stator windings of asynchronous machines. In the presented application, the magnetic field is measured by noninvasive and low-cost coil flux sensors which work by pair and which are positioned around the machine frame at 180° from each other. The advantage to using this variable is that it is more sensitive to electrical faults than to current or vibration and the measured signal is completely noninvasive.

For the analysis of measured signals, a graphical interpretation is presented in the paper considering a threshold level for the healthy machine and the representation of two specific parameters called Pearson's correlation coefficient r and ratio amplitude RA . These parameters are sensitive to the dissymmetry of the external magnetic field which appears in the faulty case and exploit the amplitudes and amplitude variations of specific harmonics which are obtained from the emf signal delivered by six external flux sensors.

Using the same measurement signals proposed method can identify for asynchronous machine three operating cases: machine operating in healthy condition, machine operating with an unbalanced voltage between the stator phases, and machine operating with short-circuited turns. Moreover, through the accurate results obtained, we can consider the possibility of developing this method into an intelligent method of detection and classification that reveals many faults such as rotor faults, eccentricity, and bearing faults.

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