Short Communications	*Curr. Appl. Sci.*, **2026**, *4*(1): 96-103 DOI:10.22034/cas.2026.589576.1063	Current Applied Sciences

Analysis of Voltage Unbalance Effects on a Three-Phase Induction Motor Performance

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Received: 01 July 2026
Revised: 07 August 2026
Accepted: 08 August 2026
Published online: 17 August 2026

Keywords

Unbalanced Voltage
Induction Machine
Ohmic Loss
Torque
CVUF

Abstract

Induction motors, especially the three-phase type, are the most common types of motors in industries that consume most of the world's electrical energy. The efficiency of these machines also depends on the quality of their power supply voltage. The uneven distribution of single-phase loads, asymmetrical faults, and large industrial electric arc furnaces can make the power system voltage unbalanced. In this paper, the three-phase induction motors performance parameters including loss, efficiency, and torque are studied when supplied by unbalanced voltage source. The results show that voltage unbalance has very negative consequences on the performance of this type of machine, so that ignoring this issue may be associated with damage or reduced life. It is worth noting that the simulations of this research were all performed in the MATLAB/Simulink environment and the precise definition of the complex voltage unbalance factor (CVUF) was also used.

1. Introduction

One of the main challenges in the power quality of electrical networks is the presence of imbalance in three-phase voltages [1]. A three-phase system is considered balanced when the voltage amplitudes of all three phases are exactly equal and their phase difference is exactly 120 degrees [2]. If there is any deviation from such conditions, it is known as voltage imbalance. Uneven load distribution among the phases of a power system is the primary cause of three-phase voltage unbalance [3]. According to the results of power quality studies, some degree of imbalance in distribution networks is inevitable, such that the level of voltage imbalance usually exists between 1% and 3% continuously [4]. It is worth noting that at the end of long lines, in rural areas or in worn-out networks, the amount of voltage imbalance can be much higher [5]. Supplying electrical equipment with unbalanced voltage directly leads to reduced efficiency, increased heat loss and ultimately a severe reduction in their useful life, so research is important to investigate the effects of unbalanced voltages [6].

Electric motors play a unique role among network-connected equipment. These motors have earned the title of "workhorse of industries" due to their robust structure, low depreciation, high reliability and reasonable price; to the extent that it is estimated that a large part of the electrical energy in the world is consumed by them [7]. Therefore, investigating the voltage unbalance effects on the induction motors performance is of particular importance. When this machine is connected to an unbalanced voltage source, a reverse rotating magnetic field (negative sequence field) is formed in its airgap, which opposes the rotation of the rotor [8]. This phenomenon not only causes torque fluctuations and mechanical vibration, but also creates unbalanced and very intense currents in the stator. As a rule of thumb, just 3% voltage unbalance can cause a current of about 20% to 30% higher than the rated current in one of the phases, which means premature destruction of the winding insulation and increased maintenance and repair costs [9]. Therefore, numerous studies have been conducted on the effects of this power quality challenge on the insulation and life [10], losses and efficiency [11], torque of this electrical machine [12]. However, the results of these studies are completely dependent on how the voltage unbalance is calculated. The two standards NEMA and IEC provide different methods for these calculations. The NEMA standard measures unbalance only based on the highest deviation of the voltages from the amplitude's mean value, which has low accuracy due to ignoring phase angles, and the IEC standard provides a more accurate assessment by relying on the symmetrical component's method, but requires accurate phasor information [13]. Despite the above explanations, neither NEMA nor IEC definitions provide an accurate description of the degree of voltage unbalance and its negative effects on equipment, as there are countless voltage imbalance conditions, all of which have equal degrees of unbalance according to these definitions. Therefore, a newer criterion called the complex voltage unbalance factor (CVUF) also used in researches, and this article purpose is to investigate this criterion accuracy in describing the voltage unbalance effect on a three-phase induction motor performance. The main innovation of this paper is the use of this new criterion to study the performance of a three-phase induction motor under voltage imbalance conditions, such that the power consumption and output, efficiency, copper losses and core losses, and motor torque were analyzed using it.

2. CVUF

It is quantified by the ratio of the negative-sequence voltage to the positive-sequence voltage, as expressed in the following equation:

$$\text{CVUF} = \frac{V_2}{V_1} = K_V \angle \theta_V \qquad (1)$$

Unlike the VUF values in the IEC standard, which only consider amplitude, CVUF has a complex value and also includes phase angle information [14]. To calculate CVUF based on line voltage phasors (V_{ab}, V_{bc}, V_{ca}), the Fortescue transformation matrix is used like below:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \qquad (2)$$

where $a = 1\angle 120^\circ = e^{j\frac{2\pi}{3}}$.

3. Simulation Procedure

We considered a 3 HP, 380 V three-phase induction motor to study, whose electrical circuit parameters are presented in Table 1. To analyze the performance of the three-phase induction motor under voltage unbalance in the MATLAB program environment, its negative and positive sequence equivalent circuits are used, which are shown in Figure 1. In this figure, $s_1$and $s_2$denote the slip of the positive- and negative-sequence circuits, respectively. Hence, $s_1$is defined as follows:

$$s_1 = \frac{n_s - n_r}{n_s} \qquad (3)$$

where $n_s$is the synchronous speed and $n_r$is the mechanical rotor speed. Finally, the motor simulated in MATLAB is shown by Figure 2.

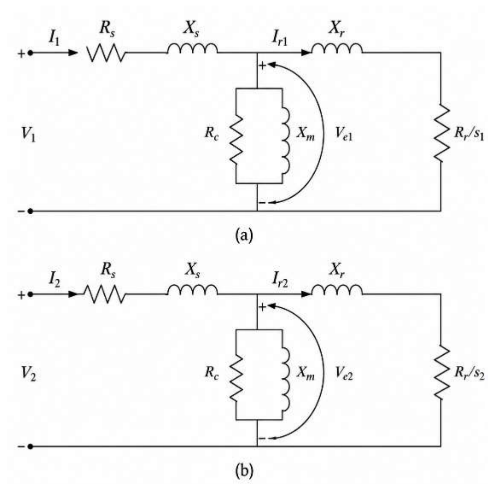

Figure 1. Sequence equivalent circuits: (a) positive, (b) negative

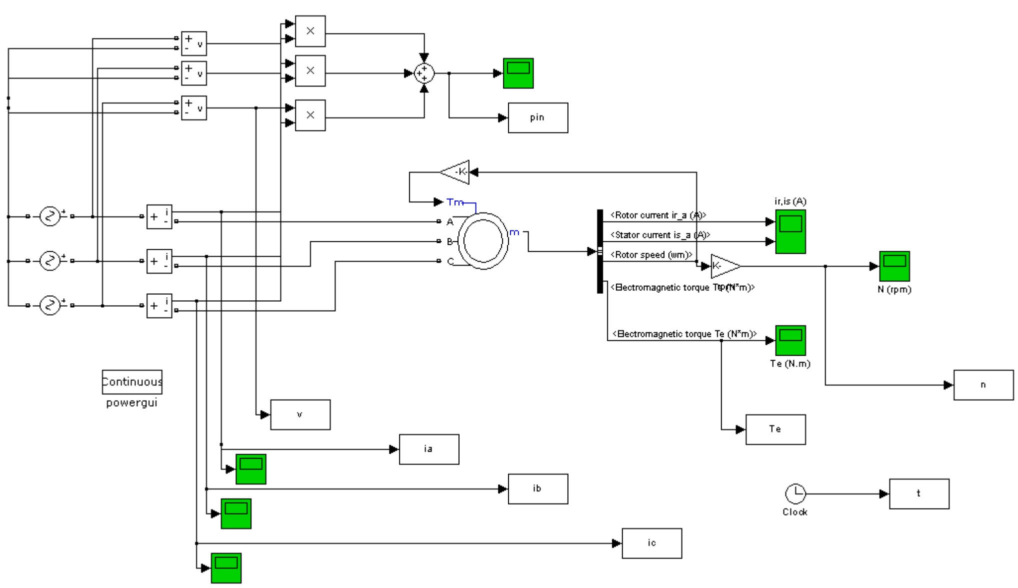

Figure 2. MATLAB/Simulink motor model

Table 1. Induction motor parameters

X_s (Ω)	R_s (Ω)	R_c (Ω)	X_m(Ω)	X_r(Ω)	R_r(Ω)
2.52	1.4	3524	75	5.1	3.1

4. Results and Discussion

First, to show the voltage imbalance effects, the motor input current and its produced torque are shown in two scenarios, including the presence of voltage balance in the power supply and a typical case of voltage imbalance in Figures 3-6. According to these figures, unlike the balanced voltage scenario, in the voltage imbalance condition, the machine currents are noticeably unbalanced and a large 100 Hz ripple (twice the power supply frequency) appears in its steady-state torque. In fact, when there is voltage imbalance, there are two positive and negative sequence components for it, and the negative sequence component creates a rotating magnetic field in the opposite direction to the main field, and the interaction between them causes the currents to become unbalanced. In such a situation, the instantaneous input power of the machine is not constant and has an oscillating component with a frequency twice the frequency of the power source, which is the cause of the appearance of ripple torque. This condition means that the machine heats up and vibrates and produces acoustic noise.

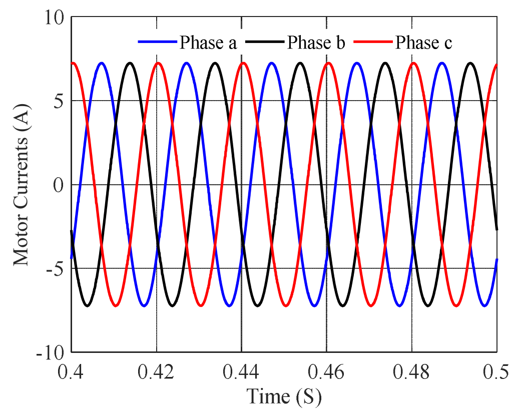

Figure 3. Motor currents under balanced voltage

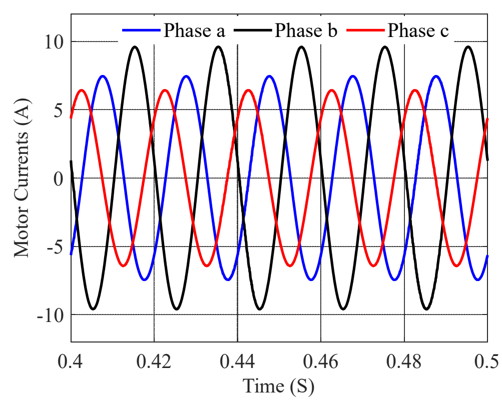

Figure 4. Motor currents under unbalanced voltage

In this article, to examine voltage unbalance impact on induction motor performance using CVUF definition, we consider 7 three-phase voltage samples whose average amplitudes are 0.9 times the rated voltage of the machine, and K_V for them is from 0% to 6%, and their angles are all 120 degrees. Figures 7 and 8 show the motor's power and efficiency, respectively. According to these figures, as the K_V increases, the machine output power decreases, which is accompanied by an increase in the machine power consumption and consequently the machine efficiency will also decrease. The ohmic losses of the machine are depicted in Figure 9. According to this figure, the rotor ohmic losses increase more sharply than the stator ohmic losses with increasing unbalance. According to Figure 10, it can be seen that the core losses of the machine do not have a significant dependence on the degree of voltage unbalance and depends on the average voltage applied to the motor. The reason for this is that core losses are mainly dependent on the main flux, and it is mostly determined by the positive sequence component, i.e. the effective mean of the voltages. It should be noted that in the above figures, all loss and power values are expressed as a percentage of the corresponding values under nominal conditions.

According to Figure 10, the average torque produced by the machine decreases slightly with increasing K_V, but the torque ripple increases sharply.

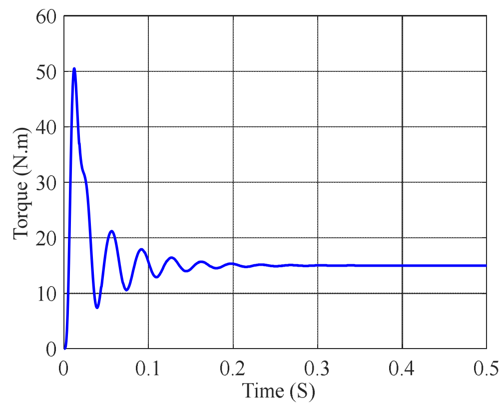

Figure 5. Motor torque under balanced voltage

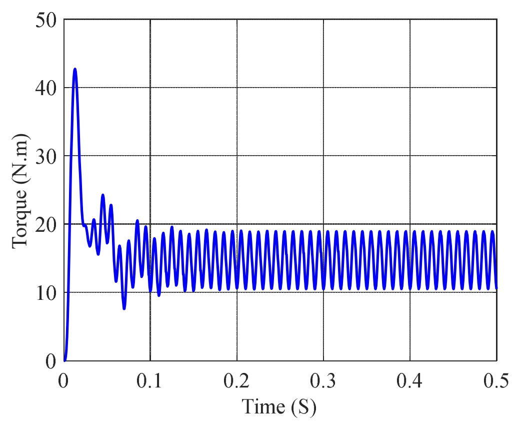

Figure 6. Motor torque under unbalanced voltage

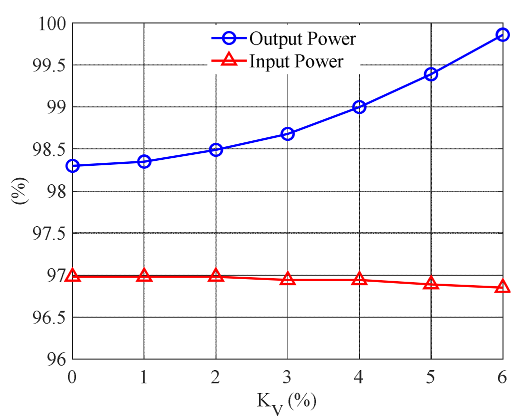

Figure 7. Input/Output powers under different conditions

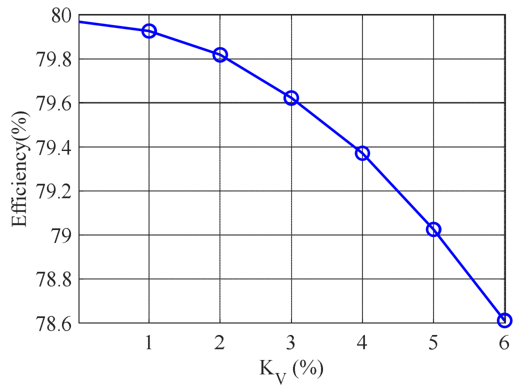

Figure 8. Efficiency under different conditions

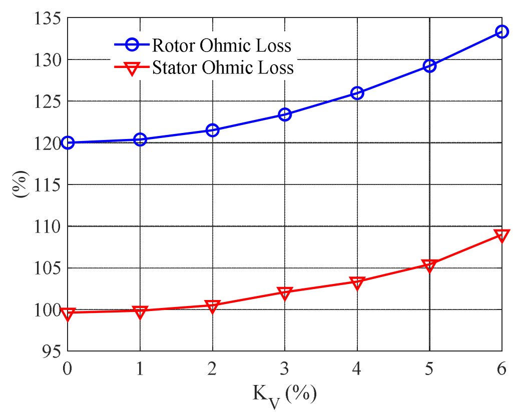

Figure 9. Stator and rotor ohmic losses under different conditions

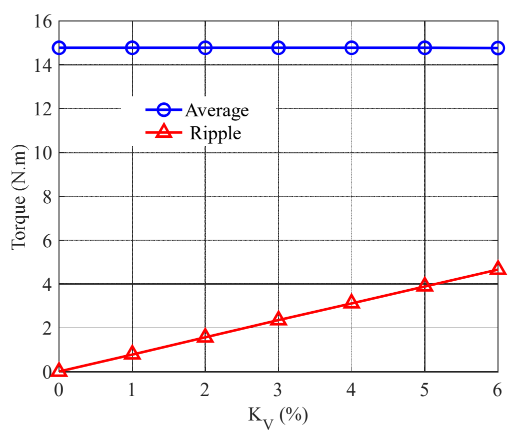

Figure 10. Average and ripple torque under different conditions

5. Conclusion

In this paper, the exact measure of the complex voltage unbalance factor (CVUF) was used to show the effects of unbalance in the power supply of a three-phase induction motor on its performance. The results showed that with increasing the CVUF value, the output power of the machine decreases along with the increase in its input power, which means that the efficiency of the machine decreases. On the other hand, assuming that the average voltage value remains constant, the core voltage did not change much with the increase in this factor, but the difference in stator and rotor impedances increased, which increased the intensity of the increase in rotor impedance losses. In addition, the reduction in the machine's produced torque and the appearance of torque ripple, which means vibration and noise of the machine, are also consequences of increasing voltage unbalance. It is suggested that a measure for reducing the motor loading based on the CVUF value be presented in future research to prevent damage to the machine in such conditions.

Conflicts of Interest

The authors declare no conflict of interest associated with this manuscript.

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How to cite this article: Yaseen LA, Aljweer HN, Abbood AM. Analysis of Voltage Unbalance Effects on a Three-Phase Induction Motor Performance. *Curr. Appl. Sci.*, 2026, 4(1):96-103. https://doi.org/10.22034/cas.2026.589576.1063