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The significance of the mode of voltage imbalance on the operation and energy losses of a 3-phase induction motor

Aderibigbe Israel Adekitan* and Ademola Abdulkareem

Department of Electrical and Information Engineering, College of Engineering, Covenant University, Ota, Ogun State, Nigeria

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Abstract

Induction motors are key to the operation of industries due to their ruggedness, but their performance is often impaired by power supply quality issues. This has triggered research on how voltage imbalance affects the operation and performance of such motors. This study considers the effect of the manner of variation of the positive sequence voltage component on the output power, losses and sensitivity of induction motor parameters. It applies three scenarios of positive sequence variation with respect to the negative sequence component. The results show that the performance of the motor, i.e., motor losses, output power, and the sensitivity of the motor's torque, power, and efficiency to sequence currents is dependent on the level of imbalance, and also, on the nature of the positive sequence voltage variation. Hence, the same level of voltage imbalance can trigger different operational scenarios and losses depending on how the imbalance occurs.

Keywords: Voltage unbalance, Motor performance characteristics, Three phase induction motor, Positive and negative sequence component, Power quality, Sensitivity analysis

1. Introduction

Power quality and reliability [1] are key requirements for efficient operation of three-phase induction motors. Usually, the nature of electrical loads varies significantly between domestic and commercial consumers. Coupled with periodic load demand changes, imbalanced line impedances and unequal sharing of single phase loads among the three (3) supply phases results in issues of line voltage variations that are referred to as voltage imbalance [2, 3]. According to [4], the under-voltage supply condition is the most common type of voltage imbalance, while the overvoltage imbalance scenario seldom occurs except in some countries where it is experienced during off-peak load periods. The efficiency of industrial processes and operations may be marred by power quality issues [5, 6]. Often the causal factors are due to external issues [7]. A detailed understanding of machine behaviour under an imbalanced supply is therefore very vital in deploying relevant corrective measures.

During a voltage imbalance supply condition, the magnitude of the negative sequence rotor resistance $\frac{R_r}{2-s}$ is small compared to R_r. As a result, the effective resistance of the rotor winding to the negative sequence current decreases depending on the slip value. This results in excessive current even for a small negative sequence voltage. It is further aggravated by the frequency $(2-s)f$ of the magnetic fields that are generating the negative sequence rotor current which is almost double the frequency of the supply resulting in harmonic currents [8], the skin effect [9], and these factors ultimately result in motor vibrations [10], high winding heat dissipation and the formation of hot spots in the motor windings. In an induction motor, the overall negative sequence current is the resultant superposition of negative sequence currents generated by motor faults and internal disturbances [11]. A negative sequence relay may be installed to protect a motor during imbalance, but the relay is often not fail proof and can be made redundant by open circuit fault [12].

Three-phase induction motors find applications in both domestic and industrial uses [13]. They are prone to the effects of voltage imbalance, which impairs a motor's operational performance, as was shown by experimental analysis [3]. The performance reliability of a three-phase motor can be improved using various fault tolerant drive topologies [14]. Voltage imbalance causes increased motor losses, reduced efficiency, motor torque pulsations and associated harmonics [15, 16]. The extent of these undesirable conditions on the motor is a function of the degree of the supply imbalance [17, 18]. The importance of the positive sequence voltage component in the derating of an induction motor was established experimentally [19]. This was done by monitoring the winding temperature changes with a varying ratio of positive and negative sequence voltage components. The study concluded that the influence of the positive sequence voltage cannot be adequately

*Corresponding author.
Email address: ade_kitan@yahoo.com
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measured using the available voltage imbalance measurement indices. A similar result was obtained in an analytical study [20], which showed that the derating curve obtained for a motor varies by the magnitude of the positive sequence voltage component. By increasing or decreasing the positive sequence voltage from the rated value, various results were obtained and this further confirms the significance of the positive sequence component. Another study [21] also recommended that the effects of positive sequence voltage should be considered to ensure adequate analysis of voltage imbalance for motor temperature and derating management.

An experimental study was conducted [3] using an array of sensors interfaced with a data acquisition board to evaluate the effect of voltage imbalance on the torque and efficiency of an induction motor. The result reveals variations in sensitivity with respect to the manner of imbalance. The study by [22], also evaluated the sensitivity of the loss model controller to variation in the parameters of induction motors as a result of magnetic saturation and temperature fluctuations. A non-linear polynomial of an induction motor was developed [23], and by means of an equivalent circuit, sensitivity analysis was carried out using mathematical and computational methods. Voltage imbalance analysis often seeks to identify and extensively determine the impact of the negative sequence component (current, voltage and torque) generated during imbalance on the operational performance and losses of a three-phase induction motor. Although, this is very important to monitor the consequences of the imbalance on a motor, this should be further supported with adequate analysis of the effects of changes in the magnitude and pattern of variation of the positive sequence component on the overall effect of the prevailing imbalance. In this study, the influence of the manner of variations of the positive sequence voltage magnitude on key motor operational parameters during voltage imbalance is examined.

2. Definition of voltage unbalance

Voltage imbalance is a random, undesired variation of the supply voltage from the nominal value. IEC 60034-26 defines voltage unbalance in terms of the symmetrical sequence component equivalent of the phase terms. As defined by IEC, the Voltage Unbalance Factor (VUF) is the ratio of the negative (V_2) and positive sequence (V_1) voltage components [24]:

$$\text{VUF}(\%) = K_v = \frac{V_2}{V_1} \times 100\ \% \quad (1)$$

The sufficiency of this definition for accurate voltage unbalance analysis, and ultimately for motor derating purposes has been questioned. This is primarily because for any value of Kv, there are an infinite number of voltage combinations that will give the same Kv value [25] The effect of each of these combinations on the motor may not be same, with each yielding varying output torque pulsations and motor losses. To account for this deficiency and provide an improved imbalance definition, the Kv is typically defined alongside another motor performance parameter. A common definition is the complex voltage unbalance factor (CVUF) [4]:

$$CVUF = \frac{V_2\angle\theta_2}{V_1\angle\theta_1} = K_v\angle\theta_v \quad (2)$$

CVUF includes the phase angle of the unbalance, and this can be used to better predict the motor losses and efficiency during unbalance operational condition [3, 25]. A study by [26] concludes that the negative sequence motor parameter components intensify the degree of efficiency and torque variation with respect to a given positive sequence voltage. The research of [27, 28] asserts the importance of considering the positive sequence voltage together with Kv. According to [29], in an under-voltage unbalance condition, a derated motor operates at a better efficiency than a normally operating induction motor. An analytical study by [30] opines that although CVUF is a better definition of voltage imbalance than Kv, the CVUF cannot sufficiently indicate the full effect of supply imbalance on motor performance without due emphasis on the manner of the imbalance. In the study by [31], a novel approach for improving the Kv definition of voltage imbalance was proposed using an unbalance voltage code that provides additional information on the nature of the imbalance. The voltage code provides information on each of the three phases and also differentiates between voltage magnitude and phase angle induced voltage imbalance.

The National Electrical Manufactures Association (NEMA) defines voltage unbalance as the ratio of the maximum voltage deviation from the average line voltage to the average line voltage as shown in Eq. 3. The voltage magnitude unbalance definition using NEMA varies slightly with definitions using Kv by IEC [2].

NEMA Voltage unbalance (%) =

$$\frac{\text{Max}\left[\left|V_{ab}\text{-}V_{Lavg}\right|,\left|V_{bc}\text{-}V_{Lavg}\right|,\left|V_{ca}\text{-}V_{Lavg}\right|\right]}{V_{Lavg}} \times 100 \quad (3)$$

$$\text{Where } V_{Lavg} = \frac{(V_{ab}+V_{bc}+V_{ca})}{3} \quad (4)$$

A number of previous studies carried out induction motor performance studies at a specific Kv values, at 5% unbalance, using various voltage combinations that gives 5% unbalance for analysis. Additionally, the positive sequence voltage is usually fixed to simplify the analysis [25]. This study considers three positive sequence voltage variation scenarios for a full understanding of the effects of various manners of voltage imbalance on motor performance. The current study evaluates the sensitivity of a three-phase induction motor’s operational parameters using sequence components. The analysis further considers the effects of the often-neglected core loss on the motor performance and sensitivity.

3. Motor analysis using symmetrical component

This study is modelled based on the Fortescue's symmetrical component theorem, which resolves an asymmetrical phase voltage into symmetrical positive, negative and zero sequence components. The equivalent induction motor circuit for the three sequence components is shown in Figures 1 and 2. In this analysis, the supply frequency is constant and constant losses are assumed included in the equivalent circuit.

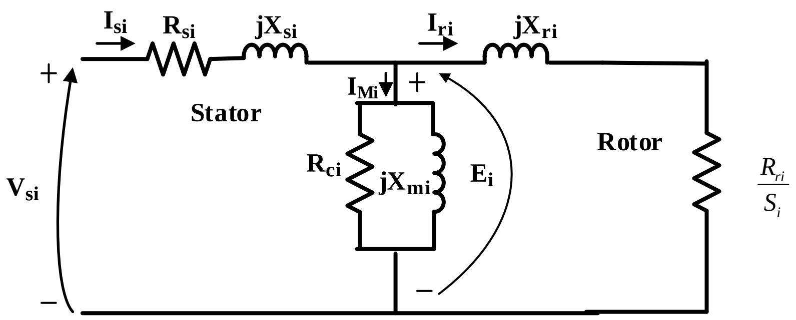

Figure 1 Positive and negative sequence equivalent circuit

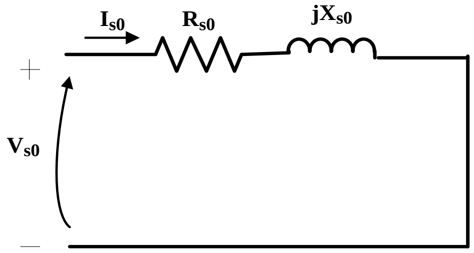

Figure 2 Zero sequence equivalent circuit

where $s_1 = slip\ (s)$ and $s_2 = 2 - s$

The positive sequence circuit impedance is given as Z_1, while the negative sequence circuit impedance is Z_2.

The phase components are transformed into sequence components as follows:

$$\begin{pmatrix} V_0 \\ V_1 \\ V_2 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (5)$$

$$a = 1\angle 120° \quad (6)$$

The stator currents are defined as follows [30]:

$$|Is_a| = |Is_1| \times \sqrt{1 + \left[\frac{k_v}{k_z}\right]^2 + 2\frac{k_v}{k_z}\cos\theta_{vz}} \quad (7)$$

$$|Is_b| = |Is_1| \times \sqrt{1 + \left[\frac{k_v}{k_z}\right]^2 + 2\frac{k_v}{k_z}\cos(\theta_{vz} - \frac{2\pi}{3})} \quad (8)$$

$$|Is_c| = |Is_1| \times \sqrt{1 + \left[\frac{k_v}{k_z}\right]^2 + 2\frac{k_v}{k_z}\cos(\theta_{vz} + \frac{2\pi}{3})} \quad (9)$$

where $k_z = \frac{Z_2}{Z_1}\angle\theta_z$ (10)

The complex current unbalance factor is given as:

$$CCUF = K_c\angle\theta_c = \frac{I_2}{I_1}\angle\theta_c \quad (11)$$

The sequence impedance B_i is defined as:

$$B_i = \frac{\alpha}{(\mathrm{R_{si}} + \mathrm{jX_{si}})\left[\alpha + (\mathrm{jX_{ri}} + \frac{\mathrm{R_{ri}}}{\mathrm{s_i}})\beta\right] + \alpha(\mathrm{jX_{ri}} + \frac{\mathrm{R_{ri}}}{\mathrm{s_i}})} \quad (12)$$

$$\alpha = \mathrm{R_c} \cdot \mathrm{jX_m} \quad (13)$$

$$\beta = \mathrm{R_c} + \mathrm{jX_m} \quad (14)$$

The positive sequence rotor current Ir_1 and the negative sequence rotor current Ir_2 can be obtained using Eq. (15) and (16).

$$Ir_1 = B_1 \cdot V_1 \quad (15)$$

$$Ir_2 = B_2 \cdot V_2 \quad (16)$$

The real power (P_{in}), the reactive input power (Q_{in}) and the output power (P_{out}) are obtained as follows:

$$P_{in} = 3(V_0 I_0 \cos\phi_0 + V_1 I_1 \cos\phi_1 + V_2 I_2 \cos\phi_2) \quad (17)$$

$$Q_{in} = 3(V_0 I_0 \sin\phi_0 + V_1 I_1 \sin\phi_1 + V_2 I_2 \sin\phi_2) \quad (18)$$

$$P_{out} = P_{in} - Losses \quad (19)$$

For i = 0, 1, 2 for zero, positive and negative components:

$$Torque = \frac{3R_r}{W_s}\left[\frac{{I_{r1}}^2}{s} - \frac{{I_{r2}}^2}{2 - s}\right] - W_s(1-s)C_L \quad (20)$$

According to [3],

$$P_{out} = -{\omega_s}^2 k_0 C_L + 3{I_{r1}}^2 R_{r1} k_1 + 3{I_{r2}}^2 R_{r2} k_2 \quad (21)$$

Where,

$$k_0 = (1 - s_1)^2 \quad (22)$$

$$k_1 = \frac{1 - s_1}{s_1} \quad (23)$$

$$k_2 = \frac{s_1 - 1}{s_2} \quad (24)$$

C_L is the rotational loss constant.

The sequence parameters can be converted back to phase terms using:

$$P^{abc} = A \times P^{0+-} \quad (25)$$

$$\text{where } A = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \quad (26)$$

A typical mathematical model has an inherent degree of uncertainty that can be examined using sensitivity analysis. This analysis allows the determination of the extent to which the output variables of the model vary with changes in the value of the input parameter. A sensitivity study can be achieved using various methods, such as a local method that determines the partial derivative of a particular model output with respect to a given input. Scatter plots and regression analysis are also some of the alternative methods. In this study, the sensitivity of a three-phase induction motor's torque, output power and efficiency to the positive and negative sequence current is evaluated in the three case studies, the rated, increased and decreased values of the positive sequence voltage.

The sensitivity of the output power with respect to the positive and negative sequence currents is defined by Eq. (27) and (28).

$$\frac{\partial P_{out}}{\partial I_1} = 6 I_{r1} R_{r1} k_1 \quad (27)$$

$$\frac{\partial P_{out}}{\partial I_2} = 6 I_{r2} R_{r2} k_2 \quad (28)$$

The sensitivity of the torque with respect to the positive and negative sequence currents is defined by Eq. (29) and (30).

$$\frac{\partial T_{out}}{\partial I_1} = \frac{6 I_{r1} R_{r1}}{s_1 \omega_s} \quad (29)$$

$$\frac{\partial T_{out}}{\partial I_2} = \frac{-6 I_{r2} R_{r2}}{s_2 \omega_s} \quad (30)$$

The sensitivity of the motor's efficiency with respect to the positive and negative sequence currents is defined by Eq. (31) and (32).

$$\frac{\partial \eta}{\partial I_1} = \frac{6 I_{r1} R_{r1} k_1}{P_{in}} - \frac{6 P_{out} \cdot V_1 \cos\phi_1}{P_{in}^{\ 2}} \quad (31)$$

$$\frac{\partial \eta}{\partial I_2} = \frac{6 I_{r2} R_2 k_2}{P_{in}} - \frac{6 P_{out} \cdot V_2 \cos\phi_2}{P_{in}^{\ 2}} \quad (32)$$

4. Simulated analysis of motor performance under a supply imbalance

A simulation was setup on MATLAB to study the outlined objectives of determining the impact of the manner of positive sequence voltage variation on the sensitivity of the motor's performance parameters to sequence currents, and the overall effect on the performance of a three-phase induction motor. The motor has the following parameters: 415 V, 50 Hz, Xm = 20.4 Ω, $Xs_{1\&2}$ = 0.402 Ω, $Xr_{1\&2}$ = 0.309 Ω, $Rr_{1\&2}$ = 0.310 Ω, $Rs_{1\&2}$ = 0.310 Ω, Rc = 1026 Ω, Rs_0 = 5.24 Ω, Xs_0 = 0.38 Ω.

Under imbalanced voltage conditions, the effect of phase angle deviation from the nominal balanced value dominates the effect of voltage magnitude unbalance as more sequence current is produced [17, 32] by increasing phase angle deviations. Since the variation of θ_v in CVUF is random during unbalance [33], to adequately study the effect of the nature of positive sequence voltage magnitude variation only on the induction motor, the phase angles of the line voltage are maintained at the normal values of $V_{ab}\angle 0°$,$V_{bc}\angle$-120°, and $V_{ca}\angle 120°$. Using a rated line voltage of 415 V, the three study cases of the positive sequence voltage (v_1) were considered, with unbalance variations between 0 to 6% as follows:

a) Study I: A constant positive sequence voltage (415 V)
b) Study II: Increasing positive sequence voltage (415V to 431.6 V)
c) Study III: Decreasing positive sequence voltage (415 to 398.4 V)

For this study, Table 1 shows the difference in the definition of voltage unbalance by NEMA and IEC, as the voltage unbalance is increased from 0 to 6%, and this confirms a slight difference between the two definitions, previous established by related studies.

The results of the three cases are shown comparatively in the graphs of Figures 3 to 18. For each of the three cases, Kv was varied between 0 - 6% and the values of the motor output parameters were carefully studied for comparative analysis. For Scenario I, the positive sequence voltage and positive sequence current remained constant at 415 V and 22.0408 A, while for Scenario II, it was increased from 415V to 431.6 V, and from 22.0408 A to 22.9225 A. For the third scenario, the voltage was reduced from 415 to 398.4 V and the current slightly dropped from 22.0408 A to 21.1592 A.

The result shows that the winding losses are significantly dependent on the manner of the voltage unbalance. From the balance state (Kv = 0) values of 317.2 W, 451.79 W and 922.4 W for the total rotor losses, total stator losses, and the total winding losses were respectively observed. For scenario I there was a maximum increase from the (Kv = 0) values by 82.29%, 59.56% and 57.48% respectively for Kv = 6%. For Scenario II, the increase was by 97.17%, 72.58% and 70.34% respectively, and for Scenario III, the increase was by 68%, 47.05% and 45.14%. The highest loss occurred when the

Table 1 Comparison of IEC with NEMA definition of percentage voltage unbalance

IEC (%)	0.000	0.500	1.000	1.500	2.000	2.500
NEMA (%)	0.000	0.499	0.998	1.494	1.990	2.484
IEC (%)	3.500	4.000	4.500	5.000	5.500	6.000
NEMA (%)	3.468	3.958	4.446	4.933	5.418	5.902

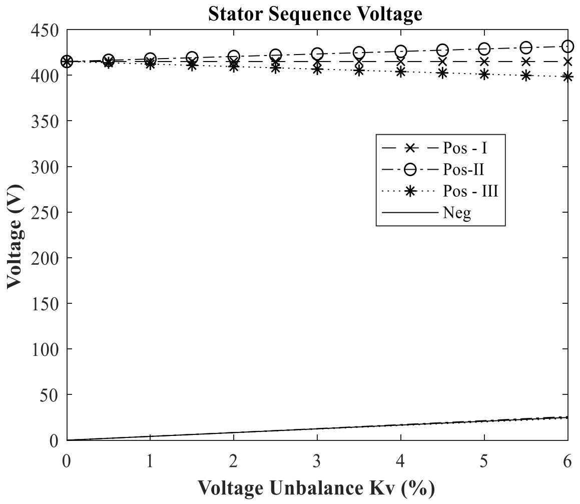

Figure 3 A plot of the variation of sequence voltage with increasing Kv

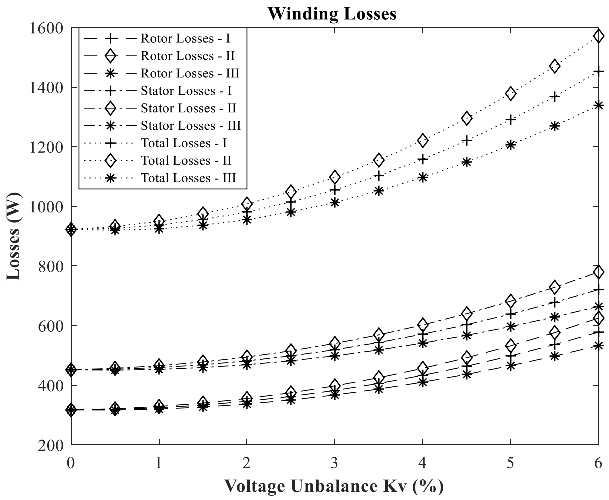

Figure 5 Comparison of motor winding losses for the three cases

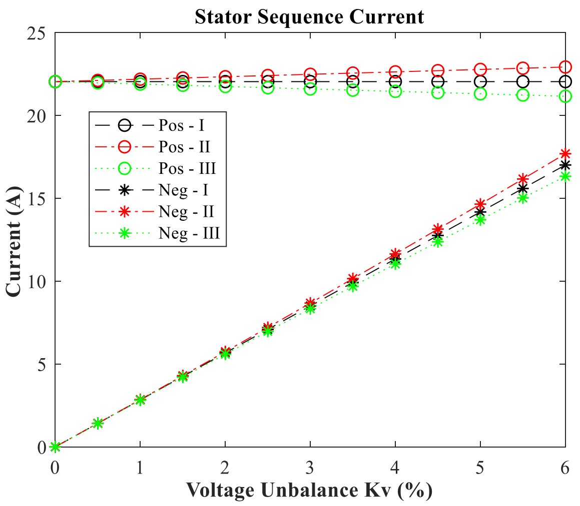

Figure 4 Comparison of sequence current for the three case

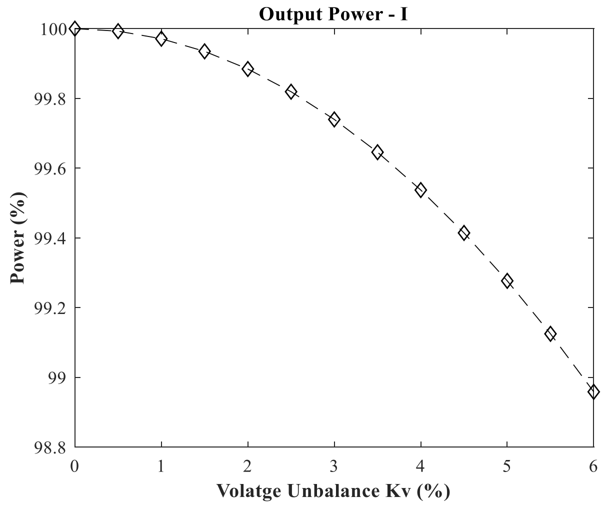

Figure 6 Output power variation with Kv for Scenario I

positive sequence voltage increased with the unbalance. This is because the small additional increase in positive sequence current further contributed to the total copper losses.

The power output of the motor from Kv = 0 to Kv = 6 for the first scenario was reduced by 1.04%, while it increased significantly by 7.03% in Scenario II, and was reduced by 8.81% for Scenario III. It is notable that even though the total losses increased more for Scenario II compared with the other two cases, the overall power output for Scenario II with increasing positive sequence voltage is still greater than that of Scenarios I and III. Scenario III showed a significant drop in output power. An efficiency plot is presented in Figure 9. It shows that even though the output power varied in the three cases, the efficiency of the motor did not significantly vary. This is because as the positive sequence voltage varies, the input power, output power and losses all vary accordingly. The extent to which a small negative sequence voltage produces a far greater negative sequence current is emphasized in Figure 10. It shows the relationship between Kv and Kc. As Kv increased from 0 to 6%, Kc increased from 0 to 77.175%.

This is quite substantial considering the associated copper loss with such a rise in current and the impact on motor winding insulation [34]. According to the study by [27], the observed Kc varied between four to eleven times the value of Kv.

Table 2 Comparison of motor efficiency with and without core loss consideration

	Motor Efficiency (%)												
With core loss	93.06	93.04	92.96	92.83	92.64	92.41	92.12	91.79	91.40	90.97	90.49	89.96	89.39
No core loss	94.22	94.19	94.11	93.98	93.79	93.56	93.27	92.93	92.54	92.11	91.62	91.09	90.51

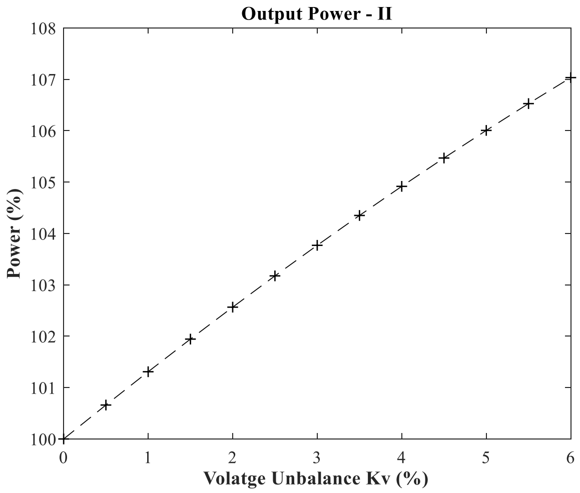

Figure 7 Output power variation with Kv for Scenario II

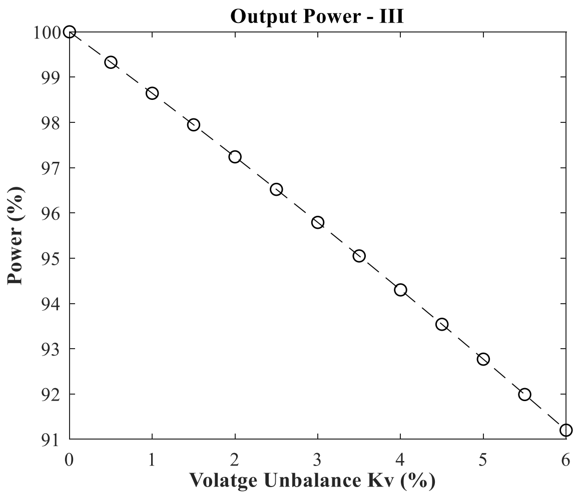

Figure 8 Output power variation with Kv for Scenario III

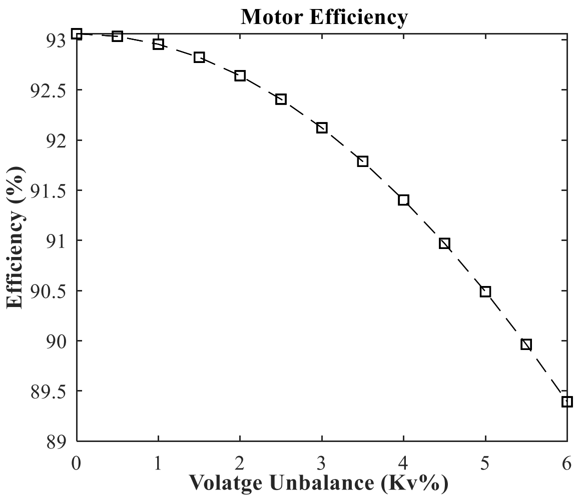

Figure 9 Motor efficiency variations with increasing Kv

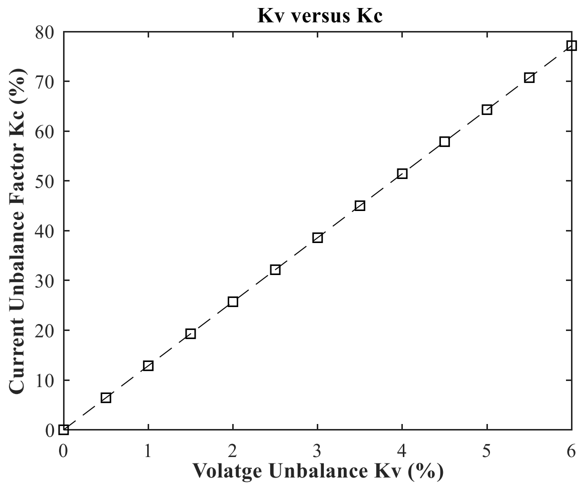

Figure 10 A plot of Kc against Kv

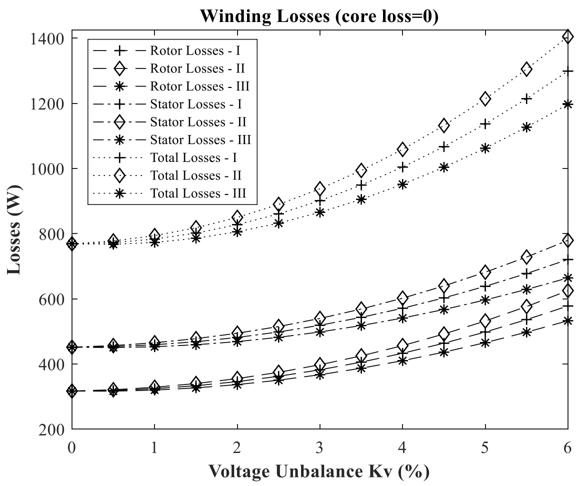

Figure 11 Winding losses when core loss is not considered

4.1 The significance of core loss

Core loss is often neglected in most induction motor winding analyses for simplicity and because a no-load test is required to determine the core loss value. The current study considers the core loss. Its importance in motor studies is emphasized by the results in Table 2. If the core loss is ignored in the motor analysis, it creates a false scenario of increased motor efficiency which does not correspond with reality. As shown in Figure 11, there is a significant reduction in total winding losses when core loss in ignored, as compared with Figure 5 which considered the motor core loss.

4.2 Sensitivity of motor parameters to positive and negative sequence current

The graphs of Figures 12 to 18 show the result of the normalized sensitivity of the motor output power, torque and efficiency to the negative and positive sequence currents. The values are plotted with respect to the value at the balanced state (Kv = 0). This expresses the extent to which these output parameters are affected by changes in the sequence currents. The power sensitivity curves of Figures 12 and 13, shows that for Scenario I with a constant positive sequence voltage, changes in the output power sensitivity are driven by the negative sequence current, while for Scenarios II and III, there is no significant difference between the contribution of the negative sequence current for these two scenarios with that of Scenario I. However, there is major additional contribution of the positive sequence current to power output reflected by the deviation of the two lines from the zero horizontal line in Figure 12. A similar result is observed for the torque sensitivity graphs of Figures 14 and 15.

The efficiency sensitivity curves of Figures 16 and 18, also show the major contribution of the negative sequence current compared with the positive sequence current for Scenario I, but for Scenarios II and III, there is a significant change in the efficiency due to the positive sequence current too, as the negative sequence current did not change significantly from the Scenario I value. Although, it should be noted that sensitivity to the negative sequence current is highest for Scenario III, which experienced a reduction in positive sequence voltage.

Furthermore, the importance of core loss is also emphasized by the difference between the graphs of Figures 16 and 17. They show the sensitivity of efficiency to positive sequence current when core loss is considered and when it is ignored. When core loss is considered starting from the balanced state value of 0.0163 (0%), it increased to 0.0191 (17.18%), presented as 0.1718 in Figure 15 for Scenario I, and 0.0184 (12.88%) for Scenario II. It was 0.0199 (22.09%) for Scenario III. When the core loss is not considered, as shown in Figure 17, starting from the balanced state value of 0.0153 (0%), the sensitivity increased to 0.0181 (18.3%) for Scenario I, and 0.0174 (13.73%) for Scenario II. It was 0.0189 (23.52%) for III. This difference in sensitivity shows that core loss considered is slightly lower than the values when it is not included in motor performance analysis.

The slope and direction of the sensitivity curve, below or above the horizontal axis determines whether the output parameter increases or decreases with changes in the sequence components. It indicates the rate of the change. From the results, in terms of the percentage change in sensitivity with increasing values of Kv from 0 to 6, the torque, the output power and the efficiency of the motor are all more sensitive to the negative sequence current than the positive sequence current. This emphasizes the impact of the rapidly changing negative sequence current on the performance of the motor during voltage unbalance. From the three scenarios studied, it becomes apparent that the magnitude and the manner of the variation of the positive sequence current significantly influences the impact of the prevailing voltage unbalance on key motor operational parameters and losses.

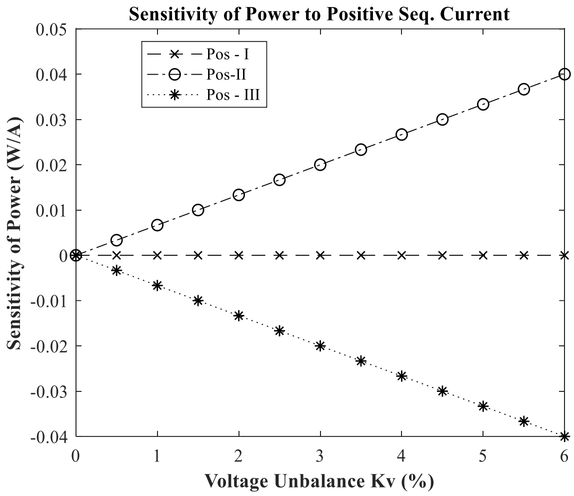

Figure 12 A plot of output power sensitivity to positive sequence current

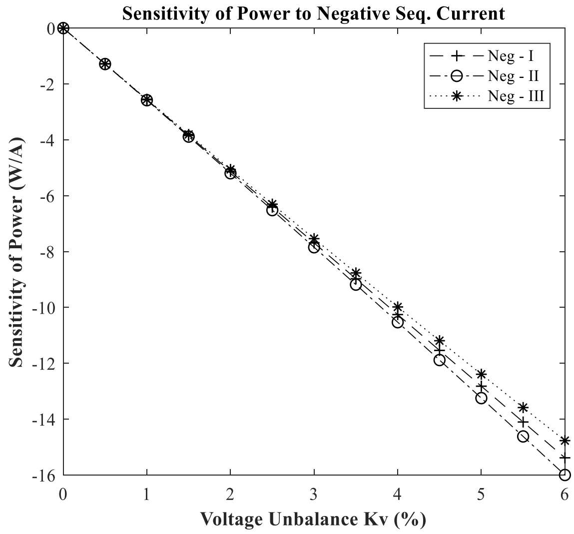

Figure 13 A plot of output power sensitivity to negative sequence current

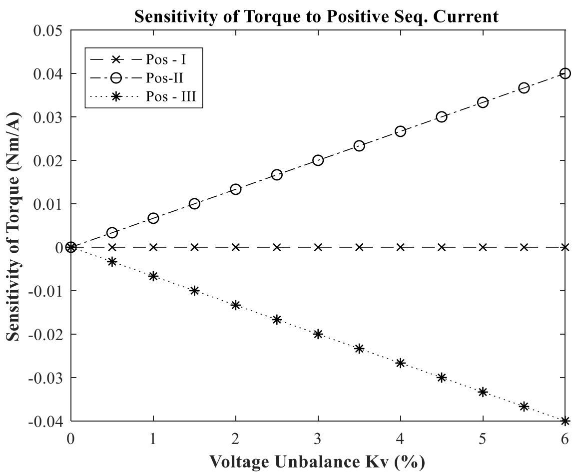

Figure 14 A plot of torque sensitivity to positive sequence current

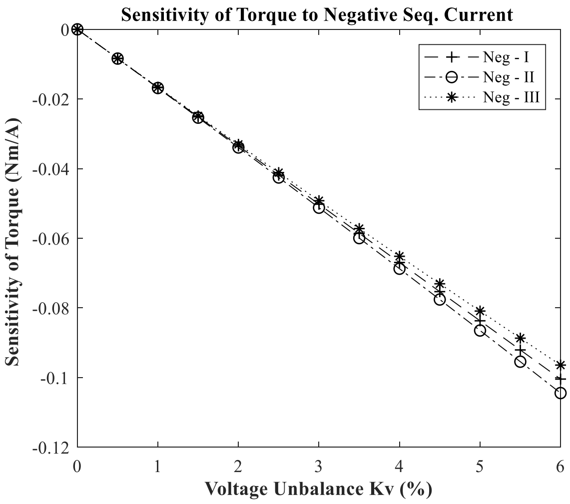

Figure 15 A plot of torque sensitivity to negative sequence current

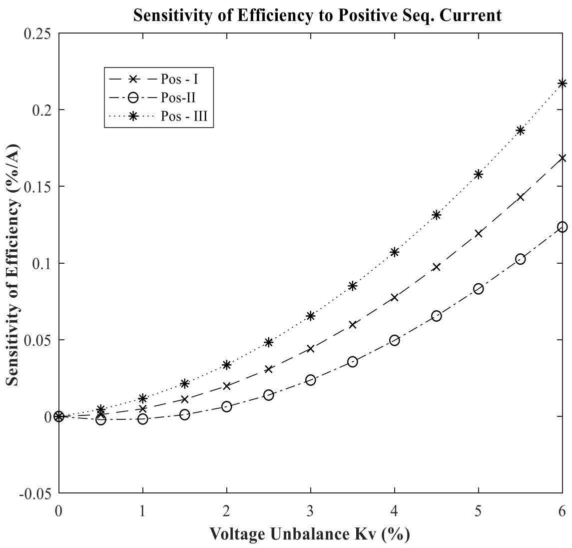

Figure 16 A plot of efficiency sensitivity to positive sequence current

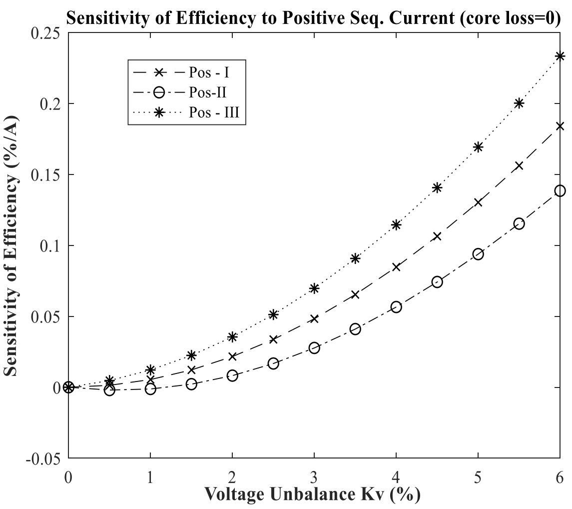

Figure 17 A plot of efficiency sensitivity to positive sequence current when core loss is not considered

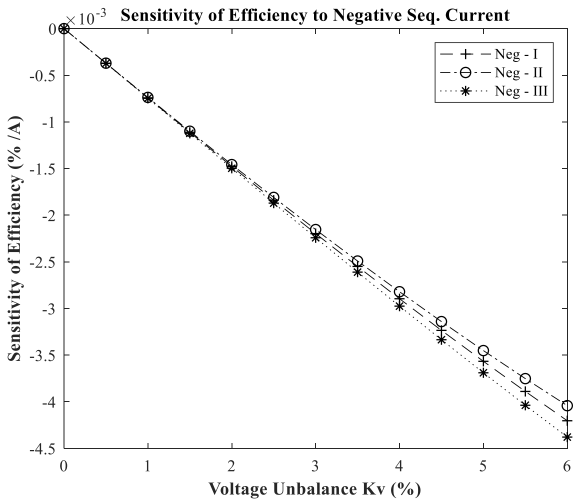

Figure 18 A plot of the sensitivity of efficiency to negative sequence current variations

5. Conclusions

Voltage umbalance is highly undesirable due to its ability to stimulate rapid and excessive generation of negative sequence current that adversely impacts winding reliability. It also increases the cost of energy consumption for the same amount of productive work. This study has revealed the significance of the manner of variation of the positive sequence voltage on motor losses, output power, and the sensitivity of key parameters of a three-phase induction motor to sequence currents during supply imbalance. The consequence of voltage unbalance on the operation of a three-phase induction motor is not only dependent on the magnitude of the deviation, but also on the manner in which the deviation occurs. The research findings also show that due consideration of motor core loss is vital for an accurate analysis. Failure to include the core loss in motor studies will give a false impression of increased efficiency and an increased sensitivity of motor efficiency to positive sequence current.

The analysis reveals that motor winding losses are more severe when the positive sequence voltage increases during voltage unbalance. The output power of an induction motor varies more when the positive sequence voltage decreases with increasing Kv. Likewise, the sensitivity of the motor's efficiency to positive sequence current is also more severe when the positive sequence voltage decreases. The motor torque and power have zero sensitivity to positive sequence current when the positive sequence voltage remains constant. Hence, this shows that the impact of voltage unbalance on the induction motor is not only a function of the magnitude of the negative sequence current and the level of voltage unbalance, but it is also dependent on the nature of the positive sequence voltage variation.

6. References

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7. Appendix

The variation of the three-phase line voltages for the three scenarios considered is presented in this section.

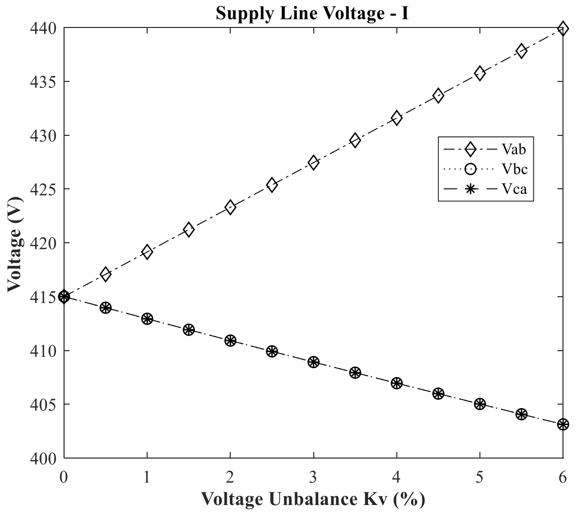

Figure 19 Voltage variations that resulted in constant positive sequence voltage

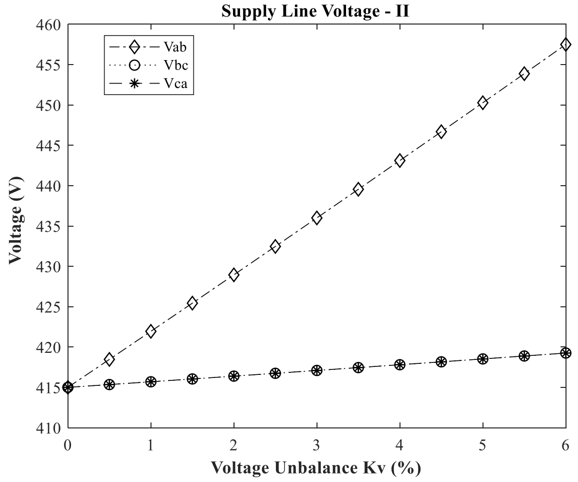

Figure 20 Voltage variations that resulted in increasing positive sequence voltage

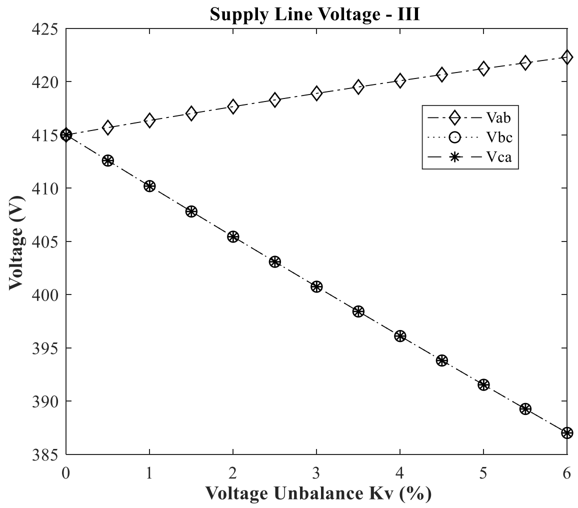

Figure 21 Voltage variations that resulted in decreasing positive sequence voltage