Simulation of the Performance of Induction Machine under Unbalanced Source Voltage Conditions.

E.J. Akpama, M.Eng.[1]; O.I. Okoro, Ph.D.[2]; and E. Chikuni, Ph.D.[3]

[1]Department of Electrical/Electronic Engineering, Cross River University of Technology, Calabar,
Cross River State, Nigeria.
[2]Department of Electrical/Electronic Engineering, Micheal Okpara University of Agriculture, Umudike,
Umuahia, Abia State, Nigeria
[3]Department of Electrical Engineering at the University of Kwazulu-Natal, Durban, South Africa.

E-mail: akpamaeko@yahoo.com[1]
oiokoro@yahoo.co.uk[2]
chikuni@yahoo.com[3]

ABSTRACT

This paper presents the simulation of induction machine performance under unbalanced source voltage conditions. Different types of unbalance conditions exist; single phasing, under-voltage unbalance, two phase under-voltage unbalance, and over-voltage. The analysis of induction machines under balance and unbalanced conditions are presented. The models representing the machine under balance and unbalanced conditions were simulated with the help of MATLAB® and the simulated results compared. The results show that there exists appreciable difference that is worth noting. To protect the life of the machine, there should be a protective device/circuitry to protect the machine against voltage unbalance and/or single phasing.

(Keywords: modeling, simulation, voltage unbalance, sequence voltage, efficiency, temperature rise, stability performance)

INTRODUCTION

The analysis of an induction machine is always carried out with the assumption that there is symmetry. That is, the source voltages in the three phases are balanced and the single phase loads connected to the system is also balanced. But in practice, there is however, a possibility on account of accidental short circuits between coils, that the three phase winding may not remain symmetrical. Also, unbalanced phase voltages do exist due to the presence of unbalance loads on the system or due to some line disturbances. Due to the enormous effects of unbalance voltage on the steady state performance of induction machine, it is imperative that these effects are investigated.

In view of the epileptic nature of power supplies in this country, phase failure and all types of unbalances and poor power quality, this study is timely. The effect of unbalance voltage on the induction machine includes; increase losses, temperature rise, reduced efficiency, reduced torque, and reduced insulation life. Voltage unbalance comes in diverse ways; single phase under-voltage, two phase under-voltage unbalance, three phase under-voltage unbalance, single phase over-voltage unbalance, two phase over-voltage unbalance, three over-voltage unbalance, unequal single phase angle displacement, and unequal two-phase-angle displacement.

Different researchers have investigated this unwanted phenomenon in induction machine operating conditions. J.F. Eatham [1] presented the effects of unbalanced supply conditions on the performance of induction machines using finite element method (FEM).

Ching-Yin Lee [2] presented a comparative analysis of the effects of unbalance voltage on the operation performance of a three-phase induction motor and suggested that the related regulations and a motor's derating factors and temperature rise curves should be used on not only a voltage unbalance factor but also magnitude of the positive sequence voltage.

In [3], Jawad et al. investigated the influence of unbalanced voltage on the steady-state performance of a three phase squirrel-cage induction motor and tried to prove that the different definitions (NEMA and IEEE) of voltage unbalance are not reliable therefore the analysis there from though adequate leads to some percentage error.

Also in [4], derating of induction motors operating with a combination of unbalanced voltages and undervoltages is investigated. In this paper, the application of MATLAB®, the developed models of induction motor under 23% and 50% voltage unbalance are simulated and the results compared.

INDUCTION MACHINE ANALYSIS

The analysis and modeling of induction machines is no longer new. This analysis is presented in [5, 6]. For a balanced, pure sinusoidal three phase supply, the sum of the three phase voltages is zero; as a result the zero sequence voltage will be zero. For a balanced three phase voltages are given by:

$$V_{as}=V\cos\omega_e t \quad \textbf{(1)}$$

$$V_{bs}=V\cos(\omega_e t-2\pi/3) \quad \textbf{(2)}$$

$$V_{cs}=V\cos(\omega_e t+2\pi/3) \quad \textbf{(3)}$$

Rotor circuit:

$$V_{qr}=R_r i_{qr}+(\omega-\omega_r)\lambda_{ds}+p\lambda_{qr} \quad \textbf{(6)}$$

$$V_{dr}=R_r i_{dr}-(\omega-\omega_r)\lambda_{qr}+p\lambda_{dr} \quad \textbf{(7)}$$

The flux equations are also given as:

$$\lambda_{qs}=L_{ls}i_{qs}+L_m(i_{qs}+i_{qr}) \quad \textbf{(8)}$$

$$\lambda_{ds}=L_{ls}i_{ds}+L_m(i_{ds}+i_{dr}) \quad \textbf{(9)}$$

$$\lambda_{qr}=L_{lr}i_{qr}+L_m(i_{qr}+i_{qs}) \quad \textbf{(10)}$$

$$\lambda_{dr}=L_{lr}i_{dr}+L_m(i_{dr}+i_{ds}) \quad \textbf{(11)}$$

The voltage equations of induction machine in d-q axis are readily written as:

Stator circuit;

$$V_{qs}=R_s i_{qs}+\omega\lambda_{ds}+p\lambda_{qs} \quad \textbf{(4)}$$

$$V_{ds}=R_s i_{ds}-\omega\lambda_{qs}+p\lambda_{ds} \quad \textbf{(5)}$$

Equations (8) – (11) are substituted into Equations (4) – (7) and the result is conveniently put in matrix form in the rotor reference frame where ($\omega_e=\omega_r$) in Equation (12) [7],

Equation 12, suggest the equivalent circuit in Figure 1.

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} (R_s+L_s p) & \omega L_s & L_m p & \omega L_m \\ -\omega L_s & (R_s+L_s p) & -\omega L_m & L_m p \\ L_m p & 0 & (R_r+L_r p) & 0 \\ 0 & L_m p & 0 & (R_r+L_r p) \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad \textbf{(12)}$$

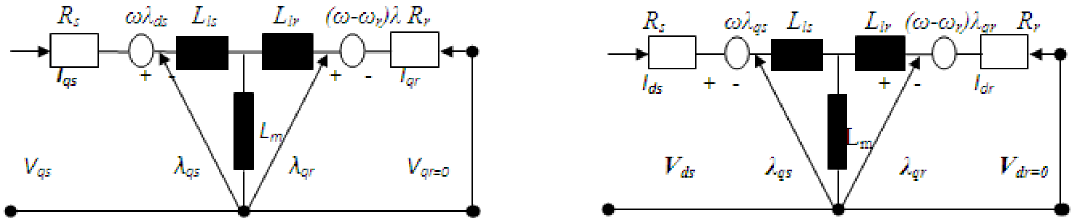


Figure 1: d-and q-Axis Model of an Induction M

Since our experimental machine's parameters are given in reactances, we now replace the inductances with reactances defined in (13):

$$L_s = \frac{X_s}{\omega_b}, \quad L_r = \frac{X_r}{\omega_b}, \quad L_m = \frac{X_m}{\omega_b}. \qquad \textbf{(13)}$$

Putting Equation (13) into Equation (12), we have Equation 14.

For the purpose of this investigation, Equation (14) is broken down and represented in state variable form with current as state variable, [8], thus:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + \frac{P}{\omega_b} X_s & \frac{\omega_r}{\omega_b} X_s & \frac{P}{\omega_b} X_m & \frac{\omega_r}{\omega_b} X_m \\ -\frac{\omega_r}{\omega_b} X_s & R_s + \frac{P}{\omega_b} X_s & -\frac{\omega_r}{\omega_b} X_m & \frac{P}{\omega_b} X_m \\ \frac{P}{\omega_b} X_m & 0 & R_r + \frac{P}{\omega_b} X_r & 0 \\ 0 & \frac{P}{\omega_b} X_m & 0 & R_r + \frac{P}{\omega_b} X_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}. \qquad \textbf{(14)}$$

$$p[i] = [E]^{-1} [V]^t - [E]^{-1} [G] [i]^t \qquad \textbf{(15)}$$

where,

$$[V] = [V_{qs} \;\; V_{ds} \;\; 0 \;\; 0] \qquad \textbf{(16)}$$

$$[i] = [i_{qs} \;\; i_{ds} \;\; i_{qr} \;\; i_{dr}] \qquad \textbf{(17)}$$

The Electromagnetic torque, Te, is given as in [5, 6]:

$$Te = \frac{3}{2}\frac{P}{2} L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right). \qquad \textbf{(20)}$$

Using base values.

$$Te = \frac{3}{2}\frac{P}{2}\frac{X_m}{\omega_b} \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right). \qquad \textbf{(21)}$$

where P is the number of pole pairs.

MECHANICAL MODEL

In trying to model the mechanical side of the IM the equation of motion of the machine and driven load as in Figure 2, the figure suggest equation (22):

$$J_m p^2 \theta_m = T_e - F\omega_r - T_L. \qquad \textbf{(22)}$$

The mechanical data of the experimental machine from the manufacturer indicates that the combined rotor and load viscous friction 'F' is appropriately zero, so that, Equation (22) becomes:

$$J_m p^2 \theta_m = T_e - T_L \qquad \textbf{(23)}$$

Breaking Equation (23) into two first-order differential equation gives [9]:

$$J_m p(\omega_m) = (T_e - T_L) \qquad \textbf{(24)}$$

Because,

$$p\theta_m = \omega_m \qquad \textbf{(25)}$$

We know that

$$\omega_r = \omega_m P \qquad \textbf{(26)}$$

and, $\theta_r = \theta_m P$ **(27)**

where P is the number of pole pairs, $P = \frac{d}{dt}$, and ω_m, θ_m, θ_r, ω_r, J_m and T_L represent angular velocity of the rotor, rotor angular position, electrical rotor angular position, electrical angular velocity, combined rotor, and load inertia coefficient, and applied load torque, respectively.

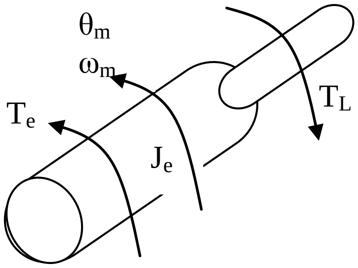


Figure 2: Induction Motor Mechanical Model.

MODELING THE SOURCE VOLTAGES

Balanced Source Voltages

The analysis of a three phase induction machine has been carried out in this paper. It was assumed that the source voltage is a balanced three phase network as shown in Figure 3(a). The three-phase winding of an induction machine is usually symmetrical as a result of proper design and construction. Based on this premise the conventional model was developed. Equations (28)-(30) is the model base on that assumption, while Equations (31-36), are models based on unbalanced conditions:

Balanced Voltages:

$V_{as}=V\cos\omega_e t$. **(28)**

$V_{bs}=V\cos(\omega_e t-2\pi/3)$. **(29)**

$V_{cs}=V\cos(\omega_e t+2\pi/3)$. **(30)**

Case of Unbalanced Voltages:

$V_{as}=1.0\text{x}V\cos\omega_e t$. **(31)**

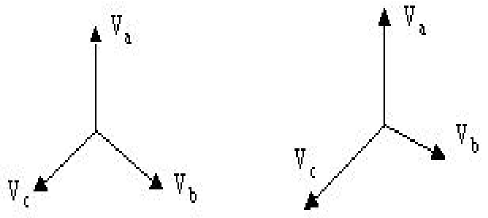
$V_{bs}=0.23\text{x}V\cos(\omega_e t-2\pi/3)$. **(32)**

$V_{cs}= 1.0\text{x}V\cos(\omega_e t+2\pi/3)$ **(33)**

Unbalanced Source Voltages

There is however, a possibility on account of accidental short circuits between coils etc., that the three-phase winding may not remain symmetrical. An unbalanced system is shown in Figure 3(b).

It should be pointed out here that, the voltages obtained from a three-phase system are usually balanced under balanced conditions. But, unbalanced phase voltages do exist due to the presence of unbalanced loads on the system or due to some line disturbances [2, 3]. Many a time, the supply to an induction motor is deliberately unbalanced to get modified speed torque curves, as in asymmetrical voltage control as applied to cranes [4], though in this case the operating efficiency is reduced.



(a) Balanced Voltage (b) Unbalanced Voltage

Figure 3: Balance and Unbalanced Source Voltages.

SIMULATION RESULT

With the help of MATLAB® (a licensed software by MathWorks), which provides a powerful matrix analysis environment for scientific and engineering computing, the differential equations that predict the performance of an induction motor under balanced and unbalanced voltage conditions are simulated and the results presented in Figures 4-7 below.

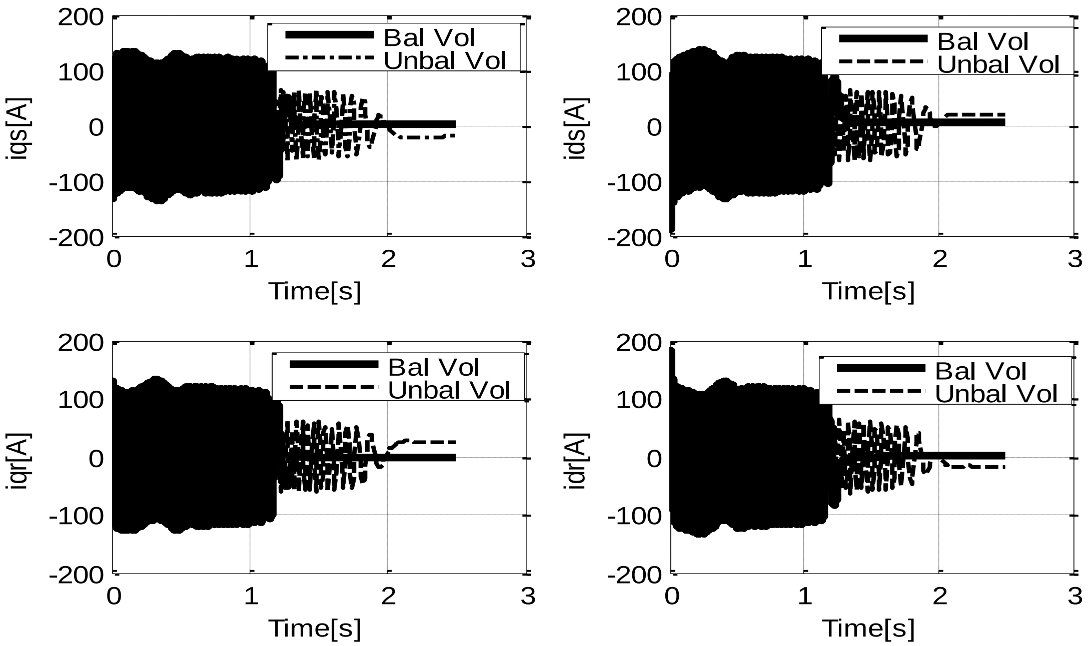


Figure 4: Phase Current and Torque against Time.

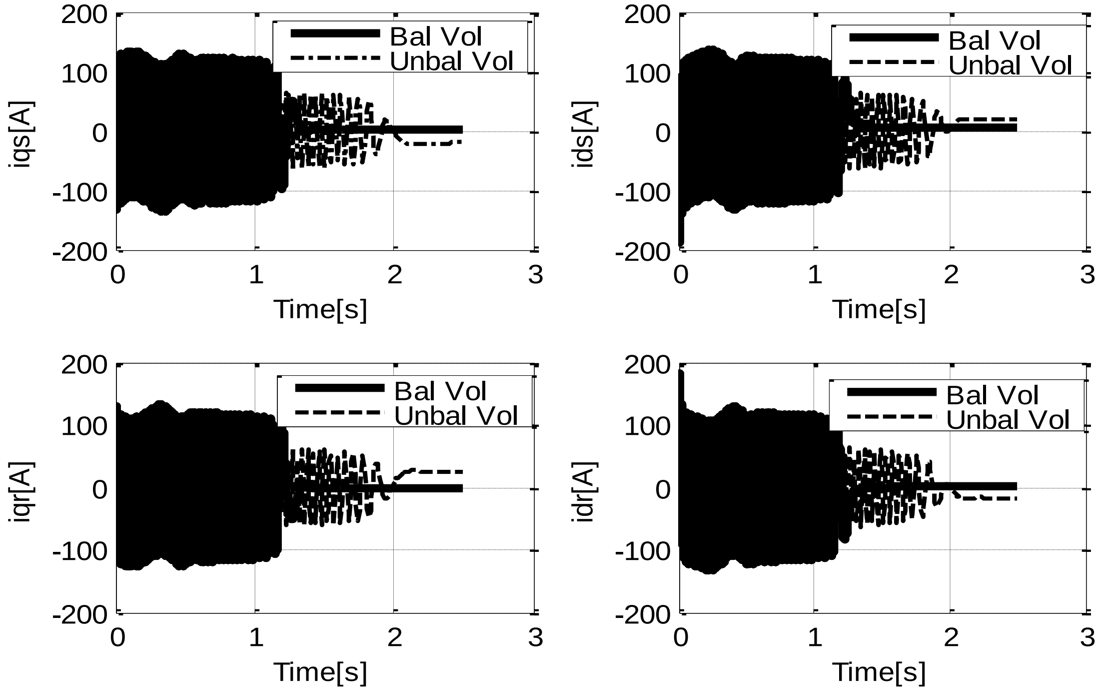


Figure 5: d-q Current and against Time.

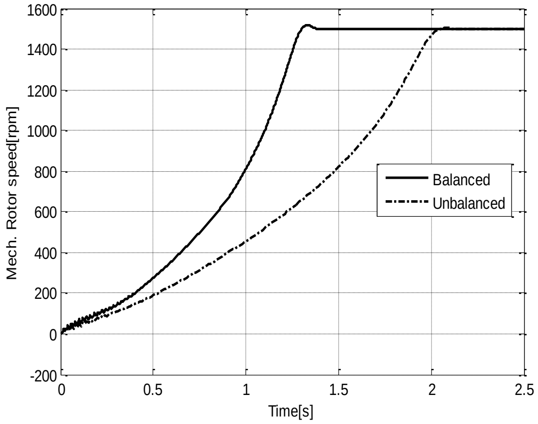


Figure 6: Msech Rotor Speed against Time.

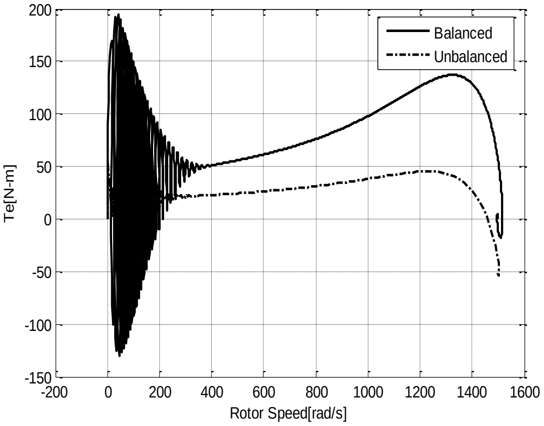


Figure 7: Torque against Rotor Speed.

DISCUSSION OF RESULTS

From simulation results of unbalanced voltage, the phase currents contains more harmonic**s** than when the source voltages are balanced and the electromagnetic torque and the mechanical rotor speed in the balanced model reaches steady state and synchronous speed, respectively, earlier as compared to the unbalance condition. From the results, it is observed that an induction motor under varying voltages will result in; increased heating at rated horsepower load, in which under extended operation may accelerate insulation deterioration and shorten motor insulation life, also varying voltage will usually result in a noticeable power factor variation, since locked-rotor and breakdown torque is proportional to the square of the voltage, therefore, a decrease in voltage will result in a decrease in available torque.

CONCLUSION

This investigation has shown that there is an appreciable difference in the performance of an induction motor under balance source voltages compared to the case in which the source voltages are not balance. The results prove that, the operation performance of an induction machine can be studied using simulated result from MATLAB$^{®}$ without going through the rigorous analytical method. Unbalanced conditions cannot be completely eradicated; therefore, it is very necessary that the motor be protected against all types of unbalances with NEMA and IEEE specifications.

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ABOUT THE AUTHORS

Eko James Akpama, received his B.Eng. in Electrical/Electronic Engineering from the Federal University of Technology, Owerri/Nigeria in 1996. He received his M.Eng. in 2008 in Electrical Power Devices from the University of Nigeria, Nsukka. He is currently working on his Ph.D. program in Electrical Machines. Since 2001 he has been with the Department of Electrical/Electronic Engineering, Faculty of the area of dynamic simulation and control of AC machines. He is a member of NSE and IAENG.

Ogbonnaya I. Okoro, received his B.Eng. and M.Eng. degrees in Electrical Engineering from the University of Nigeria. He holds a Ph.D. in electrical machines from the University of Kassel, Germany under the DAAD scholarship program. He is a Professor of Electrical Machines and Power of the Michael Okpara University of Agriculture, Umudike. He has published over 70 papers in peer reviewed journals and conference papers. He is a registered Electrical Engineer (COREN) and corporate member of the Nigerian society of Engineers (MNSE) and the IEEE (MIEEE). He is currently the Associate Dean, Faculty of Engineering at the University of Nigeria, Nsukka. He is also a moderator of examination in Electrical machines and power of the Polytechnic University of Namibia (Department of Electrical Engineering, University of Nigeria, Nsukka, Enugu State, Nigeria).

Edward Chikuni, holds a B.Eng. degree in Electrical Engineering from the University of Sierra Leone, an M.Sc. from University of Manchester Institute of Science & Technology (UMIST), and a Ph.D. from the University of Wales, Swansea. He is a Chartered Electrical Engineer (MIEE) (London) and Fellow of the Zimbabwe Institution of Engineers. At present he is a Senior Lecturer in Electrical Engineering at the University of Kwazulu-Natal.

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