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Performance analysis of Five-Phase and Three-Phase Induction Machines

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Abstract: This paper contains the performance analysis of three phases and five phase induction motor. The mathematical modelling and simulation of Five-phase induction Motor and Three-phase induction Motor is carried out. The simulation results are presented to validate modelling procedure and take a speed and torque waveform of both inductions motor. After that performance analysis of both motors has been discussed. It is concluded that five phase induction motor is more preferred.

Keywords: Three-phase inverter fed Induction Motor drive, Five-phase inverter fed Induction Motor drive, MATLAB.

I. INTRODUCTION

The first proposal of a variable speed Multi-phase induction motor drive is believed to have been made in after 1969.[1]
Multiphase inverter fed multiphase induction motors has redundant structure, and reliability with high fault tolerant capabilities. Benefits over the traditional three-phase motors are, by reducing the amplitude and increasing the frequency of torque pulsations, lowering the rotor harmonic current losses and dc link current harmonics.[2]
Earlier, multiphase motor were not in wide use because of the lack of multiphase supply for the multi-phase motor. With the advancement in power electronics, interest in multi-phase machine has been increased tremendously as high power electronic devices are used as a switch in Voltage Source Inverter (VSI), the output of the VSI is given to the multiphase machine.[1] [6]

A. Three-Phase Supply Voltage, Current & Power relations[1]
If $V_{RN} = V_{YN} = V_{BN}$ and they are equally spaced the systemof voltage is balanced (120° each phase). $V_P = V_{RN} = V_{YN} = V_{BN}$. Then $V_L = \sqrt{3}\, V_P$ and $I_L = I_P$. Where I_L is the current in any line and I_P is the current in any load or phase.[5]
Total power is,

$P = 3V_P I_P \cos Ø$ or
$P = \sqrt{3} V_L I_L \cos Ø$

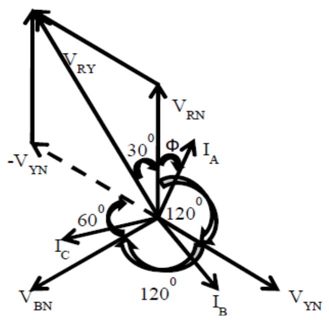

Fig. 1 Phase relationship between phase voltages and currents

B. Five-Phase Supply Voltage, Current & Power relations [1]

If $V_{AN} = V_{BN} = V_{CN} = V_{DN} = V_{EN}$ and they are equally spaced (i.e.,72°each phase) $V_P = V_{AN} = V_{BN} = V_{CN} = V_{DN} = V_{EN}$ (the phase voltage) Then $V_L = \sqrt{1.38}V_P$ or $V_L = 1.175\ V_P$ and. $I_L = I_P$. The totalpower is the sum of the amount of power in each phase.

$P = 5V_P I_P \cos Ø$
or
$P = 4.25 V_L I_L \cos Ø$

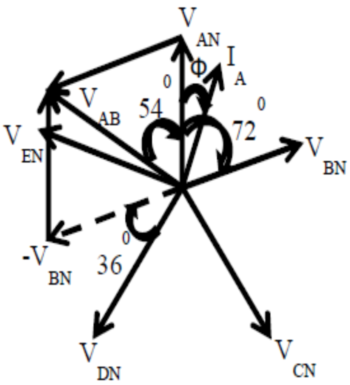

Fig. 2Phase relationship between phase voltages and currents

Supply of Five phase Induction Motor [3]
Voltage source inverter (VSI) used for supply in different phase induction motor.

Single phase VSI used for lower range power application.
Three phase VSI used for medium to higher range power application.

Five phase VSI used for above to three phase power application.

The main purpose of these topologies is to provide a five-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable.

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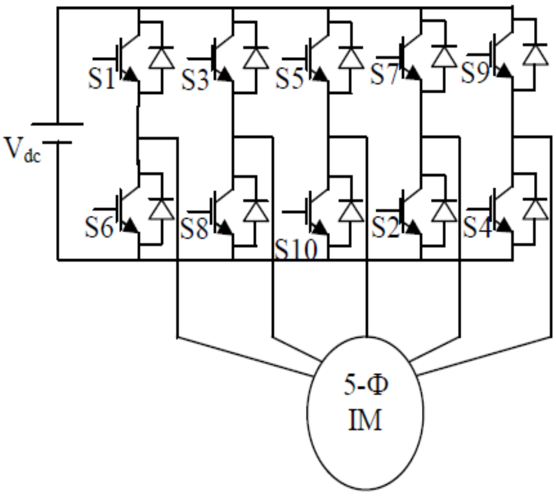

Fig. 3 Five Phase Topology of Five phase of Induction motor

II. MATHEMATICAL MODELLING OF THREE PHASE INDUCTION MOTOR [4][7]

Phase voltage of three phase induction motor

$$V_A = \sqrt{2}V_{RMS}\ SIN(\Omega T)$$
$$V_b = \sqrt{2}V_{rms}\ sin(\omega t - \frac{2\pi}{3})$$
$$V_c = \sqrt{2}V_{rms}\ sin(\omega t - \frac{4\pi}{3})$$

The flux linkages of stator and rotor d-q component can be as follows

$$\frac{df_{qs}}{dt} = w_b\left[V_{qs} - \frac{w_e}{w_b}F_{ds} + \frac{R_s}{X_{ls}}\left(F_{mq} - F_{qs}\right)\right]$$
$$\frac{df_{ds}}{dt} = w_b\left[V_{ds} + \frac{w_e}{w_b}F_{qs} + \frac{R_s}{X_{ls}}\left(F_{mq} - F_{ds}\right)\right]$$
$$\frac{df_{qr}}{dt} = -w_b\left[\frac{(w_e - w_b)}{w_b}F_{dr} + \frac{R_r}{X_{lr}}\left(F_{qr} - F_{mq}\right)\right]$$
$$\frac{df_{dr}}{dt} = -w_b\left[-\frac{(w_e - w_b)}{w_b}F_{qr} + \frac{R_r}{X_{lr}}\left(F_{dr} - F_{md}\right)\right]$$

Where

$$F_{md} = X_{ml}\left[\frac{F_{ds}}{X_{ls}} + \frac{F_{dr}}{X_{lr}}\right] F_{mq} = X_{ml}\left[\frac{F_{qs}}{X_{ls}} + \frac{F_{qr}}{X_{lr}}\right] X_{ml} = \frac{1}{\left(\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}\right)}$$

Then the equation of the stator and rotor current:-

$$i_{qs} = \frac{1}{X_{ls}}\left(F_{qs} - F_{mq}\right)$$
$$i_{ds} = \frac{1}{X_{ls}}\left(F_{ds} - F_{md}\right)$$
$$i_{qr} = \frac{1}{X_{lr}}\left(F_{qr} - F_{mq}\right)$$
$$i_{dr} = \frac{1}{X_{lr}}\left(F_{dr} - F_{md}\right)$$

Based on the above equations, the torque and rotor speed can be determined as follows

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{1}{\omega_b}\left(F_{ds}i_{qs} - F_{qs}i_{ds}\right) \qquad \omega_r = \int \frac{P}{2J}(T_e - T_L)$$

III.MATHEMATICAL MODELLING OF FIVE PHASE INDUCTION MOTOR[5]

Modelling of five phase induction motor is nearly same as that of the three phase induction motor hence before going for the modelling of five phase induction motor it was necessary to study the modelling of three phase induction motor. For five phase induction motor five phase supply is required which is then transformed into arbitrary reference frame. The only difference between the five-phase dq induction motor model and three phase dq induction motor model.

Five Phase Stator Voltage of induction machine under balanced condition is expressed as:

$$V_a = \sqrt{2}V_{rms}\ sin(\omega t)$$
$$V_b = \sqrt{2}V_{rms}\ sin(\omega t - \frac{2\pi}{5})$$
$$V_c = \sqrt{2}V_{rms}\ sin(\omega t - \frac{4\pi}{5})$$
$$V_d = \sqrt{2}V_{rms}\ sin(\omega t + \frac{4\pi}{5})$$
$$V_e = \sqrt{2}V_{rms}\ sin(\omega t + \frac{2\pi}{5})$$

Transformation equation to transform machine variable to the variable in the arbitrary reference frame is expressed as: -

$$\begin{bmatrix} V_q \\ V_d \\ V_x \\ V_y \\ V_0 \end{bmatrix} = \begin{bmatrix} cos\,\theta & cos\left(\theta - \frac{2\pi}{5}\right) & cos\left(\theta - \frac{4\pi}{5}\right) & cos\left(\theta + \frac{4\pi}{5}\right) & cos\left(\theta + \frac{2\pi}{5}\right) \\ sin\,\theta & sin(\theta - \frac{2\pi}{5}) & sin(\theta - \frac{4\pi}{5}) & sin(\theta + \frac{4\pi}{5}) & sin(\theta + \frac{2\pi}{5}) \\ cos\,\theta & cos\left(\theta + \frac{4\pi}{5}\right) & cos\left(\theta - \frac{2\pi}{5}\right) & cos\left(\theta + \frac{2\pi}{5}\right) & cos\left(\theta - \frac{4\pi}{5}\right) \\ sin\,\theta & sin(\theta + \frac{4\pi}{5}) & sin(\theta - \frac{2\pi}{5}) & sin(\theta + \frac{2\pi}{5}) & sin(\theta - \frac{4\pi}{5}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix}$$

The mathematical equation involved in modelling of five phase induction motor whereas model of five phase induction is shown below

Stator Voltage equation

$$V_{ds} = R_s i_{ds} - \omega_a F_{qs} + pF_{ds}$$
$$V_{qs} = R_s i_{qs} + \omega_a F_{ds} + pF_{qs}$$
$$V_{xs} = R_s i_{xs} + pF_{xs}$$
$$V_{ys} = R_s i_{ys} + pF_{ys}$$
$$V_{0s} = R_s i_{0s} + pF_{0s}$$

Rotor voltage equation

$$V_{dr} = R_r i_{dr} - (\omega_a - \omega)F_{qr} + pF_{dr}$$
$$V_{qr} = R_r i_{qr} + (\omega_a - \omega)F_{dr} + pF_{qr} \qquad V_{dr} = R_r i_{dr} - (\omega_a - \omega)F_{qr} + pF_{dr}$$
$$V_{xr} = R_r i_{xr} + pF_{xr} \qquad V_{yr} = R_r i_{yr} + pF_{yr}$$
$$V_{0r} = R_r i_{0r} + pF_{0r}$$

The flux linkages of stator equation

$$F_{ds} = (X_{ls} + X_m)i_{ds} + X_m i_{dr}$$
$$F_{qs} = (X_{ls} + X_m)i_{qs} + X_m i_{qr}$$
$$F_{xs} = X_{ls} i_{xs}$$
$$F_{ys} = X_{ls} i_{ys}$$
$$F_{0s} = X_{ls} i_{0s}$$

The flux linkages of rotor equation

$$F_{dr} = (X_{lr} + X_m)i_{dr} + X_m i_{ds}$$
$$F_{qr} = (X_{lr} + X_m)i_{qr} + X_m i_{qs}$$
$$F_{xr} = X_{lr} i_{xr}$$
$$F_{yr} = X_{lr} i_{yr}$$
$$F_{0r} = X_{lr} i_{0r}$$

IV. INDUCTION MOTOR MODEL

A. Simulink model of three leg inverter

Device that converts dc input voltage to ac output voltage of desired magnitude and frequency is called an inverter. If the input voltage remains constant the inverter is called a Voltage source inverter and if the input current remains constant it is known as a Current source inverter. Three phase inverters are normally used for medium to high power applications. A Three phase inverter can be obtained from a configuration of six transistors and six diodes as shown. In 180˚conduction mode each transistor conducts for 180˚

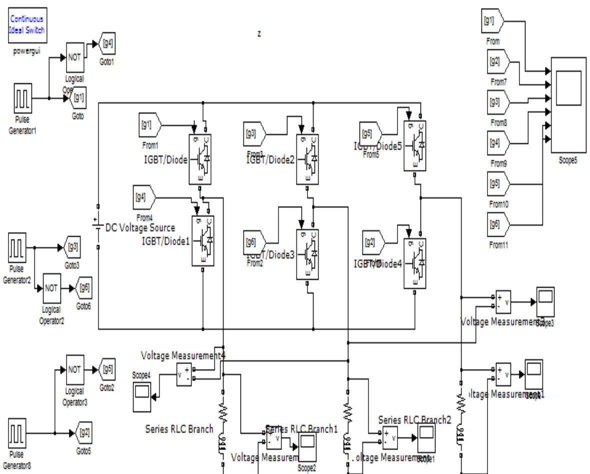

Fig. 9 Simulink Model of Three Leg Inverter

B. Simulink model of five leg inverter

Five phase inverters are normally used for above to high power applications. A Five phase inverter can be obtained from a configuration of ten transistors and ten diodes as shown. In 72˚conduction mode each transistor conducts for 72˚.

In single-Leg of VSIs, the two switches (S1 and S6, S3 and S8, S5 and S10, S7 and S2 or S9 and S4) cannot be switched on at a time, because this would result in a short circuit across the dc link voltage supply. Similarly, in order to avoid undefined states in the VSI, and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity.[1]

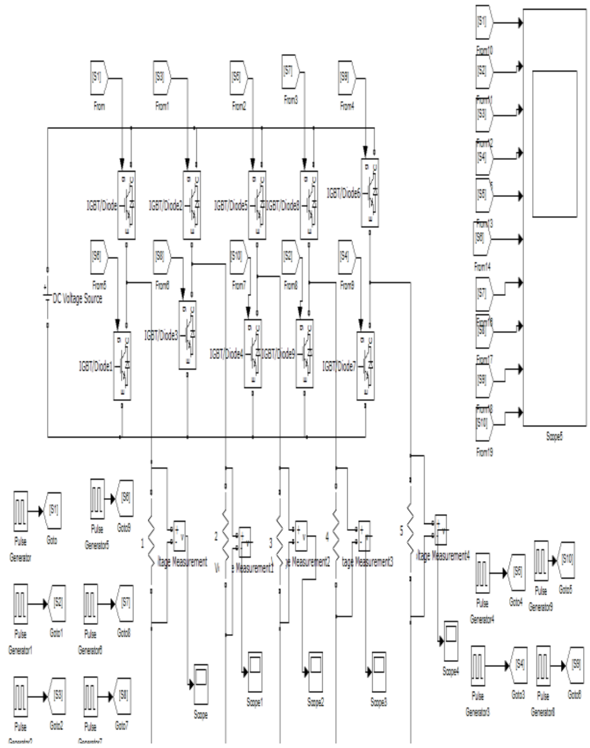

Fig. 10Simulink Model of Five Leg Inverter

C. Simulation of three phase Induction Motor

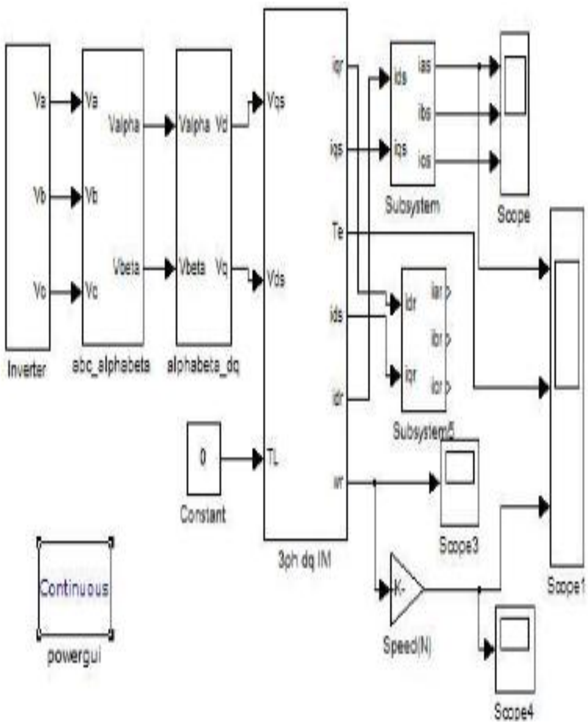

Fig. 10Three Phase Induction Motor Model.

In this model simulation starts with generation of three phase supply which is obtained by using three leg inverter, the output of five leg inverter is used as the supply to the three phase induction motor.

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D. Simulation of Five phase Induction Motor

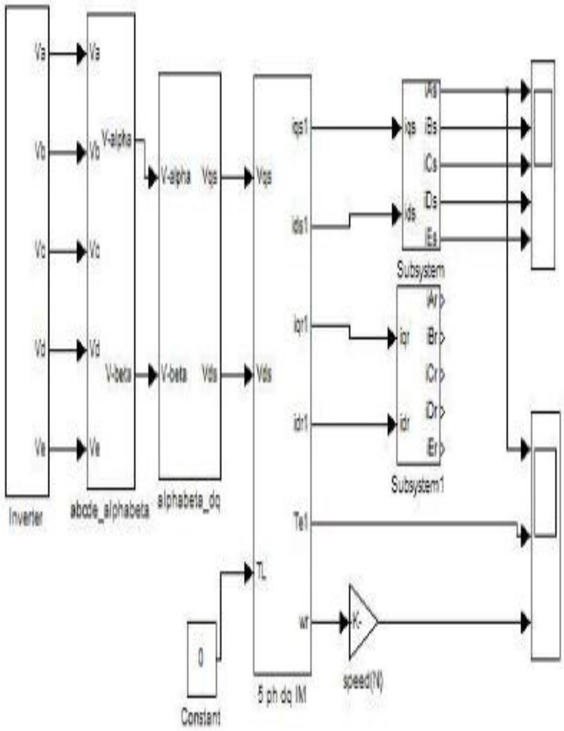

Fig. 11Five Phase Induction Motor Model

In this model simulation starts with generation of five phase supply which is obtained by using five leg inverter, the output of five leg inverter is used as the supply to the five phase induction motor.

V. MATLAB/SIMULINK RESULT

A. Output waveform of three phase inverter phase voltage $\propto = \mathbf{180°}$ PHASE VOLTAGEV_a.

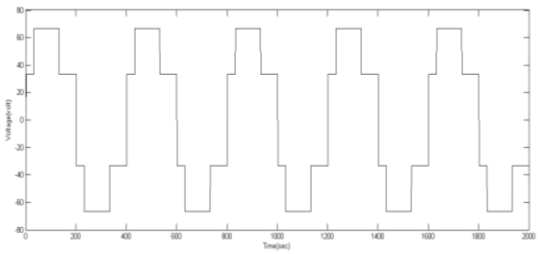

Figure 12:- Phase voltage V_a

Fig shows the phase voltage $V_a$waveform of 3 phase inverter at α=180 ˚ of the phase b. X axis represent the time in sec and on Y axis represent the voltage in volt. It starts from -60 V and has maximum value of 60 V and minimum value -60 V.

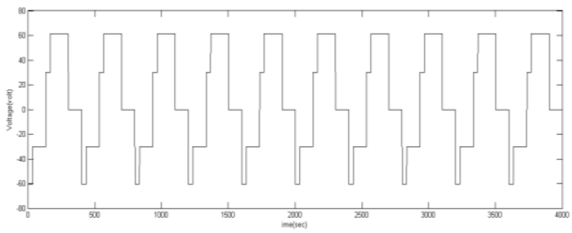

Figure 13:- Phase voltage V_b

Fig shows the phase voltageV_b waveform of 3 phase inverter at α=180 ˚ of the phase a. X axis represent the time in sec and on Y axis represent the voltage in volt. It start from zero V and has maximum value of 60 V and minimum value -60 V.

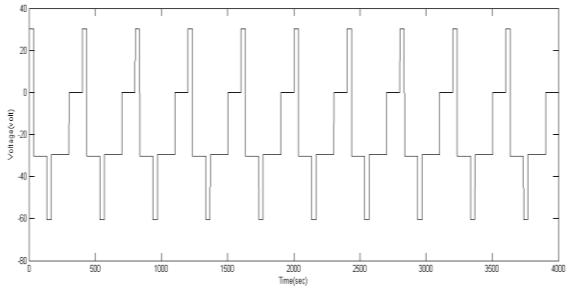

Figure 14:- Phase voltage V_c

Fig shows the phase voltage $\boldsymbol{V_c}$waveform of 3 phase inverter at α=180 ˚ of the phase c. X axis represent the time in sec and on Y axis represent the voltage in volt. It start from 30V and has maximum value of 60 V and minimum value -60

B. Output waveform of five phase inverter phase voltage $\propto = \mathbf{72°}$ $\boldsymbol{V_a}$

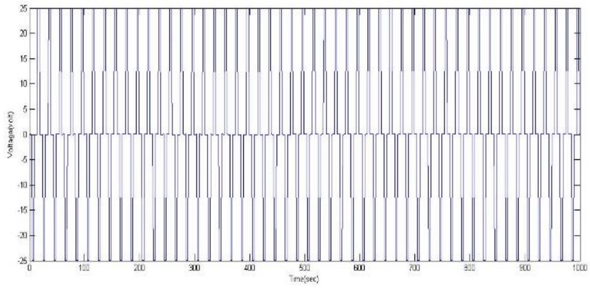

Figure 15:- Phase Voltage V_a

Fig shows the phase voltage waveform of 5 phase inverter at α=72 ˚ of the phase a. X axis represent the time in sec and on Y axis represent the voltage in volt. It start from zero V and has maximum value of 25 V and minimum value -25 V. $\boldsymbol{V_b}$

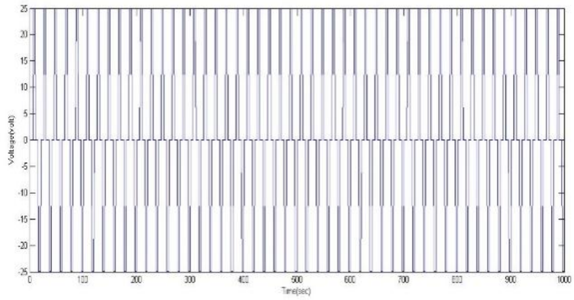

Figure 16:- Phase Voltage V_b

Fig shows the phase voltage waveform of 5 phase inverter at α=144 ˚ of the phase a. X axis represent the time in sec and on Y axis represent the voltage in volt. It start from zero V and has maximum value of 25 V and minimum value -25 V $\boldsymbol{V_c}$

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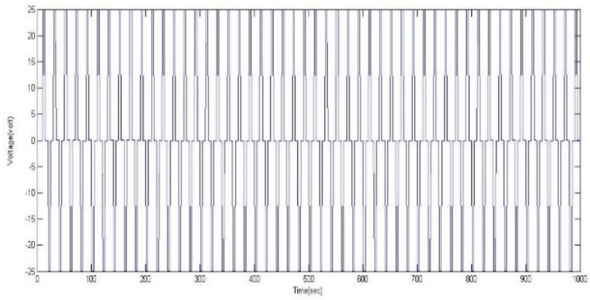

Figure 17:- Phase Voltage V_c

Fig shows the phase voltage waveform of 5 phase inverter at α=216 ˚ of the phase a. X axis represent the time in sec and on Y axis represent the voltage in volt. It start from zero V and has maximum value of 25 V and minimum value -25 V. $\boldsymbol{V_d}$

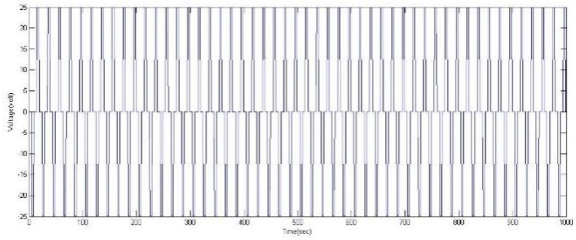

Figure 18:- Phase Voltage V_d

Fig shows the phase voltage waveform of 5 phase inverter at α= 288 ˚ of the phase a. X axis represent the time in sec and on Y axis represent the voltage in volt. It start from zero V and has maximum value of 25 V and minimum value -25 V. $\boldsymbol{V_e}$

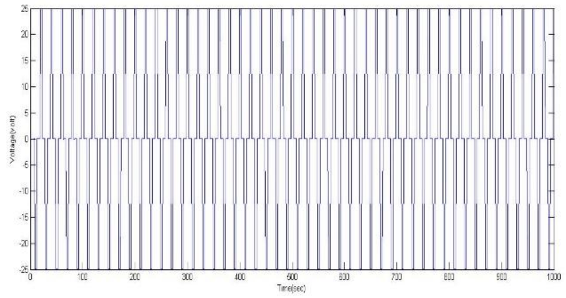

Figure 19:- Phase Voltage V_e

Fig shows the phase voltage waveform of 5 phase inverter at α= 360 ˚ of the phase a. X axis represent the time in sec and on Y axis represent the voltage in volt. It start from zero V and has maximum value of 25 V and minimum value -25 V.

C. Speed waveform of Induction motor

Fig 20 & 21 show the speed waveform of three phase induction motor and five phase induction motor.

Fig 24 show the speed vs time waveform when conduction mode 180˚and this clearly indicate that small ripple produce in this speed waveform.

Fig 21 show the speed vs time waveform when conduction mode 72˚and this clearly indicate that ripple content smoothed in this speed waveform.

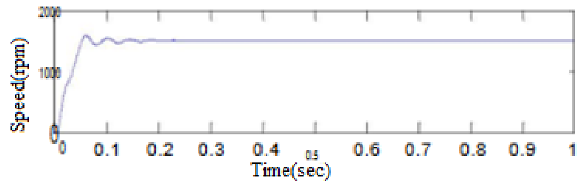

Fig. 20 Speed waveform of three phase induction motor

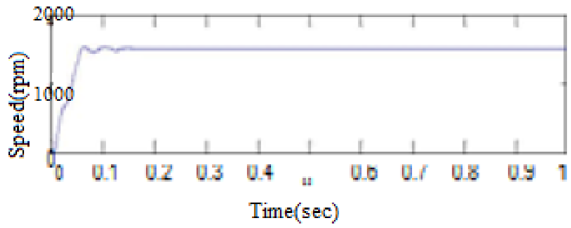

Fig. 21 Speed waveform of five phase induction motor

D. Torque waveform of Induction motor

Fig 22 & 23 show the speed and torque waveform of three phase induction motor and five phase induction motor.

Fig 23 show the torque vs time waveform when conduction mode 180˚and this clearly indicate that small ripple produce in this torque waveform

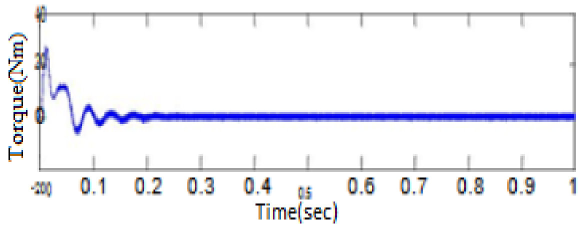

Fig. 22 Torque waveform of three phase induction motor

Fig 23 show the speed vs time waveform when conduction mode 72˚and this clearly indicate that ripple content smoothed in this torque waveform

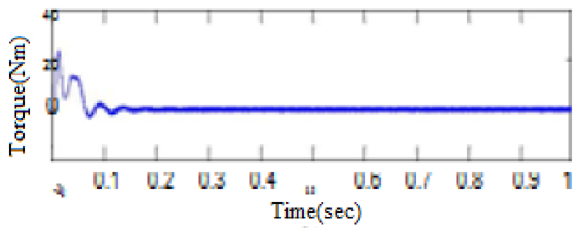

Fig. 23 Torque waveform of five phase induction motor

VI. CONCLUSION

In this paper compared the three phase and five phase induction motor and a complete simulation model to simulate a three phase and five-phase inverter fed induction motor drive. The simulation model is developed using simpower system block sets of the Matlab/Simulink software. A detailed simulation results are presented to validate the modelling procedure and take a speed and torque waveform of both phase induction motor .In this waveform(speed and toque) ripple produce in three phase induction motor but in waveform(speed and torque) of five phase induction motor ripple can be smoothed so conclude that five phase induction motor is preferable for high power application compare to three phase induction motor.

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