Comparison and Detection of Abnormal Conditions in Induction Motors

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Abstract

Deficiencies like unbalanced voltages or harmonics in the voltage source could result in problems like excessive losses, over-voltages, mechanical oscillations, and interference with control electronics. Detecting these abnormal conditions in the machine is of great importance in the interaction of the electrical machine and the power grid. In this paper the effect of the unbalanced voltages , harmonics and flicker on the motor performance, have been investigated. Then, monitoring these unhealthy condition using electrical machine parameters is carried out. In this case, motor itself can act as the sensor that detects abnormal conditions.

Also this paper investigates the negative effects of unbalanced sinusoidal voltage which always present in the power supply over balanced (inverter supply) non-sinusoidal voltage on the performance of induction motor in terms of line currents, power factor and efficiency. According to the test results and analysis, the negative effects of unbalanced sinusoidal voltage are more than the balanced no sinusoidal voltage on the motor's performance.

1. Introduction

According to the U.S. Department of Energy (DoE), 70% of the electricity is used by industrial motors, and in a typical industry the 80% of the load consists of three-phase AC induction motors [1]. Induction motors are being used more than ever before due to their versatility, dependability and economy, good self-starting capability, offers users simple, rugged construction, easy maintenance, low cost and reliability.

As the industries are developed more and more, the high quality of the electric power has been concerned in manufacturing plants. The power quality is deteriorated in terms of voltage sag, swell, surge, blackout, harmonics, or unbalanced voltage. The unbalanced voltage gives a bad influence for the power quality. If the unbalanced power is applied to the electric apparatuses, it gives a difficult problem to them, especially the electric motors. The unbalance voltage is caused by unsymmetrical transformer windings or transmission impedances, unbalanced loads, or large single phase loads. Even unbalanced voltage applied to the motor is small, large unbalanced motor current can be flowed because of relatively low negative sequence impedance. The large unbalanced current makes difficult problems in induction motor applications, such as a heat problem, increases of losses, vibrations, acoustic noises, shortening of the life, reduction in_efficiency, a decrease of the rotating torque and creating a torque pulsation. [8].

Role of induction motors in industry increased after the development of adjustable speed drives. However, it is well-known that the operation of the motor cannot be done under conditions of perfectly balanced supply voltage. This asymmetry induces negative-sequence current which in its turn produces a backward rotating field in addition to the forward rotating field produced by the positive sequence one. The interaction of these fields produces pulsating electromagnetic torque and velocity disturbances resulting in increasing losses, stresses and noise in the machine [2-5].

The efficacy of normal operation of a motor from an unbalanced supply depends directly on the degree of unbalance at the terminals of the machine. It is therefore essential that a suitable standard be used to quantify the degree of voltage unbalance. The NEMA and IEC standards introduce independent definitions for voltage unbalance and one of these is normally used for the analysis of electrical machines [6-9].

. In most cases, condition monitoring schemes have focused on one of three induction motor components: the stator, rotor or bearings. While the use of vibration monitoring is currently extensive, moderately little attention has been paid to voltage unbalance in the motor supply. Because of the wide use of the induction motors both in industrial and residential areas, the damaging effects on induction motors will cause an important economic impact. Harmonics produced by inverters can be in some cases a main source of vibration and oscillations in AC motors. The fundamental harmonic component is positive-sequence, second harmonic is negative-sequence, and third harmonic is zero-sequence, repeating this pattern higher order harmonics. Negative sequence harmonics produce a pulsating torque that causes excess of power losses in the winding as it works against the fundamental component. This is the case of the harmonic component created by the voltage unbalance. Those with positive sequence have a forward rotation and also increase the losses due to skin effect and eddy currents. Finally, triplen harmonics are zero-sequence harmonics that are multiples of third harmonic and they have no effect on torque pulsation. The harmonics caused by inverters, in practice, are odd and not a multiple of three. In [10] the impact of harmonics on induction motors is analyzed, and for example, for the lowest harmonic frequencies, which are fifth and seventh in a three phase square wave inverter, they produce a torque that pulsates at a sixth harmonic frequency. In addition, as higher order harmonics produce torque components at higher frequencies, they have a lower impact on the speed ripple because of the integrative effect of the system inertia. The harmonic content of the inverter output depends on the type of control [11].

In this paper two methodologies are applied to a three phase induction motor, using the well-know Matlab/Simulink software. The simulated results presented clearly show that the proposed techniques can accurately early detection, abnormal condition of induction motor.

2. Comparison Effect of Balanced, Unbalanced and Balanced but with Harmonics (non Sinusoidal) Voltages on Induction Motors

The motor was tested from no load condition to full load by varying applied load to the motor for three the non-sinusoidal balanced, the unbalanced and balanced sinusoidal voltage conditions.

Fig.1 shows the simulation results for a 20HP (15Kw), 400V rms line to line, three-phase squirrel-cage induction motor supplied by three conditions. Efficiency of the tested motor under unbalanced sinusoidal voltage is smaller than the motor operated with balanced non-sinusoidal (inverter) voltage shown in Fig. 1. Maximum line current drawn by the motor under both operating conditions is shown in Fig. 1. This figure shows that the maximum current drawn by the motor under first condition is higher than the current under second condition. Lower power factor is obtained by use of balanced non-sinusoidal voltage (Fig.1).

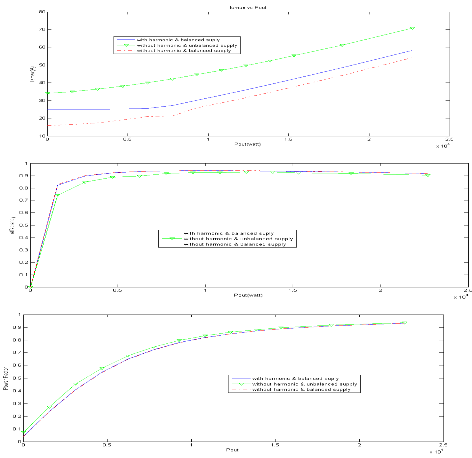


Fig. 1: Three evaluated factors of induction motor: Ismax, efficiency, power factor

3. Normal and Unbalanced Conditions Analysis

3.1. Normal Case

In this section normal operating condition has been investigated. It is necessary to accomplish this to develop a reference for comparison purposes. This model has been simulated. In normal condition, motor was supplied by its rated voltage which is 326.6 volts peak for each phase. The voltages applied are as follows:

$$Va = 326.6\angle 0, Vb = 326.6\angle 240, Vc = 326.6\angle 120, f = 50Hz \quad (1)$$

Fig. 2 depicts the simulation results in this case. As shown in this figure the torque ripple is almost negligible.

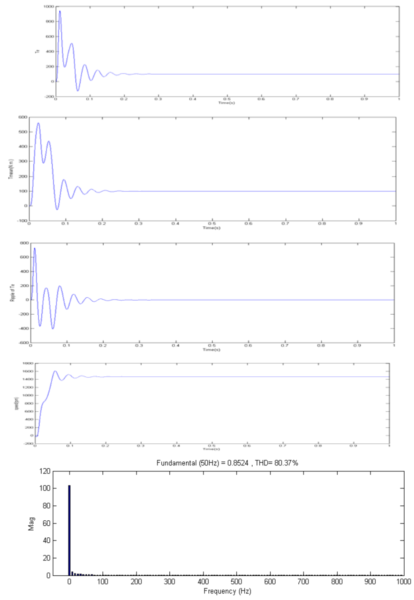


Fig. 2: balanced case: torque & speed, FFT of ripple

3.2. Unbalanced Cases

In this part the unbalance in the phase and the magnitude of the voltage has been considered. In order to model the electrical motor symmetrical components can be used. A wide variety of research has been done on modeling of unbalanced condition. In the unbalanced voltage operating condition the torque can be written as follows [12, 13]:

$$T = P/\omega = (P_0 + P_2)/\omega = T_0 + T_2 \quad (2)$$

In which, T_0 is the DC torque. T_2 , is the torque component whose frequency is twice the supply frequency. In a simpler way assuming induction motor as a RL load the torque can be written as:

$$T = \eta \times E \times I / \omega \quad (3)$$

In which E and I are input voltage and current of each phase respectively. Assuming sinusoidal waveforms for voltage and current this equation can be rewritten as:

$$T = K\cos(2\pi 50t + \alpha) \times \cos(2\pi 50t + \beta) \quad (4)$$

So,

$$T = K'[\cos(\alpha - \beta) + \cos(2\pi 100t + \alpha + \beta)] \quad (5)$$

Based on equation (5) the resulting torque would include a DC term and a term whose frequency is twice the fundamental frequency of the applied voltage. In order to detect the unbalanced supply voltage this extra torque component can be used.

3.2.1. Unbalance in the voltage magnitude

In this case an unbalance of 20% and 15% of the rated voltage is assumed for phase B and C voltages respectively. So, the value of the voltages for phases A, B and C would be as follows:

$$Va = 326.6\angle 0 \ , \ Vb = 326.6 * 0.8\angle 240 \ , \ Vc = 326.6 * 0.85\angle 120$$

The torque components from simulated model have been shown in figure 3. In order to have a better view of the torque components frequency analysis has been made using DFT. Torque components have been shown in figure 3. According to this figure there is a DC component and a 100 Hz component(second order) as expected. The magnitude of this component is big enough to be measured.

Comparing to the case of the normal operation the average torque is decreased while the ripple has increased significantly.

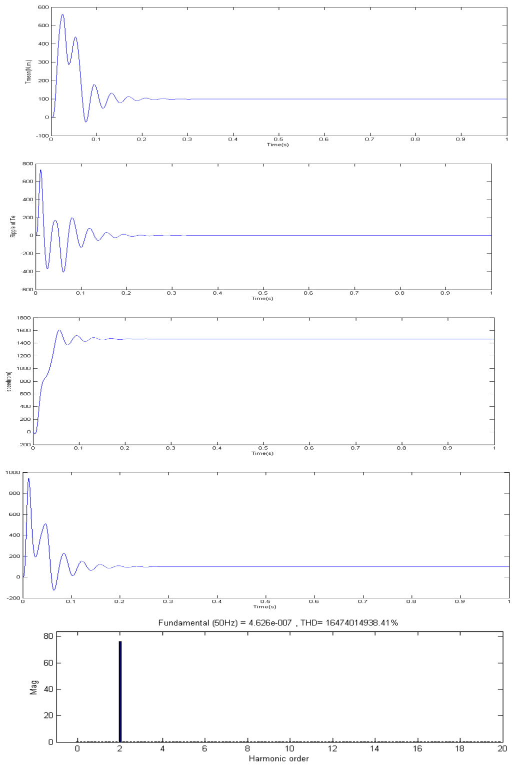


Fig. 3: vol. mag. unbalance case : torque & speed, FFT analysis of ripple

3.2.2. Unbalance in the voltage phase

In this part an unbalance of 10% is assumed for the phase of applied voltages of phase B and C. The applied 3 phase voltages are as follows:

$$Va = 326.6\angle 0,\ Vb = 326.6\angle 216,\ Vc = 326.6\angle 132$$

Fig. 5 depicts the torque components in this case. Based on the figure there is a significant increase in the torque ripple while the average torque has decreased a little bit comparing to normal case .

3.2.3. Unbalance in the Voltage Magnitude and Phase

In this case an unbalance of 10% is applied for voltage Phase and magnitude. The applied voltages are as follows:

$$Va = 326.6\angle 0,\ Vb = 326.6*.9\angle 216,\ Vc = 326.6*.9\angle 132$$

The torque components have been shown in Fig. 5 depicts the torque components in this case.

As expected in this case the ripple is increased more and the average torque is decreased. From the performance point of view pulsating torque is unaccepted so it is important to detect and avoid any kind of unbalance in the voltage

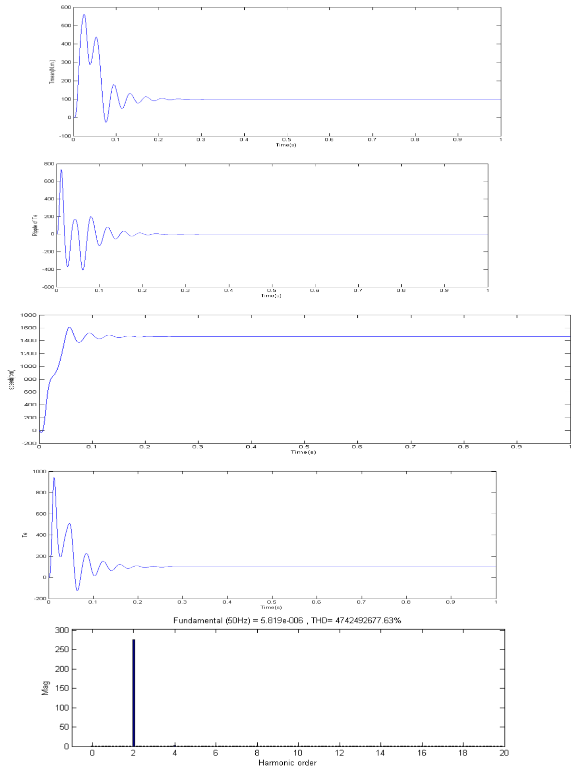


Fig. 4: vol. phase unbalance case: torque & speed, FFT analysis of ripple

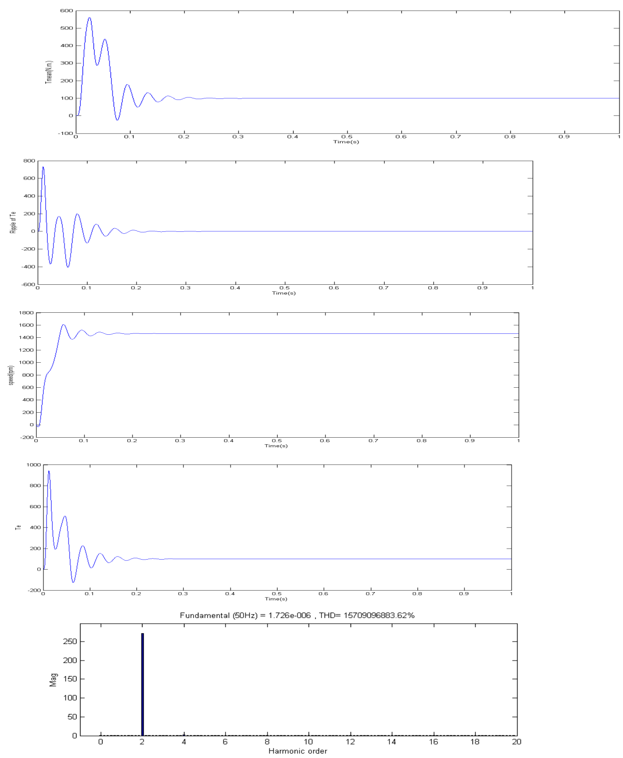


Fig.5: vol. phase & mag. unbalance case: torque & speed , FFT analysis of ripple

4. Harmonic Analysis

Because of the destructive effects of the harmonics like torque pulsation, acoustic noise and increased losses a wide variety of the research have been done to minimize the harmonics in the voltage supply [14-16]. In this part three major harmonics namely, 3rd, 5th, and 7th harmonics are introduced to the model. Moreover, a combination of these harmonics is considered as well. The machine has been supplied with the rated voltage and the harmonics are injected in the voltage source. The applied voltage can be written as:

$$V(t) = V_1 \sin(2\pi f t) + \sum_{k=3,5,7} V_k \sin(2\pi k f t + \theta_k) \qquad (6)$$

It is shown in [9] that the current in the stator windings are as follows:

$$I_k(t) = \frac{V_k(t)}{\sqrt{R_{eq}^2 + X_{eq}^2)}} \qquad k = 1,3,5,7 \qquad (7)$$

In which R_{eq} and X_{eq} are stator equivalent resistance and reactance respectively. Based on equation (7) it is expected that the harmonics with the same frequency but different amplitude would be present in the stator currents.

4.1. 3rd Harmonic

In this case the 3rd harmonic is injected into the voltage sources. As the main frequency of the voltage source is 50Hz the harmonic frequency is 150Hz. According to the standards the magnitude of the harmonics should be less than 5% of the main frequency magnitude. Two cases can assumed here. In the 1st

case the stator windings are not grounded but in the second case the stator winding is star connected and grounded. The voltages that are applied to the stator 3 phases are as follows (not grounded):

$$Va3 = 326.6 * 0.05\angle 0,\ Vb3 = 326.6 * 0.05\angle 0,$$
$$Vc3 = 326.6 * 0.05\angle 0,\ \ f = 150Hz \qquad (8)$$

The analysis results are shown in Fig. 6. In case of an ungrounded stator winding the currents due to the 3rd harmonic are not able to flow according to Kirchhoff's law.

triplen harmonics are zero-sequence harmonics that are multiples of third harmonic and they have no effect on torque pulsation.

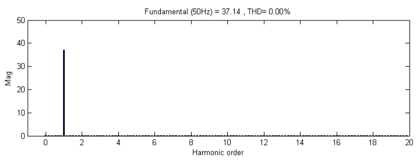


Fig. 6: FFT analysis of Ib:with 3rd harmonic

4.2. 5th Harmonic

In this case the 5th harmonic is injected into the voltage Sources. As the main frequency of the voltage source is 50Hz the harmonic frequency is 250Hz. According to the standards the magnitude of the harmonics should be less than 5% of the main frequency magnitude.

$$Va5 = 326.6 * 0.05\angle 0,\ Vb5 = 326.6 * 0.05\angle 0,$$
$$Vc5 = 326.6 * 0.05\angle 0,\ \ f = 250Hz \qquad (9)$$

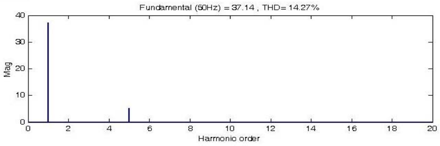


Fig. 7: FFT analysis of Ib: with 5th harmonic

The frequency analysis of the current waveforms has been depicted in Fig. 7.

4.3. 7th Harmonic

In this case the 7th harmonic is injected into the voltage sources. As the main frequency of the voltage source is 50Hz the harmonic frequency is 350Hz.

$$Va7 = 326.6 * 0.05\angle 0,\ Vb7 = 326.6 * 0.05\angle 0,$$
$$Vc7 = 326.6 * 0.05\angle 0,\ \ f = 350Hz \qquad (10)$$

The frequency analysis of the current waveforms has been depicted in Fig. 8.

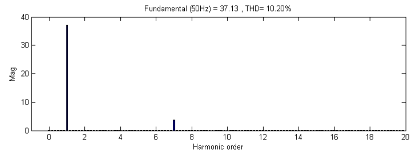


Fig. 8: FFT analysis of Ib: with 7th harmonic

4.4. All Harmonics

In this section all the above mentioned harmonics are injected simultaneously into the stator windings. The stator winding currents has been depicted in Fig. 9.

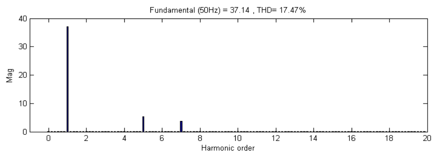
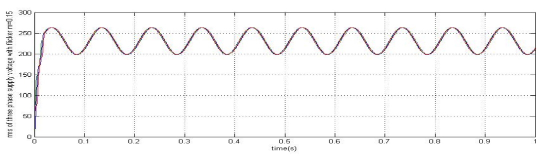


Fig. 9: FFT analysis of Ib: with all harmonics

5. Effect of Flicker

In this section the effect of voltage flicker on the performance of induction motor was investigated. A voltage flicker is a fluctuation of voltage with frequency of about 10Hz as shown in fig. 10. The loads like electric arc furnaces (EAF) causes to the voltage flicker on the terminal of load. For simulation of the effects of this type of voltage disturbance was injected. A voltage flicker with modulation index, m=0.15 to the induction motor. The speed and mean of torque and current of phase B shown in fig. 10. it can be seen from figures that torque fluctuate is as non sinusoidal with frequency 20 Hz.



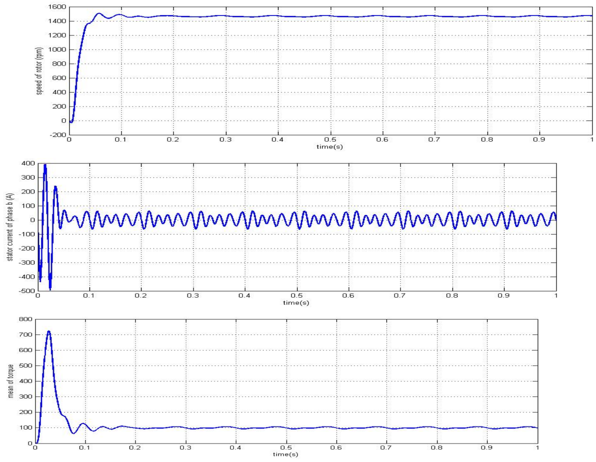


Fig.10: Flicker effect: vol. source, speed and mean of torque

6. Conclusions

This study has investigated the negative effects of three phase unbalanced sinusoidal voltage over balanced non-sinusoidal voltage on the performance of 20HP, squirrel cage induction motor, focusing on the efficiency, line currents and power factor. The main conclusions from the study are (i) efficiency of the motor under three-phase unbalanced voltage is lower than the efficiency at balanced non-sinusoidal voltage, (ii) current drawn by the motor under unbalanced supply is higher, (iii) lower power factor is obtained by use of non sinusoidal supply, and (iv) it should additionally paid per year to the electricity supplier due to voltage unbalance in one motor because of reduction of efficiency.

As the harmonics in the voltage source can cause excessive losses, extra noise and pulsating torque detecting harmonics in the voltage applied is important. The frequency analysis of the stator currents can be used for detection. In the case of unbalanced voltages the efficiency and average output torque of the motor would decrease and the ripple would increase significantly destructing the motor application. In order to detect unbalance condition torque frequency analysis can be used. In case of an unbalanced voltage with harmonics these quantities still work properly towards detection purpose.It was being seen from effect of flicker that torque and speed have damaged swings.

7. References

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