# Effect of Unbalanced Voltage on Operation of Induction Motors and Its Detection

Davar Mirabbasi[1], Ghodratollah Seifossadat[2] , Mehrdad Heidari[1],

dmirabbasi@yahoo.com, seifossadat@yahoo.com, mehrdad266@yahoo.com
[1] PhD student of Shahid Chamran University, Ahvaz, Iran
[2] Assistant professor of Shahid Chamran University, Ahvaz, Iran

## Abstract

**Deficiencies like unbalanced voltages 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 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 voltage on the performance of induction motor in terms of line currents, power factor and efficiency. According to the test results and analysis, the unbalanced sinusoidal voltage has very negative effects on the motor's performance.**

## 1. Introduction

Power quality problems and survey results have been reported in many publications [1]–[3]. The affected industry and businesses include automobile manufacturing plants, medical centers, semiconductor manufacturing plants, broadcasting facilities, and industrial and commercial buildings. It is estimated that industrial and digital economy companies collectively lose $45.7 billion a year to outages and another $6.7 billion each year to power quality phenomena. 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 [4].

The unbalance voltage is caused by unsymmetrical transformer windings or transmission impedances, unbalanced loads, or large single phase loads. Voltage unbalance exists in almost all three-phase power system networks. The level of unbalance is considerably large in weak power systems and also those supplying large single phase loads. Based on the ANSI report, the voltage unbalance of 66% of the electrical distribution systems in USA, is less than 1%, and that of 98% of the distribution systems is less than 3%, whilst in the remaining 2% it is larger than 3% [5].

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 [6]. 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.

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 [7-9].

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, and acoustic noises, shortening of the life, a decrease of the rotating torque [10-12].

Three-phase induction motors (IMs) are widely used in industrial devices, and most of them are connected directly to the electric power distribution system (PDS). Therefore, it is very important to clarify the effect of voltage variation in the PDS voltage on the characteristics of IM[13].

In this paper, the steady-state characteristics of an IM under an unbalanced voltage, using the well-know Matlab/Simulink software have been studied.

The negative effects of voltage unbalance on the performance of three-phase induction motors include: higher losses, higher temperature rise of the machine, reduction in efficiency and a reduction in developed torque [14]. Reduction of the rated power of the machine under unbalance voltage is an important effect that was introduced in 1963 [15].

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 [16-19].

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. The simulated results presented clearly show that the proposed techniques can accurately early detection, unbanced condition of induction motor.

## 2. Analysis of machine under unbalance conditions

In this paper, performance of a three-phase induction motor under unbalanced voltage imposed by power system grid is studied. The phase currents, the deliverable power to the motor, stator current and efficiency of the motor are propose. In fact, influence of power system and its unbalances on the motor itself are investigated. In order to analyze the performance of a three phase induction motor, symmetrical components analysis is normally used. In this method, positive and negative sequence equivalent circuits, as shown in Fig. 2, are utilized to calculate different parameters of the machine under unbalanced voltage operation. A Y-connected, 20HP (15Kw), 400V three-phase squirrel-cage induction motor has been used for performance analysis of a motor under unbalanced voltage operation.

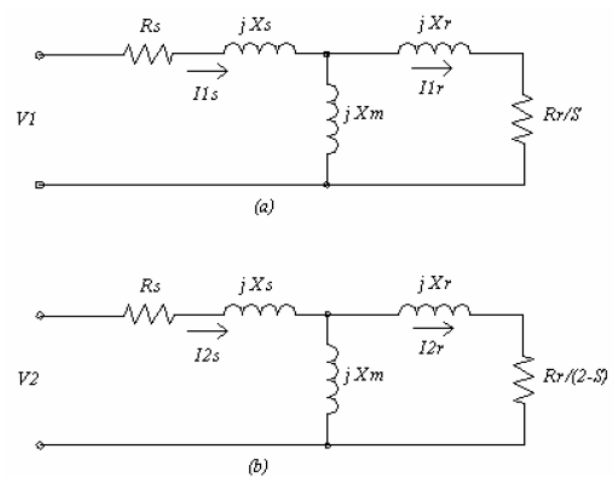


**Fig. 1**: Equivalent circuits of positive and negative sequences

In the equivalent circuits of Fig. 2, subscripts s and r denote the stator and rotor, whilst 1 and 2 refers the positive and negative sequences respectively. The core and mechanical losses of the motor are ignored.

## 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.

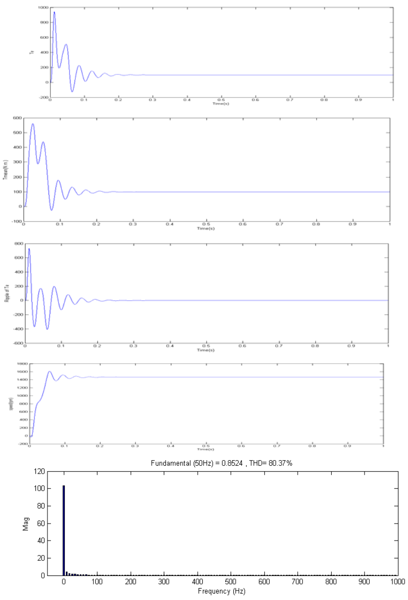


**Fig. 2:** balanced case: torque & speed, FFT of ripple

### 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 [20, 21]:

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

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,

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

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.

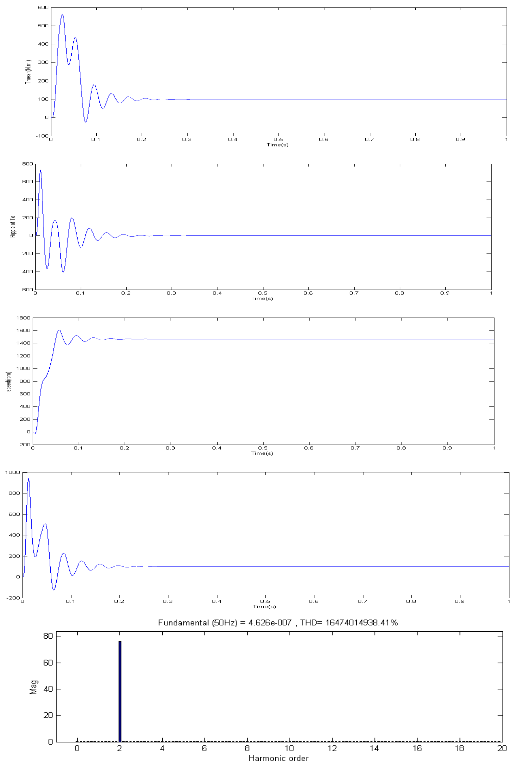


**Fig. 3:** vol. mag. unbalance case : torque & speed, FFT analysis of ripple

### 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

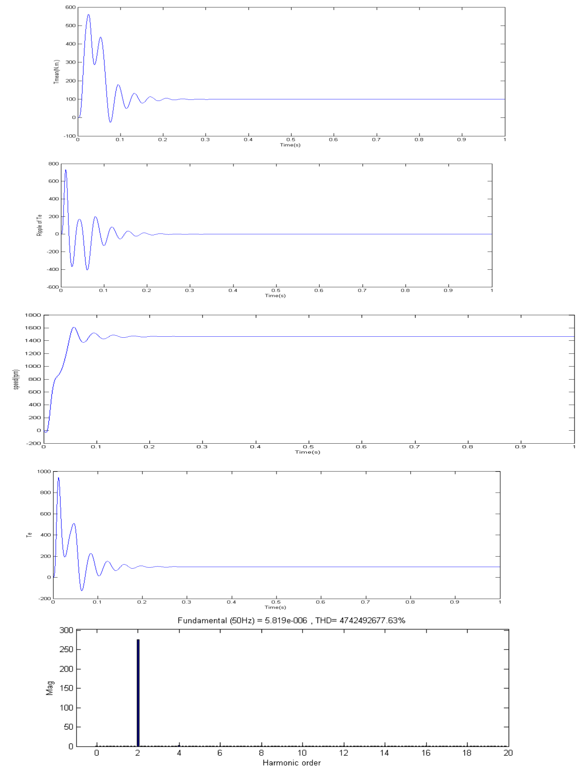


**Fig. 4:** vol. phase unbalance case: torque & speed, FFT analysis of ripple

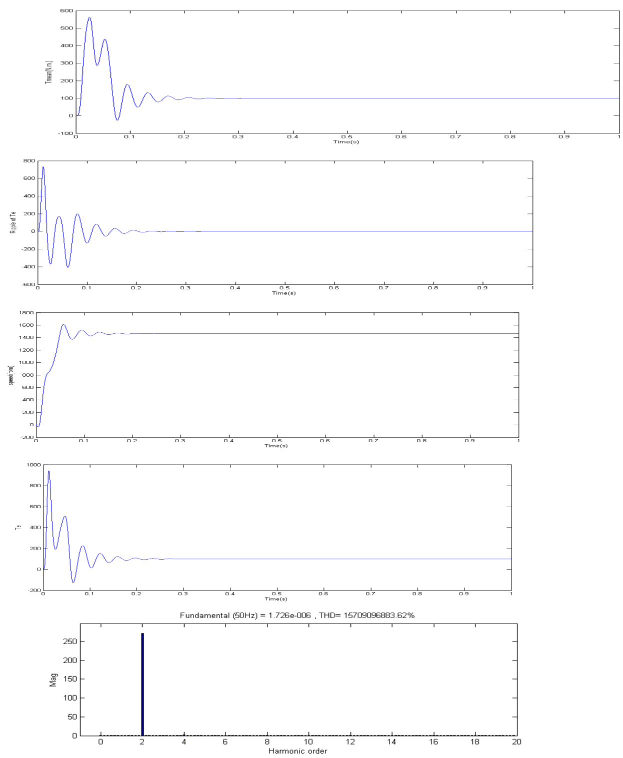


**Fig.5:** vol. phase & mag. unbalance case: torque & speed , FFT analysis of ripple

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## 4. Conclusions

In this paper, a new comprehensive and generalized procedure is presented to predict the steady-state performance of three phase motors under unbalanced conditions focusing on the efficiency, line currents and power factor. This prediction could make the control system of induction motor especially appropriate to prevent damages in high-power machines. It is well known that voltage unbalance causes extra loads to the utilities and additional charges to consumers. Also it can be seen that efficiency of the motor under three-phase unbalanced voltage is lower than the efficiency at normal condition. The maximum amplitude of the current and torque are significantly increased by increasing the voltage unbalanced factor.

As the unbalancing in the voltage source can cause excessive losses, heating, noise, vibration, torsional pulsations, slip, and motor accelerating torque, detecting of unbalancing 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.

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