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Assessment of the Influence of Voltage Unbalance on Three-Phase Operation of Power System

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Abstract

In the power system operation, efficient energy utilization is vital. However, with the advent of voltage unbalance, the system is faced with reduced efficiency in the process of energy conversion. This phenomenon occurs due to the asymmetrical behavior of the operating voltage phasor displacement and magnitudes. This occurrence has been attributed to a number of events; such as blown fuse which is as a result of unbalanced loading of the power factor correction capacitors, unbalanced source voltage, unequalled impedance in three-phase system, etc. Though, it is believed that the voltage unbalance phenomenon is more prevalent in the residential and commercial consumer supply. However, its impact on the industrial sector cannot be overemphasized. The power system operation of the induction motor; as the major energy conversion device; is modelled using the Park's transformation. This i s deployed to evaluate the influence of voltage unbalance by adopting the National Electrical Manufacturers Association (NEMA) and institution of Electrical and Electronic Engineering (IEEE) bench marking parameters for evaluating the system's Voltage Unbalance Factor (VUF). The results show that the motor efficiency drop from 93.2% at 0% of voltage unbalance to 59.51% at 5% of unbalance. This suggests that the power system operation should be closely monitored to ensure that voltage unbalance is eliminated or mitigated by all means; so as to avoid loss of revenue to poor management of the system's power quality.

Keywords: Motor efficiency, loading loss, energy conversion, electrical behaviour, voltage unbalance

1.0 INTRODUCTION

The electrical energy management study is a crucial area of research for the efficient utilization of energy. It thus encompasses a series of inter-connectivity of electricity supply from generation, to its transmission, distribution, and utilization [1]. A screwd management of energy supply and consumption has a veritable influence on uninterrupted electricity supply which is the aim of any power utility company [2]. More importantly, the modern manufacturing and commercial electrical system are sensitive to quality of power supply [3]. Thus, the electrical power grid as an interconnected network must be designed for delivering reliable power supply with very minimal interruption of service.

Meanwhile, the electricity supply in Nigeria is bedeviled with the power quality (PQ) problems. This is evidently revealed in such occurrence as the momentary interruptions, electrical noise, harmonic distortions, swells, transients, flickering lights, voltage sags, among others.

However, the three prevalent ones in respect of the industrial and commercial loads are voltage sags, harmonics, and transients [4]. This is mainly due to the electrical components and devices that are installed in the systems which include the variable nonlinear loads, voltage power regulators, and power electronics converters. These are notable for injecting harmonics into the grid; thus resulting in the advent of power quality challenges in the network [5].

It has been established that the efficiency of the system performance decreases with increasing cases of poor power quality experienced by the network. This leads to power loss due to undue heat generated in the machines as well as the capacitors connected to the system. This events results shortened lifespan of the electrical equipment and machines [6].

Most times, power fluctuations result in variation of certain operating parameters leading to voltage unbalance. In which case, whenever voltage unbalance occurs, the phase or line voltages become asymmetrical. This is mainly due to unequal magnitude and phase dispersion of the impedance in the 3-phase system. This event could be due to extrinsic and intrinsic factors. In

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case of the extrinsic activities, bank of power factor correction equipment giving rise to blown fuse or fault in a power transformer when the voltage unbalance is said to be acquired (i.e., extrinsic); which is as a result of large single-phase loads. This thus makes the three-phase induction motor-driven system experience reduced performance [6].

The induction motors, as the workhorse of the industry; are known to be very predominant means of energy conversion for both industrial and commercial loads. Therefore, it is fair to state that in view of this, the inductive loads are expected to have immense influence on the system capacity performance and efficiency in respect of the overall power factor of the system operation. Thus if the system operates at low power factor due to the inductive loads, then it leads to poor power quality condition in the entire system. In a number of instances, the industries are made to pay for apparent power used which thus means there would be penalty for industries that are operate at low power factor range. Hence, in a quest to improve the power factor status of the system, the installation of the bank of capacitors is adopted so as to improve the system capacity, performance and efficiency while at the same swing saving revenue

Thus, the penalty cost connected with deficient operation of electric motors under poor power quality condition is primarily reflected in the monthly utility bills in large loads. Beyond the extrinsic charges incurred due to poor power quality condition, there is high tendency of the burnout of the motors (if it operates under poor power quality for an extensive duration of time), which has the capability to degrade the winding of the motors, leading to short circuit and eventual failure of the motor due to increasingly high intrinsic internal heat which results in failure of the motors. This condition is sadly not covered by the warranty arrangement of the manufacturers.

More importantly, modern operation of power system is closely intertwined with control activities which is better necessitated by the programmable logic controllers and microprocessor control devices [7]. These electrical systems are highly ultra-sensitive to fluctuations which may lead to loss of memory resulting in huge loss of service to the equipment downtime, machine parts replacement, interruption of work, and possibly supplemental labour. Other electrical equipment that suffers grievously in the advent of poor power quality are the power transformers. This is because their windings suffer from increasingly high internal thermal decay under the influence of poor power quality conditions.

Thus, this study is inspired to evaluate the electrical behaviors of three-phase induction motors; as it is necessitated by the adverse effects of voltage unbalance on the operation of the electrical systems. Several methods have been employed for solving for voltage unbalance in power and electrical systems, some of these methods are experimental while others are analytical [8]. Further to this, the investigation has very limited information for the deployment of induction motors commercial and industrial loads in an environment with very poor power quality measurement facilities [9]. This is a further motivation for this work.

2.0 METHODOLOGY

2.1 Introduction

Due several qualities of the induction motors, they are widely deployed in the industries for the energy conversion process. This is due to its efficient power output, reliability, ruggedness, almost maintenance-free and cost. However, in the eventuality of poor power quality condition; thus, the aggregate influence of the dynamic characteristics of the induction motors (IMs) produce disturbances in the electrical grid. Most of the deployed motors are the 3-phase IMs. So, its operation depends on the mains supply frequency; thus, it is very reliable in constant speed applications. All these qualities shall be harnessed in the design of the improvement of the systems operation.

2.2 Materials

As earlier stated, the induction motors are highly important to the energy conversion in the industrial and commercial loads. However, the energy conversion efficiency may be determined by a number of electrical behaviours. Thus, the material required for understudying the voltage unbalance phenomenon is mainly mathematical modelling of the loads with the nature of the source of supply. This means that the mathematical modelling of the motors is simulated by observing the characteristics during starting and running stages of the motors. This is carried out with the assumption that the power source of the installed motors is unbalanced voltage-source. From the available knowledge, the modelling is approached from the decomposition of the three-phase source (abc) to two orthogonal components – direct-quadrature (dq) using Park's transformation.

In implementing this, the Simulink package of the MATLAB® 2018a 64-bit version of the software is deployed to generate results from the developed models. It is matrix-based, high-level language with an interactive Simulink® environment which is created to generate virtual representation of the real-life version of the operation of the motors under loading condition.

2.3 *Methods*

In as much as there are several methods for energy conversion process; its analysis is crucial to measuring the efficient conversion of energy [9]. It will implement the park's transformation for the analysis. The purpose of this transformation is to simplify computational efficiency and also guarantees possibility of control of the direct-axis and quadrature-axis components of the currents and voltages. The Park's transformation and symmetrical component transformation are given prominence in the analysis of the three-phase motors [10]. This and others will be addressed in the subsequent sections and subsections.

2.3.1 *Modelling of three-phase Induction Motor (IM)*

In the analysis of three-phase induction motor, using the synchronous reference frame (SRF) theory, the three-phase voltage labelled as v_a, v_b and v_c is supplied to the stator of the IM. This can be re-modelled to its equivalent stator d-axis voltage (v_{sd}) and stator q-axis voltage (v_{sq}). Thus v_{sd} and v_{sq} can be written as expressed in equations (1) and (2) respectively. While equation (3) gives the zero component of the transformation.

$$v_{sd} = {}^2\!/_3\, v_a - {}^1\!/_3\, v_b - {}^1\!/_3\, v_c \quad (1)$$

$$v_{sq} = {}^{\sqrt{3}}\!/_3\, v_b - {}^{\sqrt{3}}\!/_3\, v_c \quad (2)$$

$$v_{s0} = {}^1\!/_3\, v_a + {}^1\!/_3\, v_b + {}^1\!/_3\, v_c \quad (3)$$

Expressing equations (1)-(3) in matrix form; it leads to equation (4).

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ v_{s0} \end{bmatrix} = {}^1\!/_3 \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (4)$$

Thus, the equivalent IM per phase is as shown in ***Error! Reference source not found.*** where R_s is the stator resistance in ohms; L_s is the stator inductance in H; R_c is the core resistance; L_m is the magnetizing inductance; R_r is the rotor resistance; and L_r is the rotor inductance. The stator leakage inductance (L_{ls}) and the rotor leakage inductance (L_{lr}) are in parallel to the magnetizing inductance.

The stator angular speed (ω_s) is given as:

$$\omega_s = 2\pi f \quad (5)$$

f is the supply frequency.

For the purpose of controlling the input to the motor; the stator frequency could be varied to create synchronously rotating magnetic field at the frequency of the power supply.

Therefore, the stator leakage impedance (X_{ls}), the rotor leakage impedance (X_{lr}) and the magnetizing impedance (X_m) can be calculated as given in equations (6) through (8).

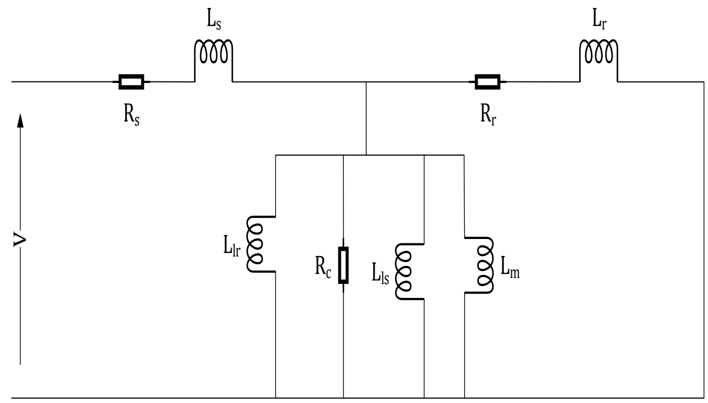

Figure 1: Single-phase equivalent circuit of IM

$$X_{ls} = \omega_s L_{ls} \quad (6)$$

$$X_{lr} = \omega_s L_{lr} \quad (7)$$

$$X_m = \omega_s L_m \quad (8)$$

As shown in the equivalent circuit (**Error! Reference source not found.**), L_{lr}, L_{ls} and L_m are in parallel to one another. Therefore, the equivalent total impedance (X_{srm}) of X_{ls}, X_{lr} and X_m is given as in equation (9).

$$X_{srm} = \frac{X_{ls}X_{lr}X_m}{X_{ls}X_{lr} + X_{lr}X_m + X_{ls}X_m} \quad (9)$$

The magnitude of the stator inductance (L_s) and the rotor inductance (L_r) are given in equations (10) and (11).

$$L_s = L_{ls} + L_m \quad (10)$$

$$L_r = L_{lr} + L_m \quad (11)$$

In order to simplify the 3-phase circuit analysis in relative motion, the circuit is transformed to two-axis equivalent circuit – direct-quadrature (d-q) axis. Also, using dq-axis analysis for IMs helps in effective control using principles such as vector control [1]. The magnetizing d-axis flux (λ_{md}) and the magnetizing q-axis flux (λ_{mq}) are given in equations (12) and (13) [2].

$$\lambda_{md} = \left(\frac{\lambda_{sd}}{X_{ls}} + \frac{\lambda_{rd}}{X_{lr}}\right) X_{srm} \tag{12}$$

$$\lambda_{mq} = \left(\frac{\lambda_{sq}}{X_{ls}} + \frac{\lambda_{rq}}{X_{lr}}\right) X_{srm} \tag{13}$$

Where λ_{sd} is the stator d-axis flux; λ_{rd} is the rotor d-axis flux; λ_{sq} is the stator q-axis flux; and λ_{rq} is the rotor q-axis flux. The stator d-axis flux (λ_{sd}) per second and q-axis flux (λ_{sq}) per second are given in equations (14) and (15) [3].

$$\frac{\lambda_{sd}}{dt} = \left(v_{sd}\omega_s + \lambda_{sq} + \left(\lambda_{md}\frac{X_{srm}}{X_{lr}} + \lambda_{sd}\frac{X_{srm}}{X_{ls}} - \lambda_{sd}\right)\frac{R_s}{L_{ls}}\right) \tag{14}$$

$$\frac{\lambda_{sq}}{dt} = \left(v_{sq}\omega_s - \lambda_{sd} + \left(\lambda_{mq}\frac{X_{srm}}{X_{lr}} + \lambda_{sq}\frac{X_{srm}}{X_{ls}} - \lambda_{sq}\right)\frac{R_s}{L_{ls}}\right) \tag{15}$$

Similarly, the rotor d-axis flux (λ_{rd}) per second and q-axis flux (λ_{rq}) per second are given in equations (16) and (17).

$$\frac{\lambda_{rd}}{dt} = \left(\lambda_{rq}(\omega_s - \omega_r) + \left(\lambda_{md}\frac{X_{srm}}{X_{ls}} + \lambda_{rd}\frac{X_{srm}}{X_{lr}} - \lambda_{rd}\right)\frac{R_r}{L_{lr}}\right) \tag{16}$$

$$\frac{\lambda_{rq}}{dt} = \left(\lambda_{rq}(\omega_r - \omega_s) + \left(\lambda_{mq}\frac{X_{srm}}{X_{ls}} + \lambda_{rq}\frac{X_{srm}}{X_{lr}} - \lambda_{rq}\right)\frac{R_r}{L_{lr}}\right) \tag{17}$$

where w_r is the angular electrical velocity of the rotor. The rotor's angular mechanical velocity (ω_{rm}) is as expressed in equation (18).

$$\omega_{rm} = \frac{\omega_r}{P} \tag{18}$$

Where P is the number of pole pairs.

The d-axis and q-axis stator current flow, i_{sd} and i_{sq}, are given in equations (19) and (20) as

$$i_{sd} = \frac{\lambda_{sd} - \lambda_{md}}{X_{ls}} \tag{19}$$

$$i_{sq} = \frac{\lambda_{sq} - \lambda_{mq}}{X_{ls}} \tag{20}$$

Similarly, the current flow in the rotor in the d-axis (i_{rd}) and q-axis (i_{rq}) are given as shown in equations (20) and (21).

$$i_{rd} = \frac{\lambda_{rd} - \lambda_{md}}{X_{lr}} \tag{21}$$

$$i_{rq} = \frac{\lambda_{rq} - \lambda_{mq}}{X_{lr}} \tag{22}$$

The angular electrical velocity of the rotor (ω_r) can be expressed as in equations (23) and (24).

$$\frac{d\omega_r}{dt} = \frac{P}{J}(T_e - T_L)i_{rd} = \frac{\lambda_{rd} - \lambda_{md}}{X_{lr}} \tag{23}$$

$$\therefore \omega_r = \int \frac{P}{J}(T_e - T_L)dt \tag{24}$$

The electromagnetic torque (T_e) is given as in equation (25).

$$T_e = \frac{3P}{2}\left(\frac{\lambda_{sd}i_{sq} - \lambda_{sq}i_{sd}}{\omega_s}\right) \tag{25}$$

where is P the number of pole pairs; T_e is the electromagnetic torque; T_L is the load torque; J is the combined load and rotor inertia.

The three-phase stator current (i_a, i_b, i_c) is given as in equation (26).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\omega_s t) & -\sin(\omega_s t) \\ \cos\left(\omega_s t - \frac{2\pi}{3}\right) & -\sin\left(\omega_s t - \frac{2\pi}{3}\right) \\ \cos\left(\omega_s t + \frac{2\pi}{3}\right) & -\sin\left(\omega_s t + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \tag{26}$$

The next step is to assess the of the developed IM to three-phase voltage unbalance.

2.3.2. *Assessment of Unbalanced Three-Phase Voltage Supply*

It is worthy of note to state that several reasons could lead to the supply of unbalanced 3-phase supply in IMs [10]. Some of these reasons include the supply of large single-phase loads which causes more current to be drawn from that phase and consequently results in voltage drop. Another reason is the occurrence of power transformer faults. Obviously, the effect of unbalanced three-phase voltage supply on the IMs is accountable for the real power losses, poor motor efficiency, and decreased pull-out and pull-up torque challenge.

There are three main approaches of the assessment of voltage conditions in electric motors as presented by National Electrical Manufacturers Association (NEMA), Institution of Electrical and Electronics Engineers (IEEE) and International Electro-technical Commission (IEC).

Thus, for NEMA, the unbalanced voltage is determined as factor in terms of ratio maximum line voltage (V_L^{max}) to average line voltage (V_{avgL}). Hence, it is referred to as the line voltage unbalance rate (LVUR) according to equation (27).

$$\%LVUR = \frac{V_L^{max}}{V_{avgL}} \times 100 \quad (27)$$

Whereas that of the Institution of Electrical and Electronics Engineering (IEEE) is expressed as the ratio of the maximum phase voltage(V_P^{max}) to the average phase voltage (V_{avgP}). Hence it is referred to as the phase voltage unbalance rate (PVUR) and expressed as shown in equation (28).

$$\%PVUR = \frac{V_P^{max}}{V_{avgP}} \times 100 \quad (28)$$

It can be observed from equations (27) and (28) that the voltage phasor angles have been neglected. Therefore, the introduction of voltage unbalance factor (VUF)[4]. The VUF is expressed as the ratio of voltage negative sequence to its positive sequence as expressed in equation (29).

$$\%VUF = \frac{V_2}{V_1} \times 100 \quad (29)$$

The positive and negative sequence voltage components are obtained by resolving the line or phase voltages into two symmetrical components, namely: V_1 and V_2.

If line voltages V_{ab}, V_{bc} and V_{ca} are given; then the positive and negative sequence voltage components can be evaluated using equation (30).

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = {}^1\!/_3 \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \quad (30)$$

Where
$a = 1\angle 120^\circ$ and $a^2 = 1\angle 240^\circ$.

In this work, the percentage voltage unbalance in the three-phase (3-ϕ) supplied to an industrial or commercial loads in the form of the induction motor (IM) is obtained from the above analysis. Therefore, the assessment of the effect of three-phase voltage unbalance on the IM is obtained by resolving the three-phase voltage supplied to its positive and negative sequence components as showed in **Error! Reference source not found.** which is a simplified version of **Error! Reference source not found.**, where U represents positive (1) or negative (2) sequence as appropriate.

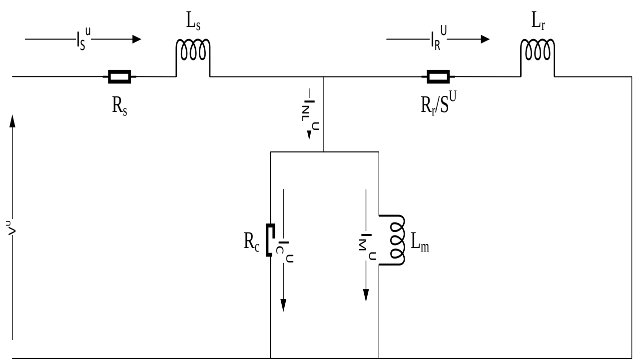

Figure 2: *Per phase equivalent diagram of IM with respect to voltage unbalance source*

2.4. *Real Power Losses*

Obviously, the higher the power loss, the higher the cost of running the IM over a period of time. This step investigates the relationship between the unbalance three-phase voltage supply and the real power losses. It is expected that the unbalance in the voltage magnitude should increase the real power losses. However, the factor of increase is estimated based on its dependence on slip,s, of IM. It is essential to note that the slip of the IM is crucial in that it induces emf which in turn produces torque. Hence, the large value of slip produces large amount of torque and vice versa. Thus, resolving the circuit into its positive and negative sequence, while neglecting the zero sequence, the choice of true definition of voltage unbalance can then be obtained. The expression for the induction motor's slip, s, for both positive and negative sequences are given in equations (31) and (32).

$$s_1 = s = \frac{\omega_{syn} - \omega_r}{\omega_{syn}} \quad (31)$$

$$s_2 = 2 - s_1 = 2 - s \quad (32)$$

where w_{syn} is the synchronous speed in rad/s. The impedances for the stator (Z_s), magnetizing component (Z_M) and the rotor (Z_{R1} and Z_{R2}) can then be expressed as shown in equations (33) through (36).

$$Z_s = R_s + jX_s \quad (33)$$

$$Z_M = \frac{R_c jX_M}{R_c + jX_M} \quad (34)$$

$$Z_{R1} = \frac{R_R}{s_1} + jX_r = \frac{R_R}{s} + jX_r \quad (35)$$

$$Z_{R2} = \frac{R_R}{s_2} + jX_r = \frac{R_R}{2 - s} + jX_r \quad (36)$$

Z_{R1} is the positive rotor impedance component and Z_{R2} is the negative rotor impedance component.
The positive sequence and negative sequence impedance for the IM equivalent circuit are expressed as presented in equations (37) and (38).

$$Z_1 = Z_s + \frac{Z_M Z_{R1}}{Z_M + Z_{R1}} \quad (37)$$

$$Z_2 = Z_s + \frac{Z_M Z_{R2}}{Z_M + Z_{R2}} \quad (38)$$

The positive and negative sequences of the stator circuit gives the current, I_{s1} and I_{s2}, as depicted in equations (39) and (40).

$$I_{s1} = \frac{V_1}{Z_1} \quad (39)$$

$$I_{s2} = \frac{V_2}{Z_2} \quad (40)$$

Using current divider's rule on the circuit diagram in **Error! Reference source not found.** the rotor current, no-load current, core current and magnetizing current can be evaluated as shown in equations (41) through (47).

$$I_{R1} = \frac{Z_M}{Z_M + Z_{R1}} I_{s1} \quad (41)$$

$$I_{R2} = \frac{Z_M}{Z_M + Z_{R2}} I_{s2} \quad (42)$$

$$I_{nl1} = \frac{Z_{R1}}{Z_M + Z_{R1}} I_{s1} \quad (43)$$

$$I_{nl2} = \frac{Z_{R2}}{Z_M + Z_{R1}} I_{s2} \quad (44)$$

$$I_{c1} = \frac{Z_M}{R_c} I_{nl1} \quad (45)$$

$$I_{c2} = \frac{Z_M}{R_c} I_{nl2} \quad (46)$$

$$I_{M1} = \frac{Z_M}{jX_m} I_{nl1} \quad (47)$$

$$I_{M2} = \frac{Z_M}{jX_m} I_{nl2} \quad (48)$$

Thus, converting from positive and negative sequences to three-phase (i.e. abc components for rotor and ABC for the rotor circuit) equivalent, the currents flowing through the IM stator, rotor, core and magnetizing components can be expressed as shown as depicted in the series of equations given as (49) to (52). this means that due to the voltage unbalance, the magnitude of currents in each phase is not equal.

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ a^2 & a \\ a & a^2 \end{bmatrix} \begin{bmatrix} I_{s1} \\ I_{s2} \end{bmatrix} \quad (49)$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ a^2 & a \\ a & a^2 \end{bmatrix} \begin{bmatrix} I_{R1} \\ I_{R2} \end{bmatrix} \quad (50)$$

$$\begin{bmatrix} I_{cA} \\ I_{cB} \\ I_{cC} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ a^2 & a \\ a & a^2 \end{bmatrix} \begin{bmatrix} I_{c1} \\ I_{c2} \end{bmatrix} \quad (51)$$

$$\begin{bmatrix} I_{MA} \\ I_{MB} \\ I_{MC} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ a^2 & a \\ a & a^2 \end{bmatrix} \begin{bmatrix} I_{M1} \\ I_{M2} \end{bmatrix} \quad (52)$$

In this case, the stator real power loss can be estimated using equation (53).

$$P_{sL} = \left(I_A^2 + I_B^2 + I_C^2\right)R_s \quad (53)$$

Similarly, the rotor real power loss and the core real power loss can be estimated using equations (54) and (55).

$$P_{RL} = \left(I_a^2 + I_b^2 + I_c^2\right)R_R \quad (54)$$

$$P_{cL} = \left(I_{cA}^2 + I_{cB}^2 + I_{cC}^2\right)R_c \quad (55)$$

The total real power loss of the induction motor (IM) is given by equation (56).

$$P_{TL} = P_{sL} + P_{RL} + P_{cL} \quad (56)$$

2.5 Reactive Power Reactive Power Loss

The stator reactive power loss can be estimated using equation (57).

$$Q_{sL} = \left(I_A^2 + I_B^2 + I_C^2\right)X_s \quad (57)$$

Similarly, the rotor reactive power loss and the magnetizing reactive power loss can be estimated using equations (58) and (59).

$$Q_{RL} = \left(I_a^2 + I_b^2 + I_c^2\right)X_R \quad (58)$$

$$Q_{mL} = \left(I_{cA}^2 + I_{cB}^2 + I_{cC}^2\right)X_m \quad (59)$$

The total reactive power loss of the induction motor (IM) is given by equation (60).

$$Q_{TL} = Q_{sL} + Q_{RL} + Q_{mL} \quad (60)$$

2.6 Power Factor Assessment

With reference to Figure 3; the power triangle can be deployed to determine the total motor loss (S_{TL}). This is presented by the diagram while the arrangement is depicted in equation (61).

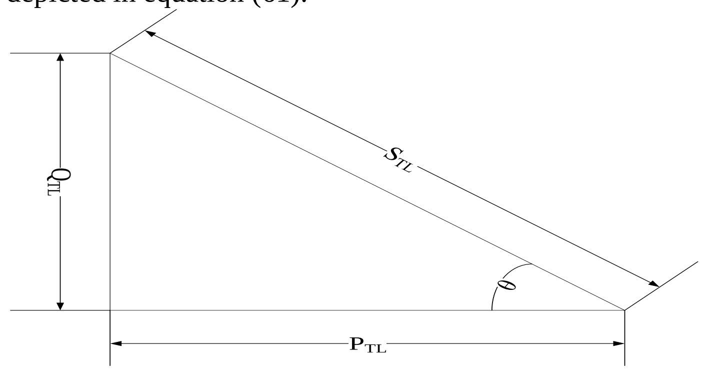

Figure 3: Power triangle showing the relationship between, total motor loss and power factor

$$S_{TL} = \sqrt{P_{TL}^2 + Q_{TL}^2} \quad (61)$$

Where
S_{TL} = Total motor loss of the induction motor (IM)
P_{TL} = Total real power loss of the induction motor (IM)
Q_{TL}= Total reactive power loss of the induction motor (IM)

The power factor (PF) is the ratio of the motor real power loss to the total motor loss. Mathematically, this can be expressed as in equation (62).

$$PF = \cos\theta = \frac{P_{TL}}{S_{TL}} \quad (62)$$

2.7 Induction Motor (IM) Efficiency Assessment

The input real power can be divided into its positive and negative sequences as shown in equations (63) and (64).

$$P_{in1} = 3\,V_1 I_{s1} \cos\phi \quad (63)$$

$$P_{in2} = 3\,V_2 I_{s2} \cos\phi \quad (64)$$

$\cos\phi$ is the power factor.
The total input power to the IM via the stator can be expressed as in equation (65).

$$P_{in} = P_{in1} + P_{in2} \quad (65)$$

Similarly, the electrical reactive power input can be expressed with equations (66), (67) and (68).

$$Q_{in1} = 3V_1 I_{s1} \sin\phi \quad (66)$$

$$Q_{in2} = 3V_2 I_{s2} \sin\phi \quad (67)$$

$$Q_{in} = Q_{in1} + Q_{in2} \quad (68)$$

The mechanical power has influence on the maximum work that can be done by the IM.

The mechanical power output for a balanced three-phase voltage is given as in equation (69).

$$P_{mech} = 3I_R^2 R_R \frac{(1-s)}{s} \quad (69)$$

However, equation (69) has to be divided into its positive and negative sequence components as shown in equation (70) and (71).

$$P_{out1} = 3I_{R1}^2 R_R \frac{(1-s_1)}{s_1} = 3I_R^2 R_R \frac{(1-s)}{s} \quad (70)$$

$$P_{out2} = 3I_{R2}^2 R_R \frac{(1-s_2)}{s_2} = 3I_R^2 R_R \frac{(s-1)}{2-s} \quad (71)$$

The real power output of IM from an unbalanced three-phase voltage supply can therefore, be expressed as in equation (72).

$$P_{out} = P_{out1} + P_{out2} \quad (72)$$

The efficiency of the motor is the ratio of the mechanical output power to the input power. Mathematically, it can be expressed, in percentage, as in equation (73).

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (73)$$

2.8 Electromagnetic Torque Assessment

For the sake of emphasis, increase in losses has a direct link with reduction in the developed torque. As a result of the three-phase unbalanced voltage supply; the positive and negative sequence components of the IM's electromagnetic torque can be expressed as depicted in equations (74) and (75).

$$T_1 = \frac{3P}{2}\frac{I_{R1}^2 R_R}{s_1 \omega_s} = \frac{3P}{2}\frac{I_{R1}^2 R_R}{s\omega_s} \quad (74)$$

$$T_2 = \frac{3P}{2}\frac{I_{R2}^2 R_R}{s_2 \omega_s} = \frac{3P}{2}\frac{I_{R2}^2 R_R}{(2-s)\omega_s} \quad (75)$$

The total mechanical electromagnetic torque can be expressed as in equation (76).

$$T_e = T_1 + T_2 \quad (76)$$

3.0 RESULT AND DISSCUSSION

3.1 Introduction

In order to assess the impact of this 3-phase unbalanced voltage source, it was compared with a balanced 3-phase voltage supply to the IM on three essential metrics: real power losses, IM efficiency and electromagnetic torque. These metrics are chosen because increase in power losses increases the cost of running the IM over a given period of time which leads to lower IM efficiency and decrease in the electromagnetic torque. Hence, the total capacity of work that can be done will decrease with decreasing electromagnetic torque. The implementation of the algorithm in Simulink environment, as shown in Figure 4.

3.2 Balanced three-phase Source Voltage

The three-phase source voltage are as shown in

Figure **5**: Three-phase balanced voltage source. The amplitude of the voltage is set to 240 V. The measurement of the phase angle is relative to phase A and it is positive counter-clockwise and negative in the opposite direction

In this work, the National Equipment Manufacturers Association (NEMA) standard regarding the Voltage Unbalance Factor (VUF) for the assessment of the consumers' loads in the advent of voltage unbalance is implemented. In order to estimate the three-phase voltage unbalance in the source, the phase values must be converted to the line-to-line equivalent values. This is obtained as the line-to-line voltage magnitude of 415.7.

The angles are measured counter-clockwisely from phase A voltage. This shows that the three-phase voltage is balanced. That is line voltage AB, BC and CA are equal and 120° apart. However, the voltage unbalance value is expected to be infinitesimally small; in the range of - $1.367 \times 10^{-14}\%$ and $2.279 \times 10^{-14}\%$ for NEMA and VUF variants respectively

The line-to-line positive sequence voltage should be equal to one of the line-to-line voltages which is 415.7V. While the negative sequence should be negligible which is measured as 9.474×10^{-14} V. The negative sequence sets up a reverse rotating field whilst the slip becomes 2-S, compared to S for positive sequence. So also, the negative sequence voltage produces negative sequence current that increases the motor loss. Furthermore, the electromagnetic torque of the 3-phase IM is equal to the load torque as shown in

Figure6: Electromagnetic torque when the 3-phase IM is loaded at 0.2 sec after starting the motor

. The IM is stable before 0.2 sec before being loaded at 0.2 sec. This implies that the IM is supplied by a balanced three-phase voltage source and hence, the electromagnetic torque equals the load torque at about 0.25 seconds

The real power loss in the stator and rotor are 4.618×10^{-11} W and 1.352×10^{-11} W respectively. This is because of the balanced nature of the three-phase source.

The stator real power loss and the rotor real power loss are connected to the display. The 3-phase IM has an efficiency of 93.2%. The efficiency is calculated as the ratio of the output power to the input power.

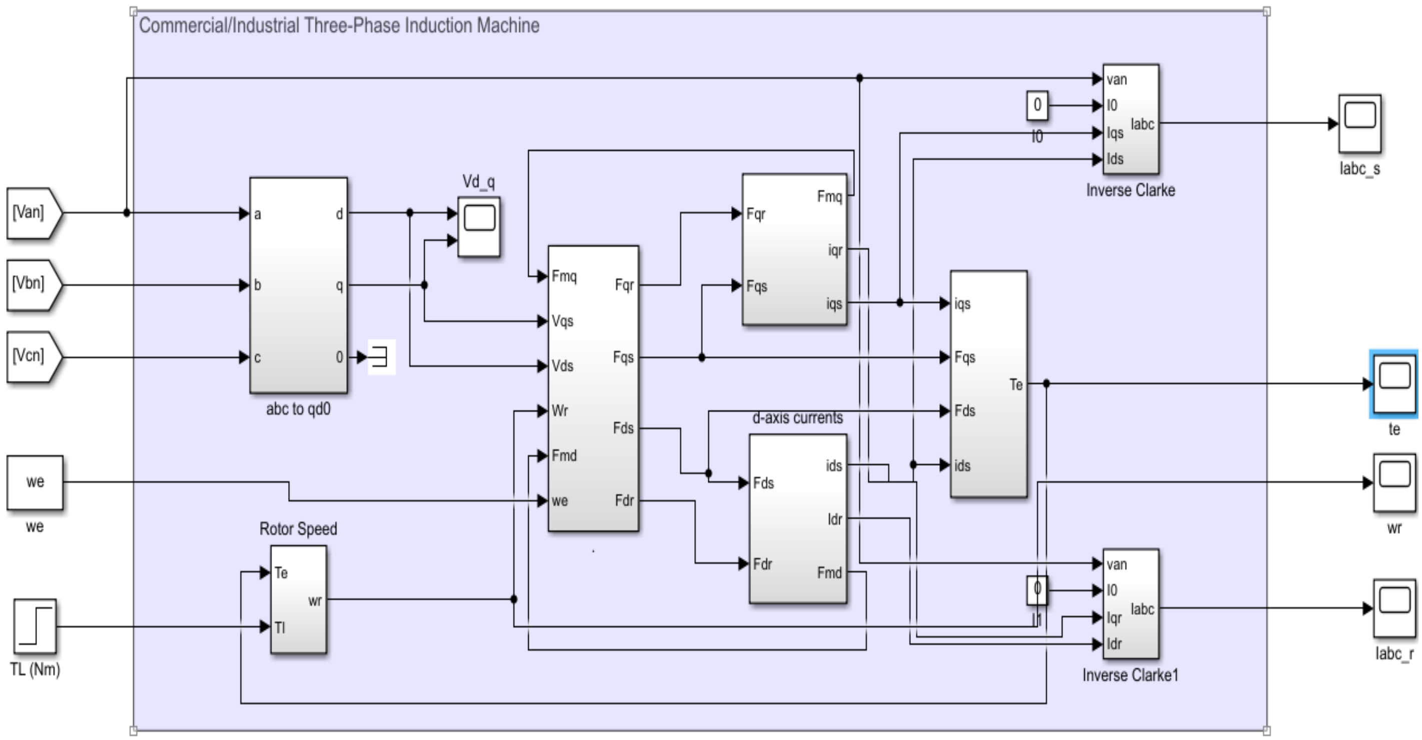

Figure 4: Simulink implementation of commercial and industrial loads: The response to three-phase unbalanced voltage

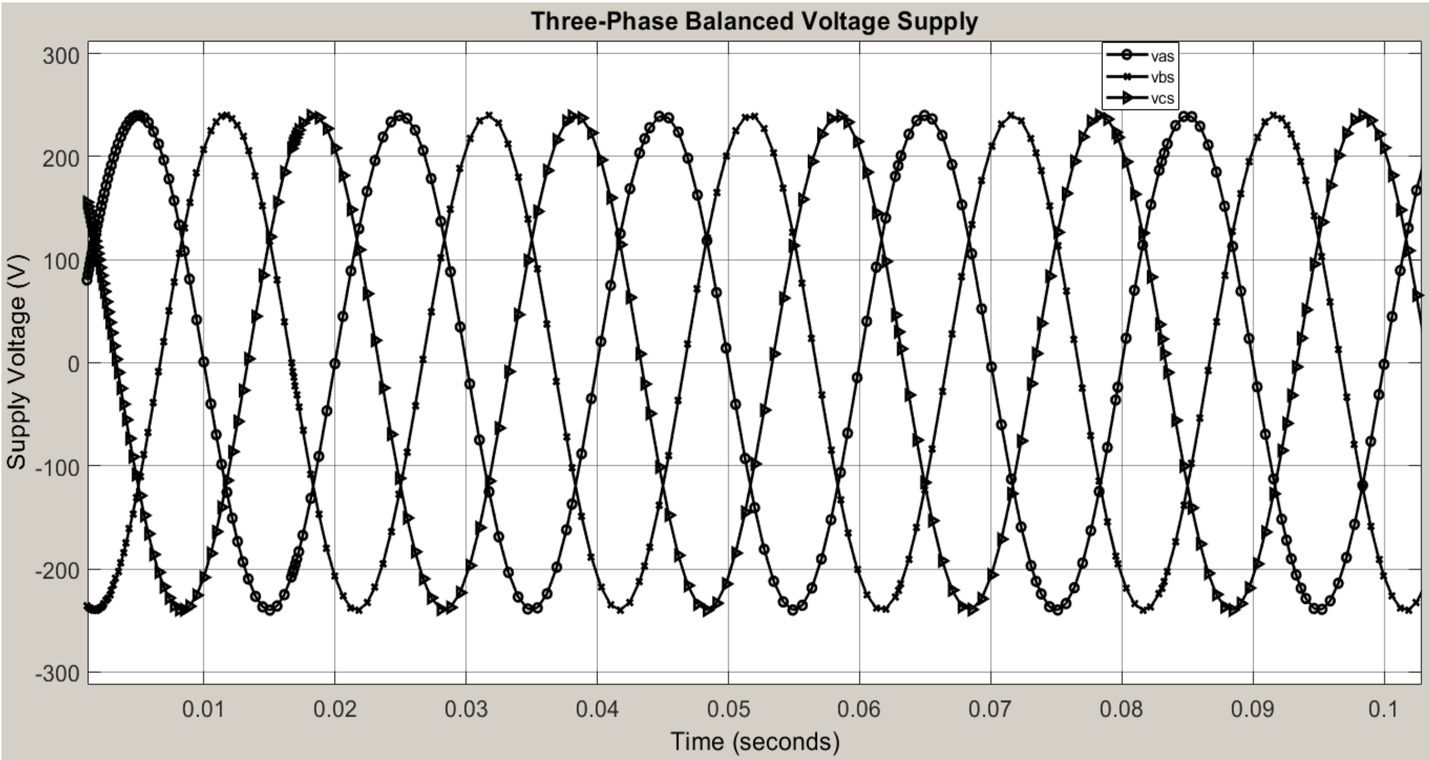

Figure 5: Three-phase balanced voltage source

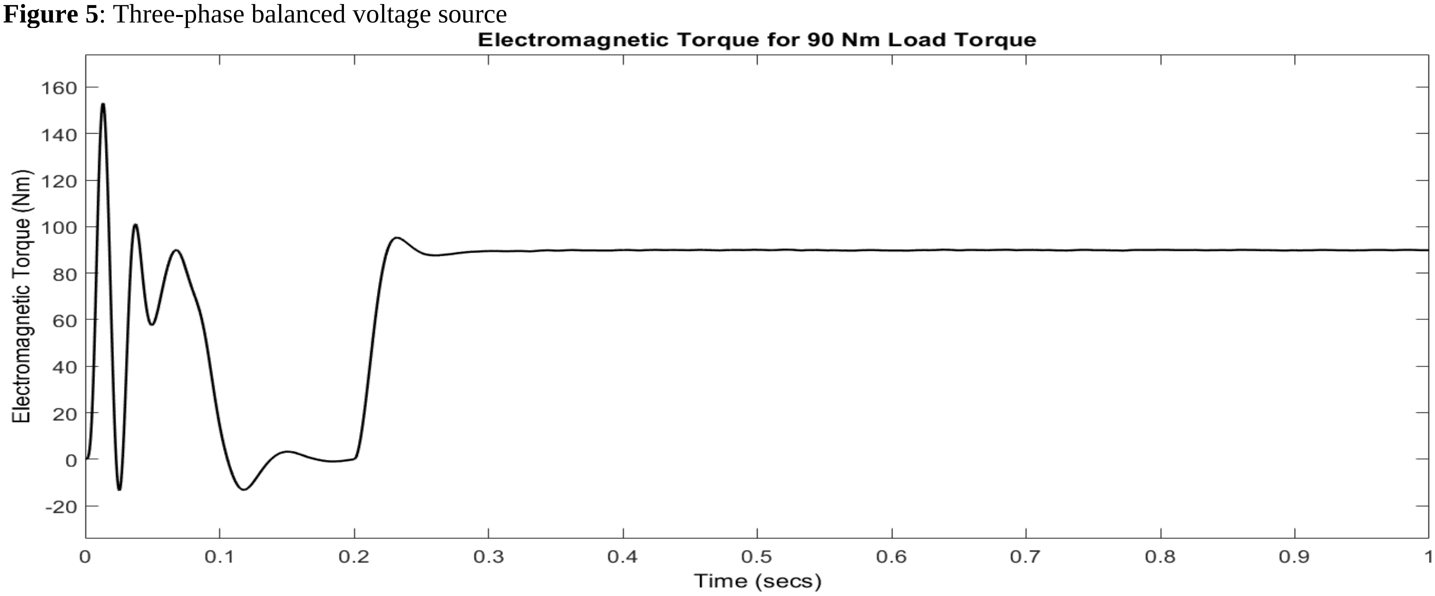

Figure6: Electromagnetic torque when the 3-phase IM is loaded at 0.2 sec after starting the motor

3.3 Unbalanced three-phase Source Voltage

In order to model three-phase unbalanced voltage source, the amplitude of phase A was changed to 230 V and that of phase C was changed to 250 V. As shown in Figure 7: Three-phase unbalanced voltage source, it can be seen that the amplitude of phase B is greater than the amplitude of phase A while it is less than phase C; hence the highest magnitude is phase C.

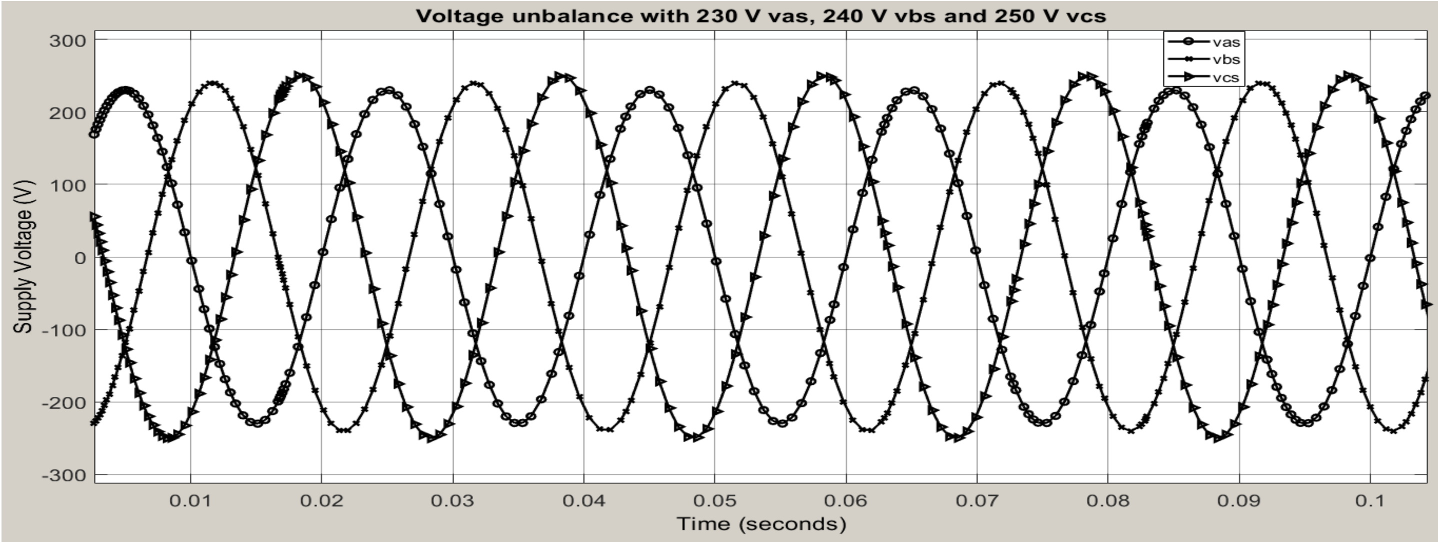

Figure 7**:** Three-phase unbalanced voltage source

From Figure 7; due to the unbalanced nature of the amplitude of the phase voltage values, the line-to-line voltage of the source will not be equal. This lead to the voltage magnitude of line AB, BC and CA being 407.1 V, 424.4 V and 415.8 V. Also, the phase difference between line AB and line CA is 117.9° while the phase difference between line CA and line BC is measured as 120.6°. This shows that the three-phase source voltage is unbalanced.

Therefore, the voltage unbalanced using the standard of the NEMA and VUF are 2.09% and 2.12% respectively. It can then be seen that the NEMA and VUF values are quite close with a difference of 0.03%. Note that the three-phase voltage shown in **Error! Reference source not found.** serves as the input into the three-phase IM.

Hence, the NEMA implementation may be acceptable for non-critical equipment as the process of positive and negative sequence component estimation is not needed. However, in order to inspect the influence of three-phase unbalanced voltage source on industrial and commercial equipment; the VUF is adopted. The negative component of the three-phase source line-to-line voltage is 8.819 V, which is not negligible.

The unbalanced nature of the three-phase source voltage leads to pulsating nature of the electromagnetic torque (**Error! Reference source not found.**). On this account, this phenomenon leads to the increase in vibrations and noise of the commercial or industrial loads. This will subsequently lead to decrease in operational life.

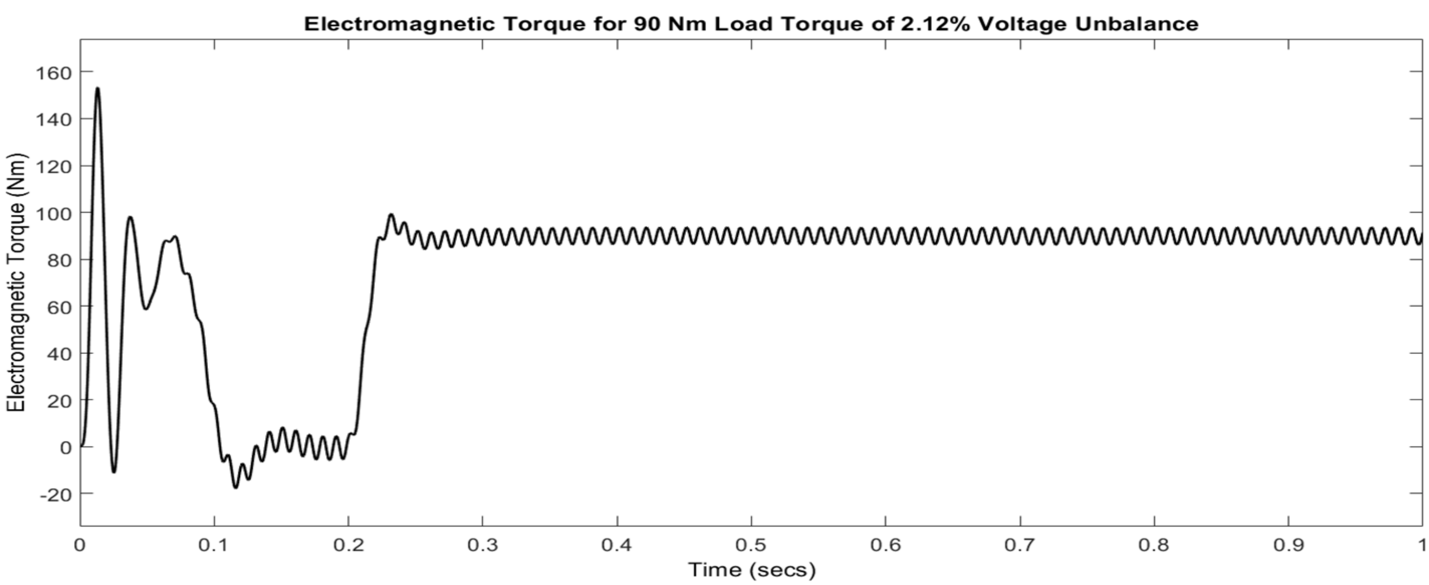

Figure 8: Electromagnetic torque due to 2.12% unbalanced three-phase voltage source

The efficiency of the machine decreased from 93.2% to 79.69% for a 2.12% voltage unbalance (true definition). The NEMA and IEEE standards recommend that motors should not be operated with voltage unbalance greater than 5%. Thereby, **Error! Reference source not**

found. shows the effect of increasing voltage unbalance on motor losses and efficiency from 0% through 5%.

Table 1: Relationship between motor losses, efficiency and the voltage unbalance

Parameters	**0%**	**1%**	**2%**	**3%**	**4%**	**5%**
Stator Loss (W)	0	1,632	3,263	4,895	6,528	8,160
Rotor Loss (W)	0	588	1,176	1,764	2,352	2,941
Motor Loss (W)	0	2,220	4439	6,659	8,880	11,101
Input Power (kW)	32.91	32.98	33.03	33.11	33.22	33.37
Output Power (kW)	30.72	28.51	26.32	24.15	22.00	19.86
Efficiency (%)	93.2	86.45	79.69	72.94	66.20	59.51

4.0 CONCLUSION AND RECOMMENDATION

4.1 Conclusion

This study has provided veritable account of the assessment of the effect of voltage unbalance on industrial and commercial loads. Since the three-phase induction motors (TPIMs) are the most commonly used type of motors in commercial and industrial environments. However, the energy conversion process of these motors is significantly influenced by the nature and quality of current and voltage supplied to the motors. The quality of the power supply is measured using both the NEMA and VUF standards for voltage unbalance definition. They were deployed for evaluating the percentage unbalance in the source voltage. The testing involves equal magnitude change in the voltage values for phase A and phase C. It was observed that +/- 5 V corresponds to a 1% variation in voltage unbalance. In addition, the TPIM loss, which include stator loss, rotor loss, core copper loss and magnetizing loss, increases with increasing voltage unbalance. Therefore, the output power decrease; so also do the efficiency of the IM. It was then observed that the input power increases slightly with increasing voltage unbalance even though the output power decreases. This event leads to increase in the heat dissipated by the IM; which therefore, reduces the lifespan of the IM.

It was also discovered that the developed electromagnetic torque is more sinusoidal as the voltage unbalance increases. This translates to increased vibration of the electric motors. Eventually, the root mean square (rms) vaule of the developed electromagnetic torque decreases with increasing voltage unbalance.

Summarily, the consequence of voltage unbalance on the three phase induction motors (TPIMs) which are being installed for the industrial and commercial load operation is that the system will record an increased motor loss, decreased motor efficiency, decreased produced electromagnetic torque, increased dissipated heat, and increased vibration.

4.2 Recommendation

From the foregoing, it is recommended that voltage unbalance should be detected as close as possible to the source of this unbalance. Thus, it should be intercepted and mitigated before feeding the power into the TPIMs. This would reduce the negative effects of directly feeding this voltage unbalance into TPIMs, which may eventually destabilize the power system operation through poor quality of power signals.

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