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# DYNAMIC BEHAVIOR OF ASYNCHRONOUS MOTOR UNDER BALANCED AND UNBALANCED VOLTAGE SOURCE CONDITIONS

**Peter Daffin Onwe[1], Eko James Akpama[2], Ogbonaya Inya Okoro[3] and Ekpenyong Nsa Oku*[4]**

[1]Department of Elect/Elect Engineering, University of Calabar, Calabar, Nigeria.
[2,4]Department of Elect/Elect Engineering, Cross River University of Technology, Calabar, Nigeria.
[3]Department of Elect/Elect Engineering, Michael Opara University of Agriculture, Umudike, Nigeria.

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***Corresponding Author**
**Ekpenyong Nsa Oku**
Department of Elect/Elect Engineering, Cross River University of Technology, Calabar, Nigeria.

## ABSTRACT

This paper analyses the dynamic behavior of a five horse-power (5HP) squirrel cage induction machine under balance and unbalance voltage sources. It includes the machine Simulink modeling under dynamic condition, its steady-state and transient analysis. Simulink modeling is used for step-by-step dynamic modeling of the machine while MATLAB is developed for the study of the transient and steady-state behavior of the machine. The torque-speed characteristics of the machine under transient and steady-state are analyzed and compared using MATLAB program developed for the studies. The electromagnetic torque, mechanical rotor speed and current were also analyzed and compared when subjected to balanced and unbalanced voltage conditions. Using reference frame theory to analyze machine performance has proven useful. The article provides a step-by-step Simulink implementation of an induction machine with d-q axis (Park) transformation for stator and rotor variables. The required equations are provided, as it's a generalized model of a three-phase induction. The motor is designed and executed in an easy-to-follow manner. The simulated results when compared show that there exists an appreciable difference when the machine operation on a balanced voltage condition as compared to the unbalanced condition in the current, voltage and mechanical rotor speed, electromagnetic torque and the torque speed characteristic are presented.

**KEYWORDS**: Induction motor, MATLAB/Simulink, Parks transformation, Modeling.

## 1.0 INTRODUCTION

Induction machine is one of the most widely used electrical machines in the universe because of its rugged, low maintenance requirement and cost-effectiveness. The machines are used in both domestic and industrial applications. Three-phase induction motors (3P-IM) are mostly used in industries due to their ruggedness, efficiency, reliability and low-cost operation. While single-phase induction motors are more often used for residential and light operations, 3P-IMs are utilized in light to heavy industrial applications. It drives conveyors, pumps, ventilation, compressors and many other drive applications in the processing and manufacturing industry (Sandhu 2013). It also drives household appliances like refrigerators, air conditioners etc (Krause et al, 2013; Theraja, 2006). A simulation can provide a reasonable estimate of what could occur in a practical situation and can even be used to provide further design recommendations for induction motors. The three-phase induction motors, which are frequently used in industrial and commercial applications, are capable of producing torque at any speed below synchronous speed (Akpama, 2010).

## 2.0 METHODOLOGY

### (a) Modeling of Three Phase Induction motor

In the development of transient equations for the conventional machine model, the following assumptions are made

i. Uniform air gap
ii. Saturation, eddy current, temperature effects neglected
iii. Skin-effect neglected
iv. Identical stator windings

There are various approaches to characterize the differential equations that control the induction motor's transient performance; the only differences are in their specificity and applicability to a particular application. The motor differential equations become linear and the torque and currents can be found analytically if the motor's speed is taken to be constant. However, where changes of motor speed have to be accounted for, analytical method becomes highly inadequate as the differential equations are non-linear and could only be solved numerically using digital or analog computers. The d-q axis model of the motor provides a convenient way of modelling the machine and is most suitable for numerical solution. This is preferable to the space-vector motor model which describes the motor in terms of complex variables. The d-q equivalent circuits for a three-phase symmetrical induction machine in an arbitrary reference frame are displayed in Figure 1. The zero-sequence component, From the below induction models, the differential equations describing the motor's dynamic performance in any reference frame are given as in (Okoro , 2002) with all the rotor parameters referred to the stator. The prime on the referred values have been omitted here for convenience.

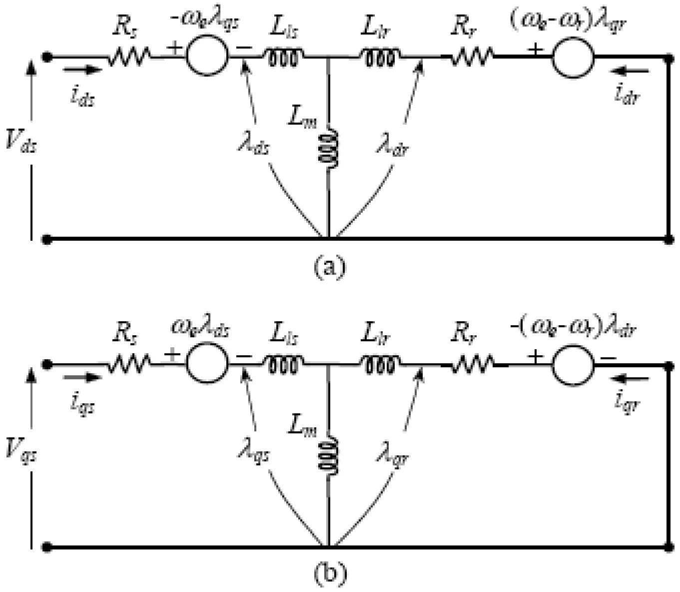

**Figure 1: Induction machine model in d-q axis: (a) q-axis model (b) d-axis model.**

### Electrical Sub Models

The following is a set of equations that, when represented in any reference frame, characterize behavior of the three-phase induction machine.

$$V_{qs} = r_s i_{qs} + \omega\lambda_{ds} + \frac{d}{dt}\lambda_{qs} \quad (1)$$

$$V_{ds} = r_s i_{ds} + \omega\lambda_{qs} + \frac{d}{dt}\lambda_{ds} \quad (2)$$

$$V_{0s} = r_s i_{os} + \frac{d}{dt}\lambda_{os} \quad (3)$$

$$V_{qr} = r_r i_{qr} + (\omega - \omega_r)\lambda_{dr} + \frac{d}{dt}\lambda_{qr} \quad (4)$$

$$V_{dr} = r_r i_{dr} + (\omega - \omega_r)\lambda_{qr} + \frac{d}{dt}\lambda_{dr} \quad (5)$$

$$V_{0r} = r_r i_{or} + \frac{d}{dt}\lambda_{or} \tag{6}$$

Where $\omega$ the speed of the reference frame $\omega_r$ is the rotor speed. The stator and rotor flux linkages are represented as

$$\lambda_{qs} = l_{ls} i_{qs} + l_m(i_{qs} + i_{qr}) \tag{7}$$

$$\lambda_{ds} = l_{ls} i_{ds} + l_m(i_{ds} + i_{dr}) \tag{8}$$

$$\lambda_{os} = l_{ls} i_{os} \tag{9}$$

$$\lambda_{qr} = l_{lr} i_{qr} + l_m(i_{qs} + i_{qr}) \tag{10}$$

$$\lambda_{dr} = l_{lr} i_{dr} + l_m(i_{ds} + i_{dr}) \tag{11}$$

$$\lambda_{os} = l_{lr} i_{or} \tag{12}$$

The electromagnetic torque equation is represented as

$$T_e = \frac{3p}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \tag{13}$$

Similarly, the machine's mechanical model, which includes the motor-driven load equation, can be shown as

$$J\frac{dw_r}{dt} = T_e - T_l - T_b \tag{14}$$

The equation that describes the electrical and mechanical behavior of the machine contain mixed variable (flux linkages and current). Therefore, the current when expressed in terms of flux linkage will be

$$i_{qs} = \delta_r \lambda_{qs} - \delta_m \lambda_{qr} \tag{15}$$

$$i_{ds} = \delta_r \lambda_{ds} - \delta_m \lambda_{dr} \tag{16}$$

$$i_{os} = \frac{\lambda_{os}}{L_{ls}} \tag{17}$$

$$i_{qr} = -\delta_m \lambda_{qs} + \delta_s \lambda_{qr} \tag{18}$$

$$i_{dr} = -\delta_m \lambda_{ds} + \delta_s \lambda_{dr} \tag{19}$$

$$i_{or} = \frac{\lambda_{or}}{L_{lr}} \tag{20}$$

Substituting equations 15 to 20 into equations 7 to 12 and solving the equation in the rotor reference frame, the integral form of the machine voltage and torque equation with flux linkages as state variables is given as

$$\lambda_{qs} = \int[V_{qs} - (\delta_r\lambda_{qs} - \delta_m\lambda_{qr})\, r_s - \omega\lambda_{ds}] \quad (21)$$

$$\lambda_{ds} = \int[V_{ds} - (\delta_r\lambda_{ds} - \delta_m\lambda_{dr})\, r_s - \omega\lambda_{qs}] \quad (22)$$

$$\lambda_{os} = \int[V_{0s} - r_s \frac{\lambda_{os}}{\mathrm{L}_{ls}}] \quad (23)$$

$$\lambda_{qr} = \int[V_{qr} - (-\delta_m\lambda_{qs} + \delta_s\lambda_{qr})\, r_r - (\omega - \omega_r)\lambda_{dr}] \quad (24)$$

$$\lambda_{dr} = \int[V_{dr} - (-\delta_m\lambda_{ds} + \delta_s\lambda_{dr}) - (\omega - \omega_r)\lambda_{qr}] \quad (25)$$

$$\lambda_{or} = \int[V_{0r} - r_r \frac{\lambda_{or}}{\mathrm{L}_{lr}}] \quad (26)$$

### (b) Implementation in Simulink

The simulation of five horse power squirrel cage induction machine model is achieved by the use of MATLAB/SIMULINK software. The five horse-power induction motor parameters used for the simulation are shown in table 1.

**Table 1: Rated specification of the 3P-IM used in these studies.**

| Specifications | Values | Parameters | values |
|---|---|---|---|
| Motor type | Squirrel-cage induction motor | Stator resistance $(R_s)$ | 1.405Ω |
| Rated power | 5HP | Stator inductance $(L_S)$ | 0.005839H |
| Rated voltage | 400V | Rotor resistance $(R_r)$ | 1.395Ω |
| Rated speed | 1430rpm | Rotor inductance $(L_r)$ | 0.005839H |
| Number of poles | 4 | Magnetizing inductance $(L_m)$ | 0.1722H |
| Coefficient of viscous friction B | 0.002985N.M.S | Moment of inertia J | 0.0131kg$m^2$ |
| Supply frequency | 50Hz | | |

In order to implement this in Simulink, the equations are arranged into four blocks as shown below

a. Inputs (three phase voltage and load torque)

b. Output (three phase current, electrical torque and other components as may be needed for identification )

c. Electrical part of the machine

d. Mechanical part of the machine.

Furthermore, to maintain proper flow of the machine variables and convenience of simulation, the equations have been separated into the q axis and the d axis. Figures 2, show the electrical sub models implemented in Simulink using equations 21 to 26

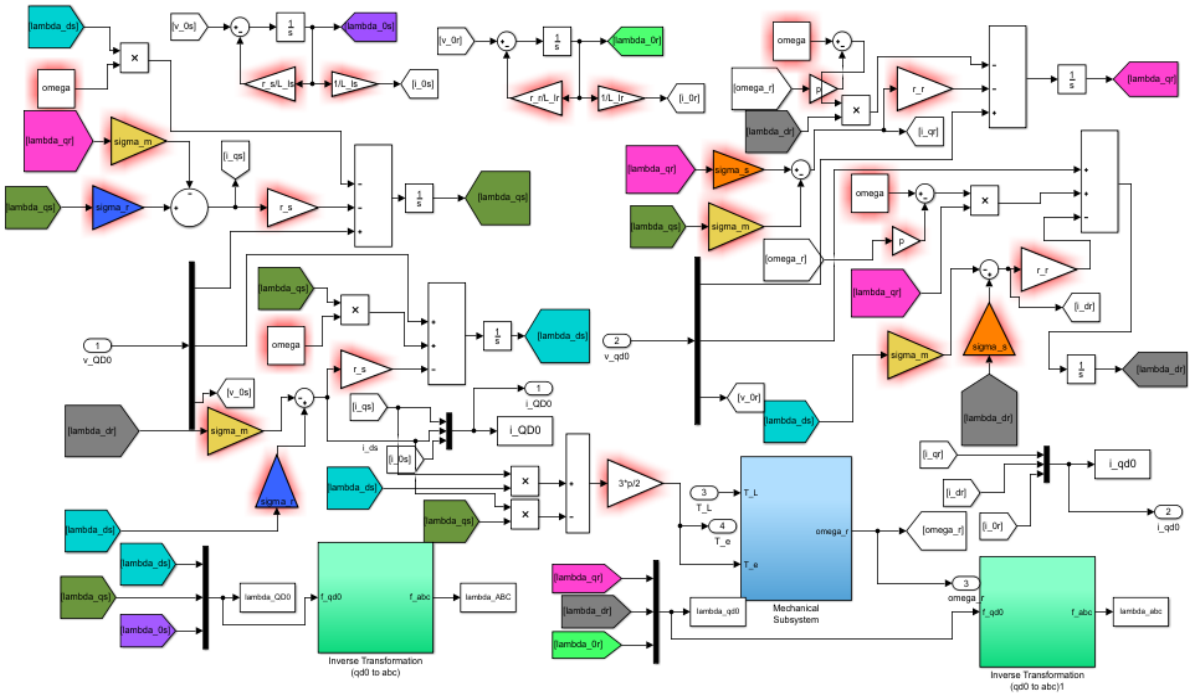

**Figure 2: Electrical sub model of the machine.**

The electromagnetic torque of the machine can be computed and implemented in simulink using equation 27 as thus

$$T_e = \frac{3p}{2}\left(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}\right) \qquad (27)$$

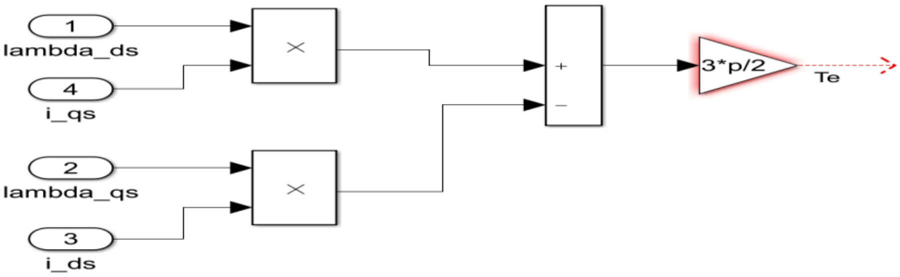

**Figure 3: torque sub model implemented in Simulink.**

The mechanical part of the machine can also be computed using equation 28 shown below

$$J\frac{dw_r}{dt} = T_e - T_l - T_b \qquad (28)$$

Where

J = moment of inertial

$\frac{dw_r}{dt}$ = Acceleration (angular speed)

$T_e$ = Electromagnetic torque

$T_l$ = Load torque

$T_b$ =Frictional torque.

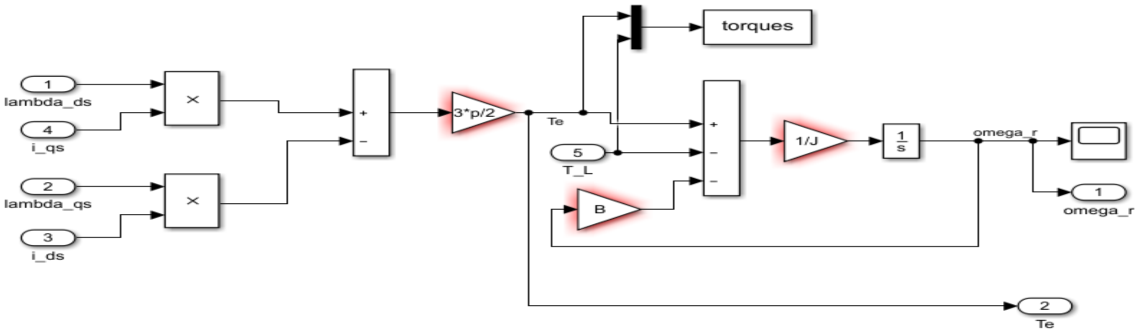

**Figure 4: Mechanical sub model of the machine implemented in Simulink.**

The sub models are then implemented into a complete asynchronous machine model as seen below

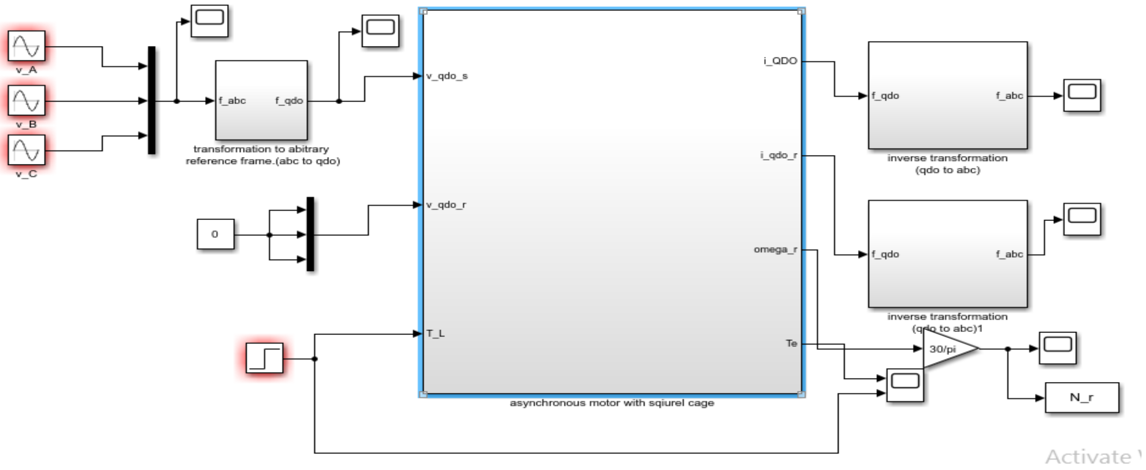

**Figure 5: inputs and outputs of the Asynchronous machine model implemented in Simulink.**

## 3.0 RESULTS AND DISCUSSION

MATLAB is a sophisticated software package used for all computation and developed by Math Works inc. it is a high performance and user-friendly software. Because of its analytical capabilities, reliability, flexibility and powerful graphical display, it has become the mostly used software for engineers and scientist. In machine analysis, MATLAB has become indispensable due to its programming capability which is very easy to learn and use and allows user-developed functions. The models of induction motors are presented in matrix form by authors like Park, Kron etc, because of this; MATLAB has become the best choice of simulation tools for such models.

The graphs of the transient and steady states analysis are presented to show the behavior of the motor when subjected to both balanced and unbalanced conditions.

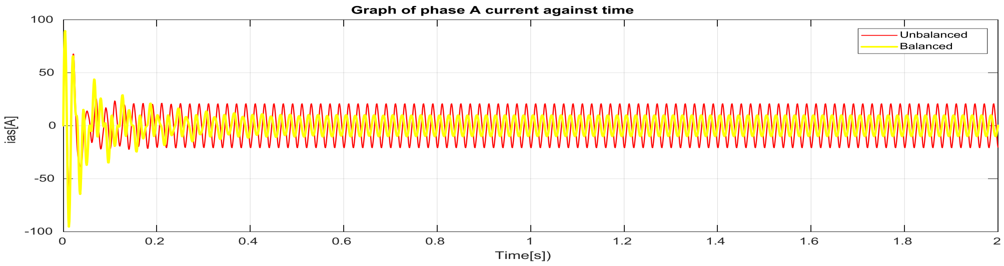

**Figure 6: Graph of $i_{as}$ against time under balanced and unbalanced conditions.**

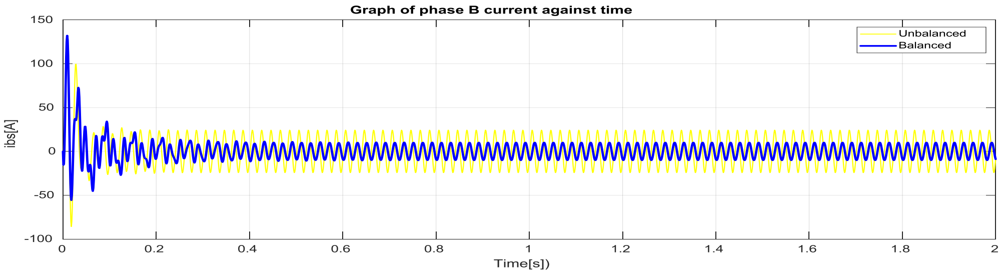

**Figure 7: Graph of $i_{bs}$ against time under balanced and unbalanced conditions.**

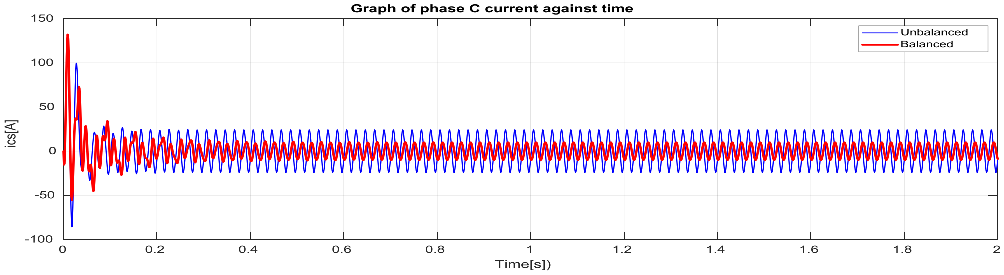

**Figure 8: Graph of $i_{cs}$ against time under balanced and unbalanced conditions.**

### Effect on Current

Figures 6, 7 and 8 show plots of comparison between the current in $i_{as}$ , $i_{bs}$ and $i_{cs}$ against time when subjected to balanced and unbalanced conditions show that at transient, the current in $i_{bs}$ and $i_{cs}$ increases to 132.1 amps at 0.009 seconds while $i_{as}$ increases to 88.3 amps at about 0.003 seconds and all settles at a steady state of 0.0 amps with much harmonics within 0.392, 0.432 and 0.364 seconds respectively under balance voltage condition while during the unbalanced condition, the current $i_{as}$ increases to 67.63amps at 0.021 seconds at the peak of transient and settles to a steady state of 0.0 amps with much harmonics at about 0.15 seconds. $i_{bs}$ and $i_{cs}$ also increases to 115.7 amps at 0.008 seconds at the peak of transient and settles at a steady state of about 0.0 amps with much harmonics at 0.166 and 0.167 seconds respectively.

Comparison between the currents when subjected to balanced and unbalanced voltage conditions shows that the transient behavior at peak is higher but settles to a steady state within 0.2 seconds with less harmonics under balanced condition while the transient behavior of the current when subjected to unbalanced voltage condition is lower and settles faster but with much harmonics.

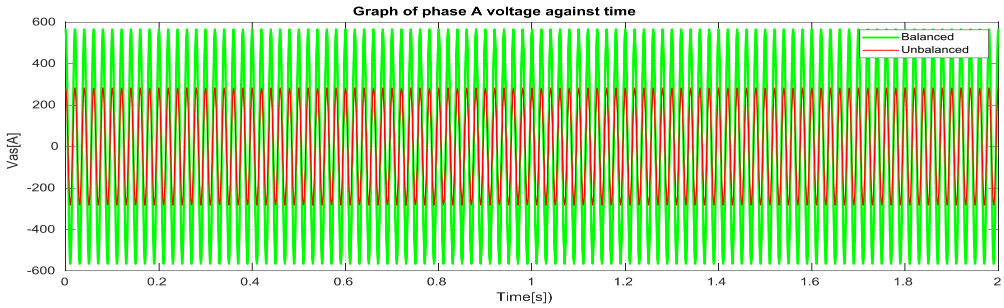

**Figure 9: Graph of $V_{as}$ against time under balanced and unbalanced voltage conditions.**

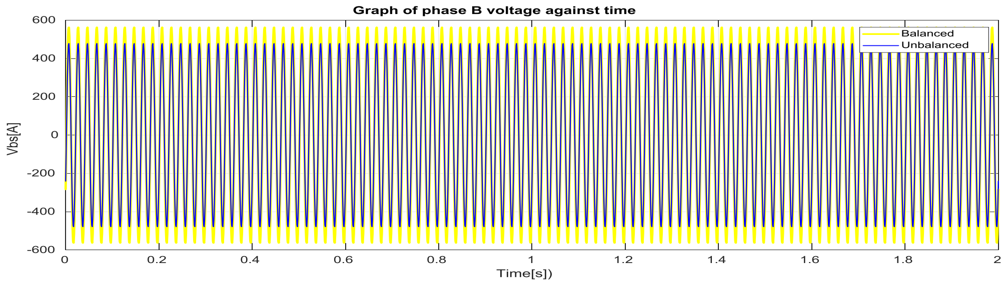

**Figure 10: Graph of $V_{bs}$ against time under balanced and unbalanced voltage conditions.**

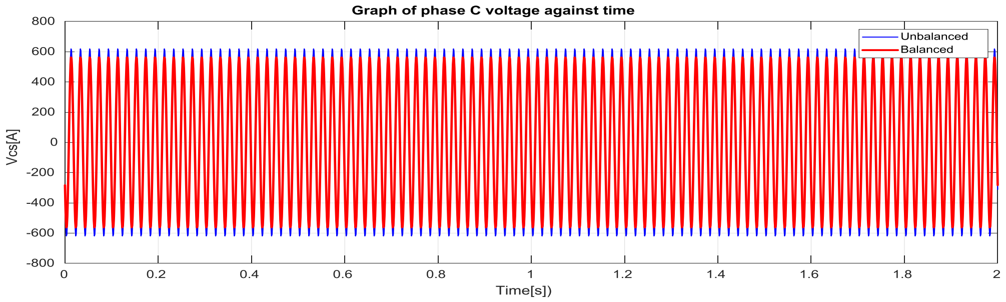

**Figure 11: Graph of $V_{cs}$ against time under balanced and unbalanced voltage conditions.**

Figures 9, 10 and 11 show the graphs of voltages of $V_{as}$ $V_{bs}$ $and$ $V_{cs}$ against time at balanced and unbalanced voltage conditions. It is seen that the voltages varies according to their degree of unbalances.

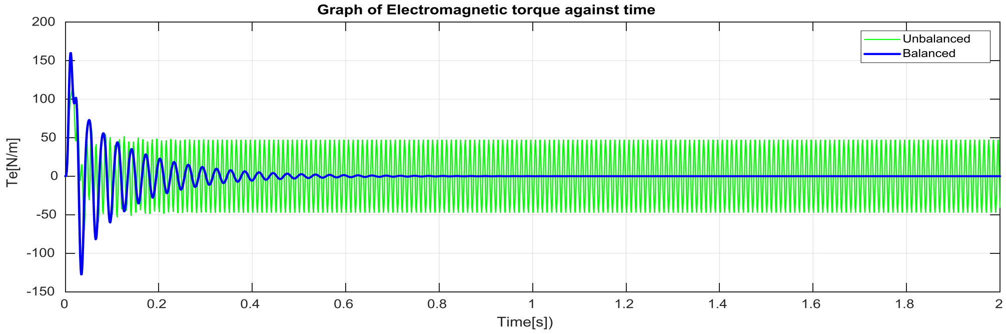

**Figure 12: Graph of electromagnetic torque ( $T_e$ ) against time under balanced and unbalanced voltage conditions.**

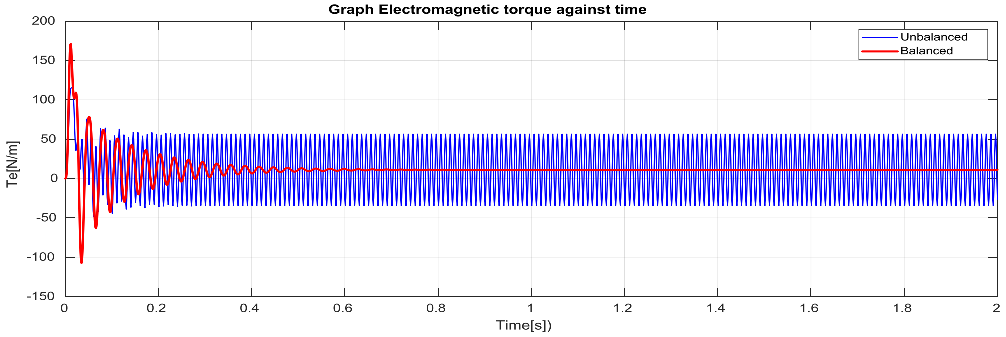

**Figure 13: Graph of $T_e$ against time under balanced and unbalanced voltage conditions at rated load.**

### Effect on Electromagnetic Torque

Figure 12 and 13 show the graphs of electromagnetic torque against time in both balance and unbalance voltage conditions with load and without load. Figure 12 present a comparison between balanced and unbalanced voltage conditions, it shows a peak value of 159.7 N-M at transient and a steady state value of 0.181N-M with less harmonics under balance voltage condition at no load. While during unbalanced condition, the electromagnetic torque rises to a peak value of 115.3 N-M at transient and settles at a steady state value of 46.98 N-M with higher harmonics under unbalanced voltages condition at no load.

Figures 13 show a comparison of the electromagnetic torque when subjected to balanced and unbalanced voltage conditions at rated load. It is observed that when a rated load of 24.8N-M is applied to the motor, the electromagnetic torque rises to a peak value of 171N-M at transient within 0.012 seconds and settles at a steady state value of 11.11 N-M at about 0.174 seconds.

It is observed that the peak value of the transient behavior of the torque is higher but settles to a steady state value with less harmonics during balance condition while the transient behavior is lower but with much harmonics under unbalanced condition.

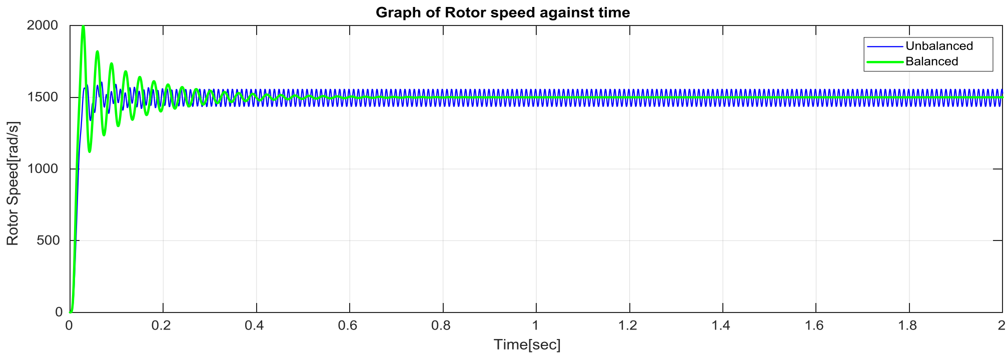

**Figure 14: Graph of Rotor speed against time under balanced and unbalanced voltage conditions.**

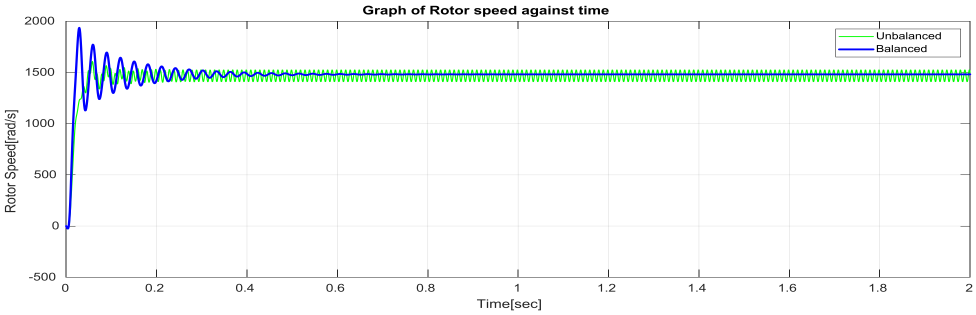

**Figure 15: Graph of Rotor speed against time under balanced and unbalanced voltage conditions at rated load.**

**Effect on Rotor Speed**

The mechanical rotor speed is plotted against time in both balanced and unbalanced voltage scenarios in Figures 14 and 15. Figure 14 displays a graph with a peak speed of 1997 RPM at approximately 0.028 seconds under balanced conditions, and a steady state speed of 1500 RPM at approximately 0.85 seconds under balanced voltage conditions. In contrast, under unbalanced voltage conditions, the speed increases to a peak speed of 1585 RPM at approximately 0.016 seconds, and then settles to a steady state speed of 1500 RPM at approximately 0.208 seconds with harmonics under unbalanced voltage conditions without load.

Figure 15 show a comparison between balanced and unbalanced voltage condition of the torque with load. When a load of 24.8 N-M is applied to the motor, figure 4.28 shows that the speed at transient reaches a peak value of 1922 RPM and settles at a steady state of 1441 RPM.

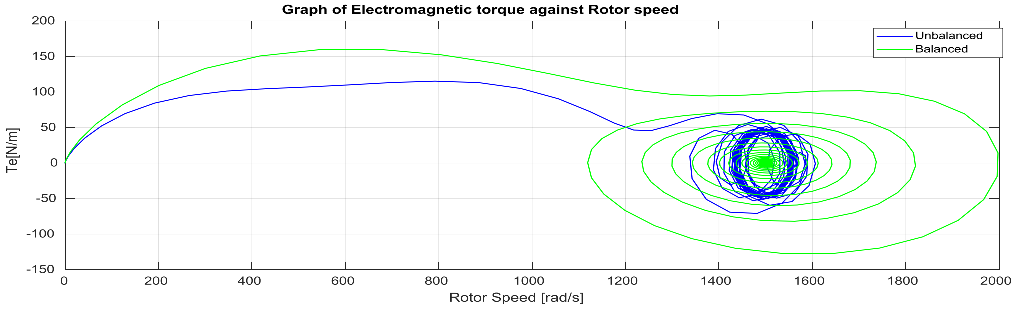

**Figure 16: Graph of Electromagnetic torque against Rotor speed under balanced and unbalanced voltage conditions.**

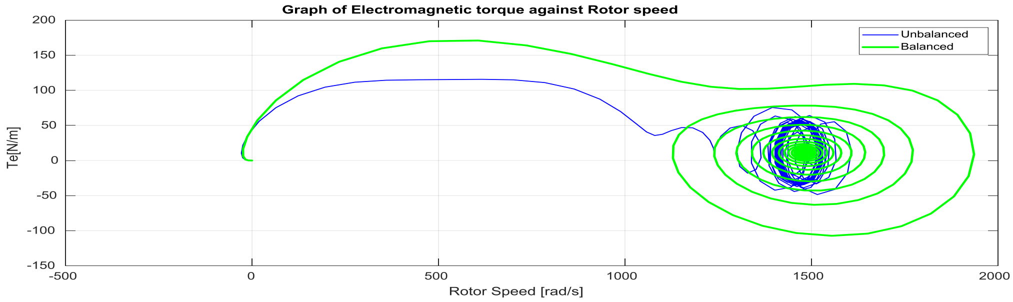

**Figure 17: Graph of Electromagnetic torque against Rotor speed under balanced unbalanced voltage conditions with rated load.**

From the simulation results obtained from the unbalanced voltage, the phase currents contain more harmonics as compared to when the source voltages are balanced. The electromagnetic torque and mechanical rotor speed reaches a steady state and synchronous speed in the balanced model as compared to the unbalanced condition. It is observed that when a rated toque is applied to the machine, the electromagnetic torque increases while the mechanical rotor speed decreases. Also, induction motor under varying voltages will result in increased heating at rated horsepower load. If the machine operates under such condition for a period of time, it may lead to deterioration and shorten the motor life span.

## 4.0 CONCLUSION

This paper presents the dynamic behavior of an asynchronous motor under balanced and unbalanced voltage source conditions. Its aimed on detailed study of induction motor, the study includes developing dq-model equation for five horsepower (5HP) squirrel cage induction machine and Simulink modeling of the machine under dynamic condition as well as the transient and steady-state analysis of the machine. MATLAB program were developed for both the electrical and mechanical equations. The computer simulation model presented in this paper is effective for transient and steady state analysis of the induction motor. Investigation from simulation results has shown that there is an appreciable difference in the behavior of an induction motor under balance voltage source as compared to its behavior when the voltage is unbalanced. The results further proves that the operational behavior of an induction motor can be studied using simulated results from either SIMULINK or MATLAB without necessarily going through the rigorous analytical method. The results obtained from the simulation is similar from previous literature and traditional simulation method. **Also, by** using the SIMULINK tool, each block of the model may be connected and modified easily. Since unbalanced conditions may not be totally eradicated, it is necessary to protect the motor against all types of unbalances with NEMA and IEEE specifications.

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