Analysis Of Speed Control of Induction Motor Performance Under Pulse Width Modulation and Phase Angle Controlling Techniques

Echegi Judith Unoma[1] and Echegi Christian Uche[2]
[1]Department of Electrical/Electronic Engineering Enugu State University of Science and Technology (ESUT) Enugu, Nigeria.
[2]School of Engineering, Institute of Management and Technology (IMT) Enugu, Nigeria.
achime@imt.edu.ng
DOI:10.56201/ijemt.v10.no7.2024.pg116.126

Abstract

In this research, the speed control of induction motor using PWM and Phase angel controlling techniques was investigated under the following conditions. In the first stage, the induction motor was operated at a speed set point of 2830 RPM and with rated torque 10Nm. While in the second part, the induction motor was operated at 50% of the rated set point speed of 1415 RPM and 50% of the rated torque (5Nm). The result shows that PWM and phase angle controllers exhibited varying degrees of high efficiency in the reduction of speed overshoot and settling time. From the performance improvement of the simulation carried out, the PWM controller reduced the speed response overshoot and settling time of the phase angle controller by 1.51% and 13.51% respectively for the reference speed set point of 2830 RPM and torque of 10NM. But for the case of 50% of these rated parameters of speed set point and torque, the reduction in speed overshoot and settling time of phase angle controller by the PWM are 15.11% and 13.64% respectively. This implies that the speed control under PWM leads in efficiency of machine operations and effective energy utilization.

Introduction

Induction motor is widely used in both industrial and household applications due to its excellent characteristics in robustness, reliability, durability, power factor, stable output, economy, among others. Generally, induction motors are specially designed to run at rated speed when connected to the main power supply [Mohammed Alizadeh, et al, 2017]. Maximum utilization of the induction motors does not only require fast response but also speed control [Echegi and Echegi, 2022].

There are many techniques that are designed for the effective applications of induction motor. Pulse width modulation technique which dated back to 1960s, is of the most popular methods in the control of Variable Frequency Drive (VFD) fed AC motors. However, the variable speed drives are faced with many limitations such as poor efficiencies, unstable control and large space-consumption [Egwaile et al 2016; Iidarabadi and Ahmadi 2017]. In recent years several efforts have been put up by various researchers toward achieving the most efficient methods for the optimization of the speed control of induction motors. These series of past work carried out by various researchers involving different techniques including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Artificial Neutral Networks (ANN), Fuzzy logic and

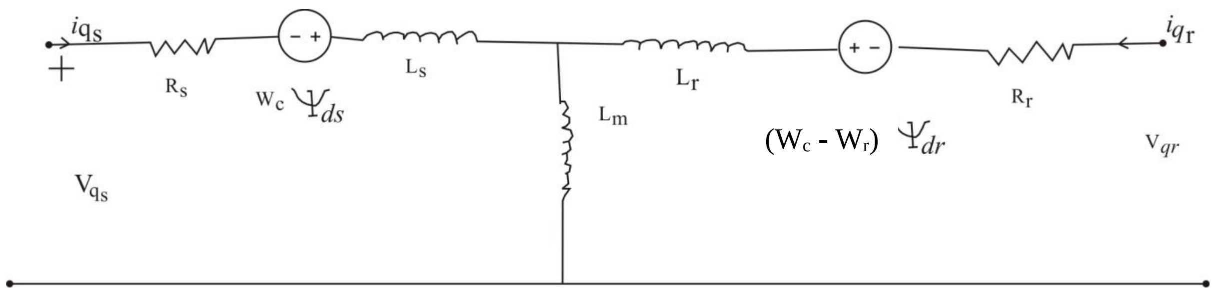
Neuro-Fuzzy Logic (NFL) were geared toward providing the required solutions [Ahamed et al., 2015; Power et al., 2015: Rahman et al., 2020].

However, the general review of all the past works carried out so far reveals that induction motors have not been investigated under the combined variations of speed and torques set points as well as the comparison of the analytical performance of PWM and Phase angle controlling techniques (Rajeshbabu et al., 2018: Echegi, 2021]. This, therefore, informed the rationale for the investigation of the analytical performance of the induction motors using the techniques of phase angel and PWM.

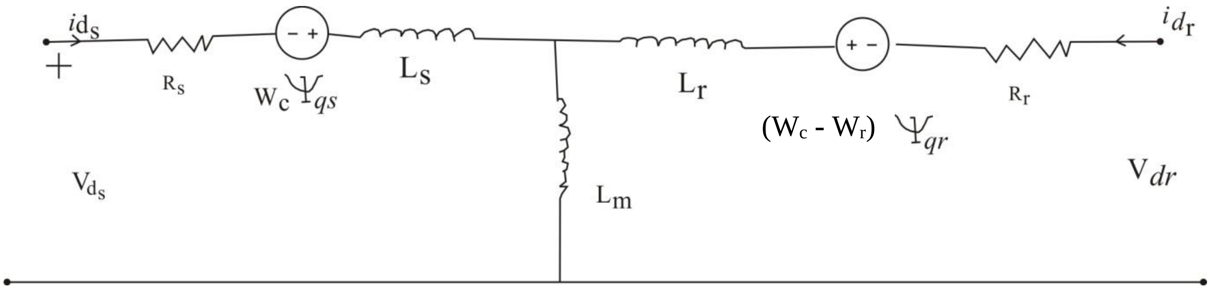
MODEL OF INDUCTION MOTOR

To obtain the model of the induction motor, a dynamic d-q model of a three-phase induction motor in state space form is developed. This is because most high-performance drive control is based on dynamic **d-q** model of the induction motor. Furthermore, the dynamic model in state space form is useful in order to carry out simulations studies of induction motor in MATLAB/SIMULINK program. In the induction motor model development carried out here, the state space equations of the motor in rotating frame are considered and the three-phase to two axis transformation is used.

Considering the goal of carrying out dynamic simulations studies of induction motor control, an equivalent circuit of the induction motor suitable for dynamic simulations is necessary. This equivalent circuit should have only electrical components to emulate the electrical and mechanical behavior of the induction motor. Unlike the induction motor equivalent circuit for steady state analysis, the **d-q** equivalent circuit is suitable for dynamic simulation (Diaz et al, 2009). This is necessary in the modeling of the speed control of induction motors. Hence in this work, the dynamic or **d-q** equivalent circuit of the induction motor is used. The **d-q** equivalent circuit enables the 3-phase stationary frame reference variable V_{as}, V_{bs} and V_{cs} (which represents phase a to neutral voltage, phase b to neutral voltage and phase c to neutral voltage respectively) to be represented in the **d-q** reference frame. The **d-q** equivalent circuit is a representation of the induction motor in the two phase reference frame (i.e. in the **d-q** reference frame). In the The **d-q** equivalent circuit, the induction motor is represented in the two phase synchronous rotating variables V_{qs} and V_{ds}. The **d-q** equivalent circuit of the induction motor is shown in figure 1. Figure 1(a) shows the **q-axis** equivalent circuit whereas Figure 1(b) shows the **d-axis** equivalent circuit.



(a) q-axis equivalent circuit



(b) d-axis equivalent circuit

Figure 1: d-q equivalent circuit of the induction motor

Let equations (1) - (3) represent the three phase voltages supplied to the induction motor.

$$V_{as} = V_m \sin(\omega_e t) \quad (1)$$

$$V_{bs} = V_m \sin(\omega_e t - \frac{2\pi}{3}) \quad (2)$$

$$V_{cs} = V_m \sin(\omega_e t + \frac{2\pi}{3}) \quad (3)$$

where the variable V_m represents the amplitude of terminal voltage, whereas the variable ω_e represents the supply frequency.

For the 3-phase to two axis transformation, the 3-phase stationary reference frame variables V_{as}, V_{bs}, V_{cs}, are transformed into two phase stationary reference frame

variables ($V_{qs}{}^s$ and $V_{ds}{}^s$). The axis transformation is carried using the following equations:

$$V_{qs}{}^s = V_{as} \quad (4)$$

$$V_{ds}{}^s = -\frac{1}{\sqrt{3}} V_{bs} + \frac{1}{\sqrt{3}} V_{cs} \quad (5)$$

The two phase stationary reference frame variables $V_{qs}{}^s$ and $V_{ds}{}^s$ are then are transformed into two phase synchronously rotating frame variables V_{qs} and V_{ds}. The following equation achieves this:

$$V_{qs} = V_{qs}{}^2 cos\theta_a - V_{ds}{}^2 sin\theta_e \quad (6)$$

$$V_{ds} = V_{qs}{}^2 sin\theta_a + V_{ds}{}^2 cos\theta_e \quad (7)$$

where θ_e is the angle of rotating frame with respect to stationary frame.

The induction motor's stator and rotor circuits and their variables have to be represented in the synchronous rotating frame. Equations for the stator circuit are given as follows:

$$V_{qs}{}^s = R_s i_{qs}{}^s + \frac{d\Psi_{qs}{}^2}{dt} \quad (8)$$

$$V_{ds}{}^s = R_s i_{qs}{}^s + \frac{d\Psi_{ds}{}^2}{dt} \quad (9)$$

Where $\Psi_{qs}{}^2$ is the stator flux linkages for q-axis; and $\Psi_{ds}{}^2$ is the stator flux linkages for d-axis.

The following equations are obtained after converting the above equations to

synchronously rotating $d^e - q^e$ frame:

$$V_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_e \Psi_{ds} \quad (10)$$

$$V_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_e \Psi_{qs} \quad (11)$$

The circuit equations for the rotor are given by

$$V_{qr} = R_s i_{qr} + \frac{d\Psi_{qr}}{dt} + \omega_e \Psi_{dr} \quad (12)$$

$$V_{dr} = R_s i_{dr} + \frac{d\Psi_{dr}}{dt} - \omega_e \Psi_{qr} \quad (13)$$

The speed at which the rotor actually moves is ω_r . Hence the d-q axes fixed on the rotor move at speed relative to synchronously rotating frame. Therefore, the actual rotor equations, in the $d^e - q^e$ frame are written as follow:

$$V_{qr} = R_s i_{qr} + \frac{d\Psi_{qr}}{dt} + (\omega_e - \omega_r)\Psi_{dr} \quad (14)$$

$$V_{dr} = R_s i_{dr} + \frac{d\Psi_{dr}}{dt} - (\omega_e - \omega_r)\Psi_{qr} \quad (15)$$

The flux linkage variables are given as:

$$F_{qs} = \omega_b \Psi_{qs} \quad (16)$$

$$F_{qs} = \omega_b \Psi_{qr} \quad (17)$$

$$F_{ds} = \omega_b \Psi_{ds} \quad (18)$$

$$F_{dr} = \omega_b \Psi_{dr} \quad (19)$$

where ω_b, is the machines' base frequency. Substituting the equation (16) to (19) in stator and rotor equations (8), (9), (14) and (15), the following equations are obtained assuming $V_{qr} = V_{dr} = 0$.

$$V_{qs} = R_s i_{qs} + \frac{1}{\omega_b}\frac{dF_{qs}}{dt} + \frac{\omega_e}{\omega_b} F_{ds} \quad (20)$$

$$V_{ds} = R_s i_{ds} + \frac{1}{\omega_b}\frac{dF_{ds}}{dt} - \frac{\omega_e}{\omega_b} F_{qs} \quad (21)$$

$$0 = R_r i_{qr} + \frac{1}{\omega_b}\frac{dF_{qr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr} \quad (22)$$

$$0 = R_r i_{qr} + \frac{1}{\omega_b}\frac{dF_{dr}}{dt} - \frac{(\omega_e - \omega_r)}{\omega_b}F_{qr} \quad (23)$$

In terms of currents, the flux linkage expressions are written as follows:

$$\Psi_{qs} = L_{ls}i_{qs} + L_m(i_{qs} + i_{qr}) \quad (24)$$

$$\Psi_{qr} = L_{lr}i_{qr} + L_m(i_{qs} + i_{qr}) \quad (25)$$

$$\Psi_{qm} = L_m(i_{qs} + i_{qr}) \quad (26)$$

$$\Psi_{ds} = L_{ls}i_{ds} + L_m(i_{ds} + i_{dr}) \quad (27)$$

$$\Psi_{dr} = L_{lr}i_{qr} + L_m(i_{ds} + i_{dr}) \quad (28)$$

$$\Psi_{dm} = L_m(i_{ds} + i_{dr}) \quad (29)$$

Another set of expressions for the flux linkage can be derived by multiplying equations (24) to (29) by ω_b :

$$F_{qs} = \omega_b\Psi_{qs} = X_{ls}i_{qs} + X_m(i_{qs} + i_{qr}) \quad (30)$$

$$F_{qr} = \omega_b\Psi_{qr} = X_{lr}i_{qr} + X_m(i_{qs} + i_{qr}) \quad (31)$$

$$F_{qm} = \omega_b\Psi_{qm} = X_m(i_{qs} + i_{qr}) \quad (32)$$

$$F_{ds} = \omega_b\Psi_{ds} = X_{ls}i_{qs} + X_m(i_{ds} + i_{dr}) \quad (33)$$

$$F_{dr} = \omega_b\Psi_{ds} = X_{lr}i_{dr} + X_m(i_{ds} + i_{dr}) \quad (34)$$

$$F_{dm} = \omega_b\Psi_{dm} = X_m(i_{ds} + i_{dr}) \quad (35)$$

Where X_{ls} is the stator leakage reactance; $X_{ls} = \omega_b L_{ls}$

$X_{lr}$is rotor leakage reactance; $X_{lr} = \omega_b L_{lr}$

If magnetizing reactance; $X_m = \omega_b L_m$

Equations (20), (31), (33) and (34) are written as,

$$F_{qs} = X_{ls}i_{qs} + F_{qm} \quad (36)$$

$$F_{qr} = X_{lr}i_{qr} + F_{qm} \quad (37)$$

$$F_{ds} = X_{ls}i_{ds} + F_{dm} \quad (38)$$

$$F_{dr} = X_{lr}i_{dr} + F_{dm} \quad (39)$$

Expressing currents in terms of flux linkages:

$$i_{qs} = \frac{F_{qs} - F_{qm}}{X_{ls}} \quad (40)$$

$$i_{qr} = \frac{F_{qr} - F_{qm}}{X_{ls}} \quad (41)$$

$$i_{ds} = \frac{F_{ds} - F_{dm}}{X_{ls}} \quad (42)$$

$$i_{dr} = \frac{F_{dr} - F_{dm}}{X_{ls}} \quad (43)$$

Equations (40) to (43) are used in equations (36) to (39) to obtain expressions for F_{qm} and F_{dm} written as follows:

$$F_{qm} = X_m \left(\frac{F_{qs} - F_{qm}}{X_{ls}} + \frac{F_{qr} - F_{qm}}{X_{lr}} \right) \quad (44)$$

$$F_{qm} = \frac{X_{m1}}{X_{ls}} F_{qs} + \frac{X_{m1}}{X_{ls}} F_{qr} \quad (45)$$

Similarly,

$$F_{dm} = \frac{X_{m1}}{X_{ls}} F_{ds} + \frac{X_{m1}}{X_{ls}} F_{dr} \quad (46)$$

where,

$$X_{m1} = \frac{X_m X_{ls} X_{lr}}{X_{ls} X_{lr} + X_m X_{lr} + X_m X_{ls}}$$

By substituting equations (40) to (43) in equations (20) to (23), the equations for the induction motor stator and rotor are obtained as follows:

$$V_{qs} = \frac{R_s}{X_{ls}} (F_{qs} - F_{qm}) + \frac{1}{\omega_b} \frac{dF_{qs}}{dt} + \frac{\omega_e}{\omega_b} F_{ds} \quad (47)$$

$$V_{ds} = \frac{R_s}{X_{ls}} (F_{ds} - F_{dm}) + \frac{1}{\omega_b} \frac{dF_{ds}}{dt} - \frac{\omega_e}{\omega_b} F_{qs} \quad (48)$$

$$0 = \frac{R_r}{X_{lr}} (F_{qr} - F_{dm}) + \frac{1}{\omega_b} \frac{dF_{qr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr} \quad (49)$$

$$0 = \frac{R_r}{X_{lr}} (F_{dr} - F_{dm}) + \frac{1}{\omega_b} \frac{dF_{qr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr} \quad (50)$$

Via modification, equations (47) – (50) can be expressed in state space form as follows:

$$\frac{dFqs}{dt} = \omega b \left[Vqs - \frac{\omega eFds}{\omega b} + \frac{Rs}{Xls} \left\{ \frac{FqrXm}{Xlr} + Fqs \left(\frac{Xm}{Xls} - 1 \right) \right\} \right] \quad (51)$$

$$\frac{dFds}{dt} = \omega b \left[Vds - \frac{\omega eFqs}{\omega b} + \frac{Rs}{Xls} \left\{ \frac{FdrXm}{Xlr} + Fds \left(\frac{Xm}{Xls} - 1 \right) \right\} \right] \quad (52)$$

$$\frac{dFqr}{dt} = \omega b \left[\left(\frac{\omega e - \omega r}{-\omega b} \right) Fdr + \frac{Rr}{Xls} \left\{ \frac{FqsXm}{Xls} + Fqr \left(\frac{Xm}{Xls} - 1 \right) \right\} \right] \quad (53)$$

$$\frac{dFdr}{dt} = \omega b \left[\left(\frac{\omega e - \omega r}{\omega b} \right) Fqr + \frac{Rr}{Xls} \left\{ \frac{FdsXm}{Xls} + Fdr \left(\frac{Xm}{Xls} - 1 \right) \right\} \right] \quad (54)$$

METHOD, DESIGN AND IMPLEMENTATION

The characterization of a 3-phase induction motor under phase angle control is used to establish the reference situation by which the performance improvement to be achieved by the proposed pulse width modulation control technique is based on. The mathematical model of the 3-phase induction motor is used to obtain the MATLAB/SIMULINK model of the motor. The Simulink model of the induction motor is used to carry out simulation studies to evaluate the performance of the PWM speed control method. A computer running the windows operating system of 2.15 gigga hertz clock speed, 4GB or RAM, 500GB of HDD is used to run the MATLAB/SIMULINK programme for the simulation studies carried out.

The speed responses of the induction motor are simulated and evaluated under two different speed set points and torque loading. The PWM control scheme for the speed control of the 3-phase induction motor is implemented in the simulation carried out as MATLAB M-file programme code. The PWM programme carried out a signal exchange with the SIMULINK model of the induction motor using the MATLAB S-function block and the MATLAB workspace structure.

For the mathematical model of the PWM scheme developed, matrix converter is used as the drive transform and fourier series are used for the modeling of PWM control signal generation process, to show how the PWM are generated and to modulate the 3-phase voltage input to the induction motor in order to control the motor's speed.

RESULT AND DISCUSSION

Characterization of the Response of the Induction Motor Based on the existing Phase Angle and PWM Controlling Techniques.

In the characterization of the speed response of the 3-phase induction motor, the MATLAB/SIMULINK simulation of the d-q model was employed. The speed response characteristics are obtained by using phase angle control as the benchmark controller. The MATLAB m-file programme code of the phase angle controller and the SIMULINK model of the induction motor are integrated via the MATLAB S-function.

The speed response characteristics of the induction motor were obtained for two operating conditions. In the first case, the induction motor was operating at set point speed 2830 RPM (ie the rated or nominal speed) and loaded with rated torque 10Nm. In the second case, the induction motor was operated at 50% of the rated torque and at speed set point of 50% of the rated value stated earlier.

Similarly, for the PWM technique, the same operating conditions with that of the phase angle controller were employed for the analysis. The MATLAB m-file script code that implements the phase angle and PWM controller induction motors are given in figures 3.1. These responses are obtained for the case of induction motor controlled with the set point at the rated speed of 2830 RPM and loaded with rated torque of 10Nm for the phase angle and PWM controlling techniques.

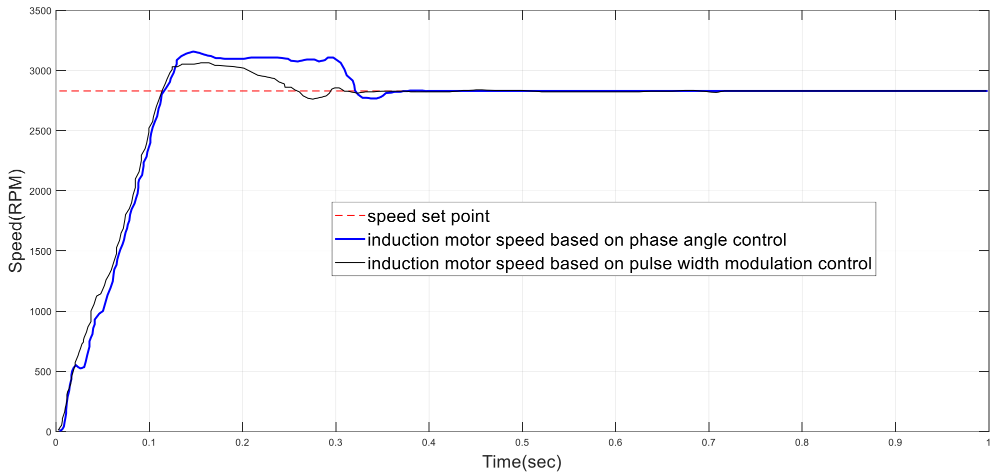


Figure 3.1: Speed trajectory of the induction motor under phase angle and PWM controlling techniques at the rated speed of 2830RPM and loaded with rated torque of 10Nm.

The trajectory of the phase angle controller shows that the speed of the motor rose past the speed set point of 2830 RPM, reduced but later increased to the rated value and thereafter maintain constant for some time. The settling time which is time taken to match the set point was obtained as 0.37 sec. The motor speed exceeds the set point and at about 0.15 sec, the speed rose to 3152 RPM, representing an overshoot of about 10.24%.

For the PWM controlling techniques, the speed trajectory exhibited a similar characteristics. The speed exceeded the set point and rose to 3077 RPM, producing and overshoot of 247 RPM, representing 8.73% while the settling time of 0.32 sec was obtained. This observation shows that the PWM had a lower overshoot than that the phase angle controller thereby exhibiting a better advantage of higher performance. In the same vein, with the value of the phase control as the baseline, the PWM controller reduced the overshoot by 1.5% this reduction in overshoot is reflected in the value of the settling time obtained which reduces from 0.37 sec to 0.32 sec, representing 13.5%.

The analysis of the speed responses of two controlling techniques for the case of the induction motor operating at the set point of 50% of the rated speed and the 50% rated torque is contained in a combined plot of figure 3.2.

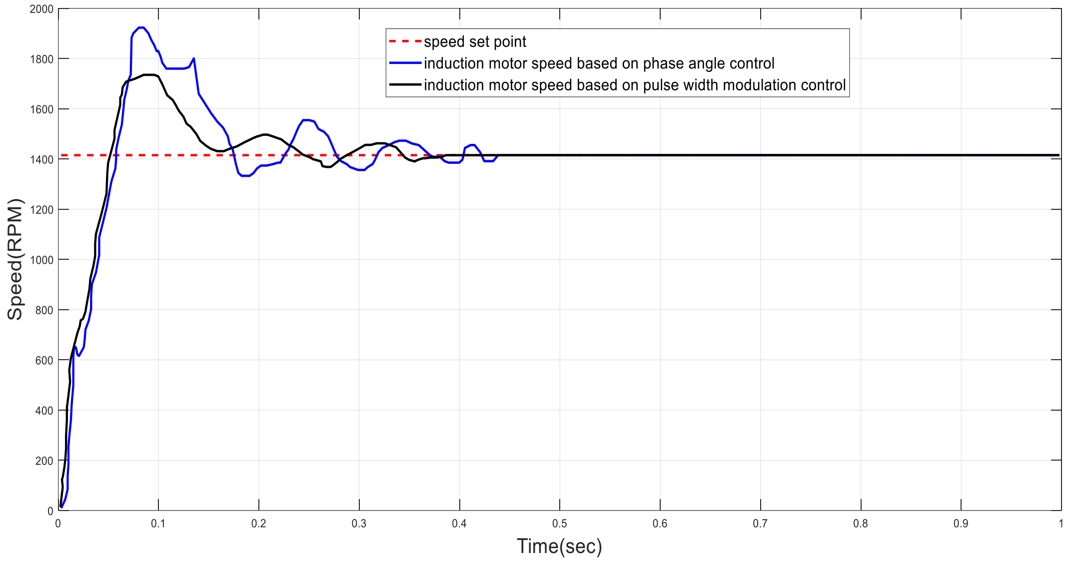


Figure 3.2

The speed response of the induction motor for the phase angle and PWM controlling techniques at the 50% of the rated speed and the 50% of the rated torque.

As in the first case, figure 3.2 shows that the PWM controller has better speed oscillation damping performance than the phase angle controller counterpart. For the phase angle, it can be observed that it took the induction motor longer time than in first case for the speed to rise past the speed set point. The speed rose past the set point of 1415 RPM to 1927 RPM representing the overshoot of 26.60%. But for the PWM controlling technique, the speed reached a maximum of 1740.32 RPM thereby producing speed overshoot of 325.32 RPM representing 11.49%. The settling time obtained using the phase angle and PWM are 0.44 sec and 0.38 sec respectively. This rise in time followed the same trend as the value of 0.12 sec recorded for the phase angle decreased to 0.008 sec for the PWM counterpart.

In this two set-point cases considered, PWM controller reduced the overshoot, the settling time and the time to provide the required load balancing torque. This indicates that the motor under PWM control would be faster in reaching the desired operational speed than under the phase angle controller. This might informed the basis for the industrial application of the motor as machine tools for cutting, bending, milling, positioning operations etc. Accordingly, this is the domain in which PWM controller exhibits higher operational efficiency, optimum energy conservation and better machine tolerance.

Generally, a faster settling time indicates higher efficient motor operations. This leads to a favourable economy of operation and more effective energy utilization. The effect has tremendous impact on the cost of running industrial systems that are driven by induction motor. Similarly, the speed overshoot has serious impact on the settling time. The higher the overshoot, the greater the effort required by the system to stabilize the speed and the industrial processes of the motor.

CONCLUSION

The analysis of the performance of the induction motor reveals that PWM controller achieved a higher degree of efficiency in the reduction of speed overshoot and settling time when compared to phase angle controller under the same conditions investigated. Accordingly, the PWM controller displayed a higher performance in machine operations and better energy utilization and therefore recommended for its universal applications.

REFERENCES

Mohammed Alizadeh, Mahyar Masourni and Ehasn Ebrahim (2017), Close Loop Speed Control of Induction Motor using Constant V/F Applying SPWM and SVPWM based Inverter, International Journal of Engineering and Advanced Technology (IJEAT), Vol. 6, Issues 5, 234 – 240.

Echegi Judith Unoma, Ilo Fredrick and Echegi Christian Uche (2022), Improving the Speed Control of the Induction Motor Using Pulse Width Modulation Technique, American Journal of Applied Sciences and Engineering, Vol. 3, No. 3, 1-11.

Egwaile J. O., Oriahi M.A., and Omoze E.L (2016) Speed Control of Induction Motor Using modified Pulse Width Modulation Technique, International Journal of Electrical and Telecommunication System Research, Vol.8, No 8, 109 – 116.

Iidarabadi Rahim and Ahmadi Azadeh (2017), Simulation study of space Vector Pulse Width Modulation Feeding a three phase induction motor, International Journal of Research studies in Electrical and Electronic Engineering, Vol. 3, Issue 2, 19 – 25.

Ahamed Raiz S., Chandra Sekhar J.N and Dinakara Prasad R. P (2015), Special Control of Induction Motor by using Intelligence Techniques, International Journal of Engineering Research and Application, Vol. 5 (Part 5), 130 – 135.

Pawer Harsha Chavan, Shinde Ashwini and Rugandhard Chavan (2015) Speed Control of Induction Motor using PWM Technique, International Journal of Engineering Research and Technology, Vol. 4, Issue 04, 174 – 179.

Rahman Sharjil, Azwin Aidil and Abidin Zainal (2020) A review of induction Motor Speed Control Methods, International Journal of Core Engineering and Management, Vol. 3, Issue 5, 116 – 124.

Rajeshbabu S., Manikanda B.V and Arulkumar A. (2018) Speed Control of A.C Induction Motor using PWM Controlled Voltage Source Invester, International Journal of Pure and Applied Mathematics, 118(24), 1-9.

Echegi Judith Unoma (2021) Improving the Speed Control of Induction Motor using Pulse Width Modulation Technique, Master Degree Dissertation, Enugu State University of Science and Technology, Enugu, Nigeria, 6 – 12.

Diaz A., Saltares R., Rodriguez C. Nunez R. F., Ortiz-Rivera E.I and Gonzalez-Lorente J. (2009, Induction Motor Equivalent Circuit for Dynamic Simulations, IEEE, International Electric Machines and Drives Conference, 858 – 863, Dio 101109/IEMDC.2009.5075304.

APPENDIX

The variables for the induction motor parameters are defined as follows:

V_{qs} = equivalent stator quadrature voltage. V_{ds} = equivalent stator direct voltage

R_s = stator resistance. L_s = stator leakage inductance

L_m= magnetizing inductance. L_r= rotor leakage inductance

R_r= rotor resistance. ω_r = rotor angular speed in electrical degrees

ω_c = reference frame angular velocity in electrical degrees.

i_{qs} = stator equivalent quadrature current. i_{ds} = stator equivalent direct current

i_{qr} = rotor equivalent quadrature current i_{dr} = rotor equivalent direct current

$d\Psi_{qs}$ = stator flux linkage for q-axis $d\Psi_{ds}$ = stator flux linkage for d-axis

$d\Psi_{qr}$ = rotor flux linkage for q-axis $d\Psi_{dr}$ = rotor flux linkage for d-axis

V_{as} = phase a to neutral voltage V_{bs} = phase b to neutral voltage

V_{cs} = phase c to neutral voltage