The investigation of induction motors under abnormal condition

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Abstract: This paper aims to present the negative effects of the unbalanced sinusoidal voltage on the operating of induction motors; this voltage quality anomaly could cause serious problems such as highly unbalanced currents on the stator, mechanical oscillations and interference with control electronics. In this research the detection of this unhealthy situation of the motors has been investigated; using firstly, the stator currents data patterns recognition, as a preliminary diagnosis. Secondly, the focus on the second harmonic of the supply frequency in the torque spectrum signal has shown its effectiveness as a complementary indicator of voltage unbalance. The steady-state of the induction motor and the several unbalanced voltage systems presented, were done by a simulation using the well-known Matlab.

Key words: induction motors, Voltage unbalance, Fault detection, Current patterns, THA.

Introduction

The three-phase squirrel cage induction motors are widely used in modern industry because of their Simple construction and ruggedness. However condition monitoring of the induction motor (IM) becomes a necessity to prevent any unplanned stops and breakdowns (Çakır et al, 2009).

Various phenomena can create difficult problems in the performance of IM. The stator unbalanced voltages is one of them, the most of IM is directly connected to the power grid. Hence, it is very important to clarify the effect of voltage unbalance on the characteristics of IM.

The effects of voltage unbalance on the induction motors are stated as reduction on efficiency, mechanical oscillations and highly unbalanced currents on the stator; this last lead to a temperature rise, and decrease the insulation of the electrical conductors in the stator. This thermal stresses lead to the loss of life in induction motors (Çakır et al, 2009).

Voltage unbalance generates negative sequence component in the voltage. The sense of rotation of the field corresponding to the negative sequence is opposed to the one of the field corresponding to the positive sequence. That is why in the case of unbalanced voltage, the resulting magnetic field becomes elliptic rather than circular. This negative sequence flux produces several adverse effects, such as increased copper losses in the stator and in the rotor, power pulsations and torque pulsations. This last is because of a supplementary torque with a double frequency of the applied voltage (Çakır et al, 2009, Donolo et al, 2011).

In this paper the behavior of a simulated IM, under an unbalanced supply voltage have been studied using the well-know MATLAB/Simulink.

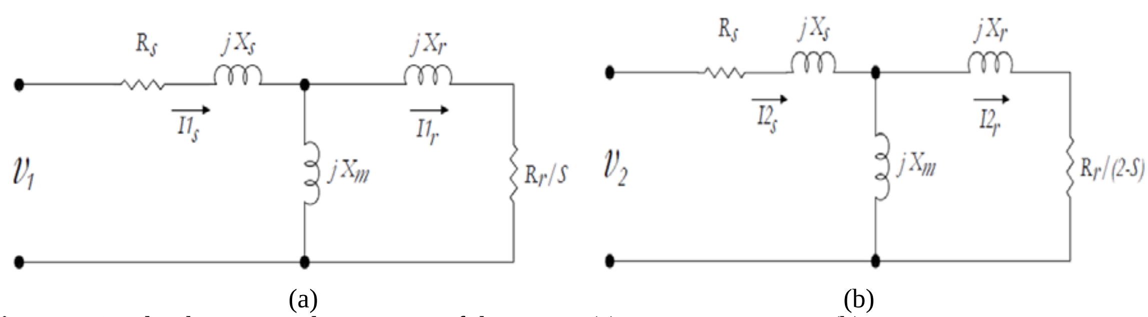


Figure 1: Single-phase equivalent circuits of the motor: (a) Positive-sequence, (b) negative-sequence.
The subscripts s and r denote the stator and rotor, 1 and 2 refers the positive and the negative sequences respectively.

Classification of the voltage unbalances and its different cases

The appearance of some symptoms in the induction motors like vibrations, increased noise levels and the temperature rises in the stator is not necessarily an evidence of an internal fault, like Bearing Faults or stator short-circuit… etc. The stator unbalanced voltage is an external fault, which may cause these symptoms. So, the faults that affect the motor are divided into two parts: internal and external faults, the following figure summarize the various external faults:

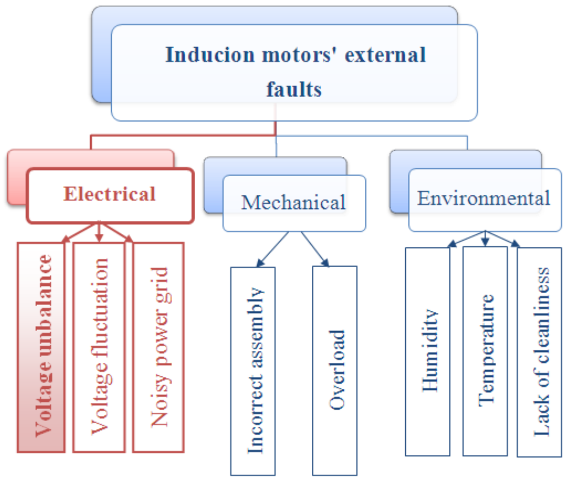


Figure 2: Classification of the external faults

The different unbalanced cases in the three phase systems are (Lee, 1998):
Single phase under-voltage unbalance (1Φ-UV), two phases under-voltage unbalance (2Φ -UV), three phases under-voltage unbalance (3Φ-UV), single phase over-voltage unbalance (1Φ -OV), two phases over-voltage unbalance (2 Φ -OV), three phases over-voltage unbalance (3 Φ -OV), unequal single phase angle displacement (1 Φ -Ang), unequal two phase angles displacement (2 Φ -Ang).

Analysis of balanced and unbalanced condition

Balanced case

The simulated motor (0.75 kW) was supplied by its rated voltage which is 311.12(V) peak for each phase. The simulation of the motor in the steady state and the unbalanced operation is done at no-load condition.

Most of the common methods used to identify faults in induction motor are based on the analysis of the stator currents. The Park's vector and the 3D current pattern approaches, also use the analysis of stator currents. However, in these methodologies, the fault detection will be converted into the pattern and depends on the change on this latter (Samsi et al, 2009). Considering three-phase induction motors without neutral connection, and ideal conditions for the motor and with "unbalanced voltage supply" (Martins et al, 2011), the stator currents are given by:

$$\begin{cases} I_A = I_m \sin(\omega t - \varphi) \\ I_B = I_m \sin(\omega t - \frac{2\pi}{3} - \varphi) \\ I_C = I_m \sin(\omega t - \frac{4\pi}{3} - \varphi) \end{cases} \quad (1)$$

Where I_A, I_B,and I_c :are the three stator currents; I_m : maximum value of the supply phase current; ω : Supply frequency; φ : The phase angle; t: Time variable.

The components of the stator current in a reference system formed by two octagonal shafts which are fixed to the stator are obtained by the following reports:

$$\begin{cases} i_d = \sqrt{\frac{2}{3}} I_A - \frac{1}{\sqrt{6}} I_B - \frac{1}{\sqrt{6}} I_C \\ i_q = \frac{1}{\sqrt{2}} I_B - \frac{1}{\sqrt{2}} I_C \end{cases} \quad (2)$$

Where i_d and i_q are the direct and quadrature axis currents respectively, under ideal operating conditions, when the supply currents constitute a positive sequence system, the three phase currents lead to a Current Park's vector with the components:

$$\begin{cases} i_d = \frac{\sqrt{6}}{2} I_m \sin(\omega t) \\ i_q = \frac{\sqrt{6}}{2} I_m \sin(\omega t - \frac{\pi}{2}) \end{cases} \quad (3)$$

Under this Ideal condition the direct and quadrature axis currents represent a circle centered at the origin of the coordinators. So, this is very simple reference figure that allows the detection and the identification of abnormal conditions by monitoring the deviations of acquired patterns (Cruz et al, 2001).

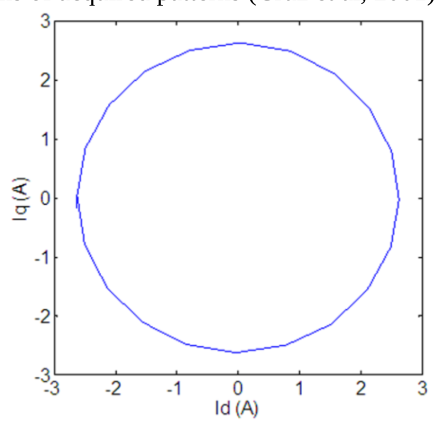


Figure 3: Current Park's vector pattern for ideal operating condition

In the 3D stator current pattern, also we denote a circle centered at the origin of the coordinates, for ideal condition where its radius R is:

$$R^2 = I_A^2 + I_B^2 + I_C^2 \quad (4)$$

Unbalanced cases

The stator asymmetry is a general concept of any stator unbalance, whether stator winding fault or/and voltage unbalance. So under these abnormal conditions, the previous circle pattern no longer appears because the motor supply current will contain negative-sequence component besides the positive-sequence component.

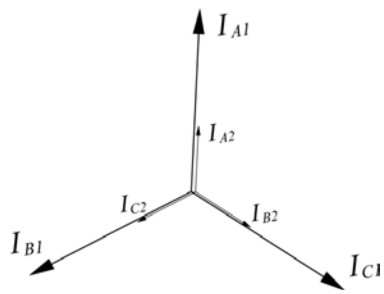


Figure 4: Induction motors' currents under unbalanced voltage

$$\begin{cases} I_A = I_{A1}\sin\left(\omega t-\varphi\right)+I_{A2}\sin\left(\omega t-\varphi\right) \\ I_B = I_{B1}\sin\left(\omega t-\dfrac{2\pi}{3}-\varphi\right)+I_{C2}\sin\left(\omega t-\dfrac{4\pi}{3}-\varphi\right) \\ I_C = I_{C1}\sin\left(\omega t-\dfrac{4\pi}{3}-\varphi\right)+I_{B2}\sin\left(\omega t-\dfrac{2\pi}{3}-\varphi\right) \end{cases} \quad (5)$$

The motor supply current can be expressed as the sum of a positive and a negative- sequence component. It can also be shown that the length of the major axis is directly proportional to the sum of the amplitudes of the positive and negative-sequence components of the motor supply current, while the difference between the amplitudes of these two components is directly proportional to the length of the minor axis.

$$\begin{cases} i_d = \dfrac{\sqrt{6}}{2}(I_1+I_2)\sin(\omega t) \\ i_q = \dfrac{\sqrt{6}}{2}(I_1-I_2)\sin(\omega t-\dfrac{\pi}{2}) \end{cases} \quad (6)$$

So for an induction motor with a stator asymmetry the current pattern assumes an elliptic pattern whose major axis orientation is associated with the faulty phase (Cruz et al, 2001, Pires et al, 2010, Nejjari, Benbouzid, 2000).

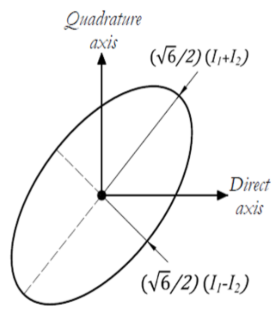


Figure 5: Current Park's vector representation for a stator asymmetry (Cruz et al, 2001)

As the stator currents differ from each other by 120° electrical, it is important to note that the three ellipses' major axis differ from each other by 120 spatial degrees in both park's vector approach and the3-D current referential (Pires et al, 2010, Martins, 2011). The severity of the motor fault must be reported, which is related with the eccentricity of the ellipse. In this way, the new index is proposed, allowing the pattern identification and the fault severity measure.

$$S_{st} = 1 - \frac{\lambda_{low}}{\lambda_{hig}} \qquad (7)$$

The parameters λ_{high} and λ_{low} denote respectively, the highest and lowest length of the ellipse axes. It is important to note that λ_{high} refers to the axis where the fault occurs - principal direction carrying more energy (Morsia, El-hawary , 2011, Martins, 2011). This severity index assumes values between zero and one, being the absence of any fault reported by a zero severity index (S_{st} = 0).

The symmetrical components transformation (Fortescue transformation) is ubiquitous and is used to transform any three-phase system voltages or currents into three single-phase systems using the following symmetrical components transformation matrix in the phasor domain:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}, \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \qquad (8)$$

the subscripts A, B, and C, refer to each one of the components of the phase of the real system, while 0, 1, and 2, are the zero, positive and negative sequence voltages and currents respectively, The operator '*a*' is the Fortescue operator : $a = 1\angle 120°$.

In this paper the obtained elliptic patterns in the following simulation experiments, are resulted from the unbalanced voltage.

Fault detection

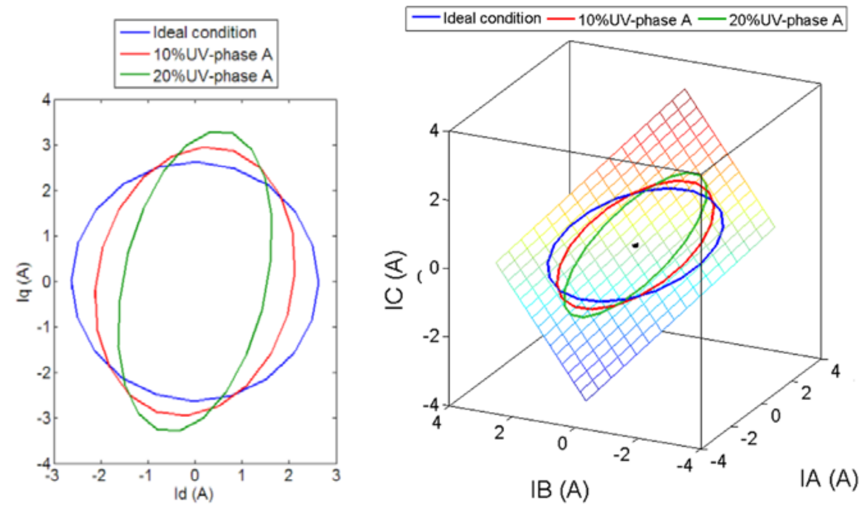
Unbalance in the voltages magnitude

- Under voltage in phase A and healthy state for phase B and phase C:

First an unbalance of 10% after this, an unbalance of 20% of the rated voltage is assumed for phase A. The values of the voltage for the three phases in these two cases are:

10% UV-phase A {V_A=280∠0, V_B=311.12∠-120, V_C=311.12∠-240}

20% UV-phase A {V_A=248.89∠0, V_B=311.12∠-120, V_C=311.12∠-240}



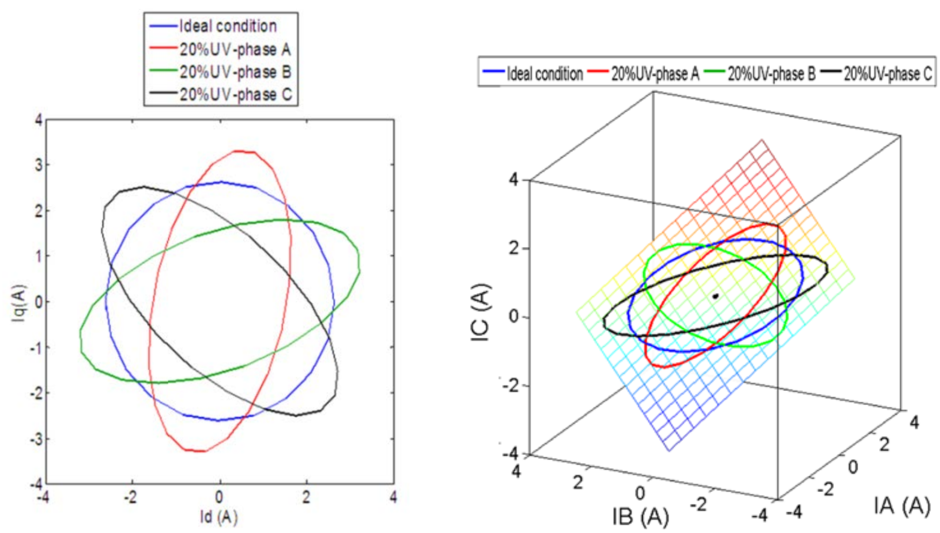
(a) (b)

Figiure 6: (a) Current Park's vector pattern, (b) 3D stator current pattern; for 10% and 20% under voltage in phase A

- Under voltage in phase A, B and C:

An unbalance of 20% of the rated voltage is assumed for phase A, B and C. The values of the voltage for the three phases in these cases are:

20%UV-phase A {$V_A=248.89\angle 0$, $V_B=311.12\angle -120$, $V_C=311.12\angle -240$}
20%UV-phase B {$V_A=311.12\angle 0$, $V_B=248.89\angle -120$, $V_C=311.12\angle -240$}
20%UV-phase C {$V_A=311.12\angle 0$, $V_B=311.12\angle -120$, $V_C=248.89\angle -240$}



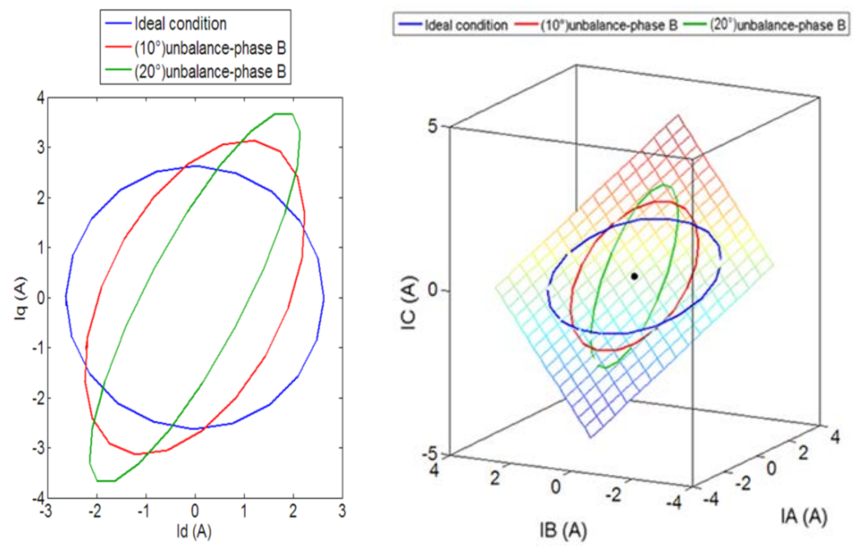
(a) (b)

Figure 7: (a) Current Park's vector pattern, (b) 3D stator current pattern; for 20% under voltage in phase A, B and C

Unbalance in the voltage phase

- (10°) and (20°) angle unbalance displacement of angle's phase B :

First an unbalance of 10° after this, an unbalance of 20° are assumed for the phase A, the values of the voltage for the three phases in these two cases are:
(10°) unbalance -phase B {$V_A=311.12\angle 0$, $V_B=311.12\angle -110$, $V_C=311.12\angle -240$}
(20°) unbalance -phase B {$V_A=311.12\angle 0$, $V_B=311.12\angle -100$, $V_C=311.12\angle -240$}



(a) (b)

Figure 8: (a) Current Park's vector pattern, (b) 3D stator current pattern; for (10°) and (20°) angle displacement in phase B

In certain research the obtained elliptic pattern from the Park's vector approach is considered as direct sign of an unbalanced voltage. Other researches consider the elliptic plot from the 3D currents pattern as sign of a stator winding fault. From a physical point of view, it should be considered as a stator asymmetry in general (stator winding fault and/or voltage unbalance). So, in this work we consider these results as a preliminary diagnosis. And the voltage unbalance must be distinguished from stator winding fault signatures. So using another complementary technique to finalize the investigation is necessary, and that is the content of the next section.

Torque harmonic analysis (THA)

A variety of researches have been done on modeling of unbalanced voltage condition (Phase or Magnitude) in induction motors. To detect this anomaly, has turned to the use of the torque harmonic analysis (THA), in the case of unbalanced voltage, the component spectrum that appears is (100Hz) in the spectrum of the torque, this effective technique will be used in this research. The torque can be written by the following equation (Mirabbasi et al, 2009, Khoobroo et al, 2008):

$$T = \frac{P}{\omega} = \frac{P_0 + P_2}{\omega} = T_0 + T_2 \qquad (9)$$

T_0 is the DC torque; T_2 is the torque component whose frequency is twice the supply frequency.

In order to simplify the survey, we suppose that the induction motor is as an RL load, the torque will be written as follows:

$$T = \left(\frac{1}{\omega}\right) \times \eta \times V \times I \qquad (10)$$

V is the input voltage, I is the current of each phase, η is the motor efficiency.

As we supposed previously, sinusoidal waveforms for voltage and current is applied, so the equation can be rewritten as:

$$T = K\cos(2\pi 50t + \alpha) \times \cos(2\pi 50t + \beta) \qquad (11)$$

So,

$$T = K'\{cos(\alpha - \beta) + cos(2\pi 100t + \alpha + \beta)\} \qquad (12)$$

Based on this equation the resulting torque would include a DC term and a term with twice of the fundamental frequency of the applied voltage (*2.fs*) as expected, this component which is absent in normal operating condition, can detect the fault. So any kind of unbalanced voltage in induction machines is detectable via torque harmonic analysis.

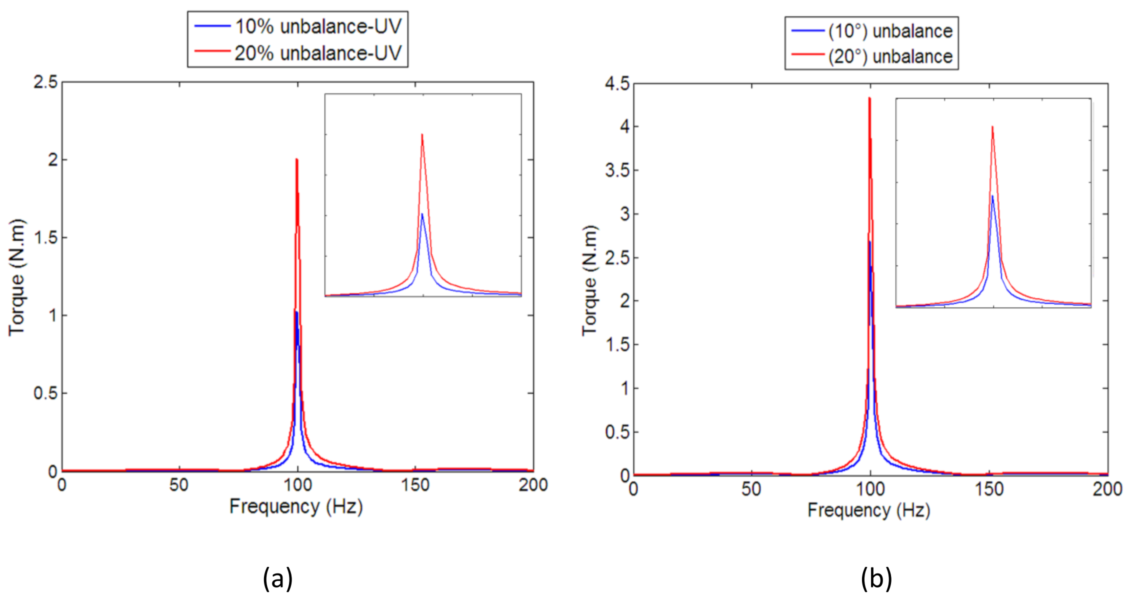


Figure 9: Torque harmonic analysis in case of (a) 10% and 20% under voltage; (b) 10° and 20°angle displacement

Conclusion

It has been reviewed that the stator voltage imbalance has a negative effects on the performance and the efficiency of the induction motors.

In order to detect this anomaly the stator currents data pattern (Park's vector approach or 3D stator currents pattern) is used. Because of the similarity of the obtained signatures between the stator unbalanced voltage and the stator winding fault, these last are considered as an initial diagnosis. To distinguish between these two faults, the torque harmonic analysis is used as a complementary technique in this study. The second frequency component (*2.fs*) that appears in the spectrum of the torque can detect and specify any kind of voltage unbalance in the induction motors.

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