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Modeling & Simulation of Seven levels Multilevel Inverter fed Induction motor Drive

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Abstract- Nowadays, the industries demanding more power with low harmonics for the high power applications. Thus Multilevel Inverter concept is introduced. The concept of the Multilevel Inverters becoming trendier for the high power applications due to less harmonics and high power ratings. The importance of the multilevel converters has been increase since the last decade. The ability to synthesize waveforms for high voltage with better harmonic spectrum, these new types of multilevel converters is suitable for high power applications. Several topologies have been introduced, amongst these topologies, the Cascaded H-bridge Multilevel Inverter is proposed. Also the main concept is Harmonics. So to reduce the harmonics the modulation topologies (PWM techniques) for multilevel inverters are proposed. Three phase induction motors are widely used in Industrial drives because of their ruggedness, reliability and simplicity in construction. Accurate control of Induction Machine was always a matter of concern starting from the modulation technique used, to the closed loop control strategy. In this work a complete Induction Motor drive is designed for pumping application with modulation strategy as Sinusoidal pulse width modulation (SPWM). The proposed concept is further implemented with seven level inverter replacing five level system and results are obtained using Matlab/Simulink software

Keywords- Induction Motor, Sinusoidal pulse width modulation (SPWM), Indirect field oriented control (IFOC), Multi/evelInverter (MLI), Centrifugal Pump

I.INTRODUCTION

Induction motor has gained an upper hand in every sphere of motoring application due to its low cost, reliability, low maintenance, no brushes to wear out and very simple rotor assembly. Squirrel cage induction machine when operated at constant line voltage and frequency delivers constant speed. However in industries the applications is not confined to constant speed. Variable speed can be achieved using Induction motor drives where speed control is possible below the rated speed [1]. Main application of Induction Motor drives are Fans, blowers, Compressor, Pumps, machine tools like lathe, drilling machine, lifts, and conveyer belts etc. Induction motor is widely used to drive the industrial pump loads. Centrifugal pump are the most common type of kinetic pump, and it is widely used in the field of irrigation and industrial fluid pumping applications [2]. In this Paper our objective is to analyze the MLI Fed Induction Motor drive with IFOC for pump application [3].

We have connected a Multilevel Inverter to feed the Induction Motor as it possesses several advantages over Voltage source Inverters. Multilevel inverters are suitable for high voltage and high power applications due to their ability to synthesize waveforms with better harmonic spectrum, reduced filter requirements, suitable for renewable and distributed generation system. Using multilevel technique, the amplitude of the output voltage is increased, switching stress in the devices is reduced and the overall harmonic profile is improved. Two level inverter output has high harmonic distortion content and cannot be used for high power applications and drive systems.

There are several control schemes devised for the control of Induction Motor both in open loop as well as in closed loop. Vector control or Field oriented control (FOC) of Induction motor is widely accepted control scheme due to its better dynamic response. In Indirect Field Oriented control (IFOC) scheme speed and position are not directly measured [3], [14].Speed and position are estimated from parameters such as phase voltages and currents which are directly measured from Induction motor output. The closed loop control strategy used in this paper is IFOC

A pump is device that supplies energy to fluid. Pumping application shares about 20% of the total power consumed in Industries. The most common and efficient pumps used in Industries are centrifugal pumps. Centrifugal pumps are generally sized to operate at or near the best efficiency point at maximum flow. The maximum flow requirements, however, frequently occur for a very short period during the operating cycle with the result that some method of flow control is required. The traditional approach to flow control has used valves; which increase system pressure, inherently waste energy, and generally cause the pump to operate at reduced efficiencies. Adjustable speed drives (ASDs) can achieve reduced flow by providing adjustable speed pumping operation. This results in reduced system pressure and operation near the pump's Best Efficiency Point (BEP). In addition, maintenance costs will also be reduced.

In this work a 5 level cascaded H-bridge MLI is used to feed the induction motor driving the centrifugal pump. Indirect Field oriented control (IFOC) strategy is used for the closed loop control of the drive. Alternate Phase opposition disposition (APOO) multicarrier PWM technique is used to produce the control signals for the IGBT switches. A complete drive is modeled using MATLAB Simulink and the affinity laws of centrifugal pump is validated using this model.

II. CASCADED H BRIDGE MLI

The basic block diagram of a cascaded H bridge MLI is shown in Fig 3.1 Here 4 switches are used in H-shape 2 switches in first leg & 2 in second leg and NOT gate is connected to upper switch of the first leg and lower switch of the second leg. Not gate is used in order to avoid short circuit across a leg.

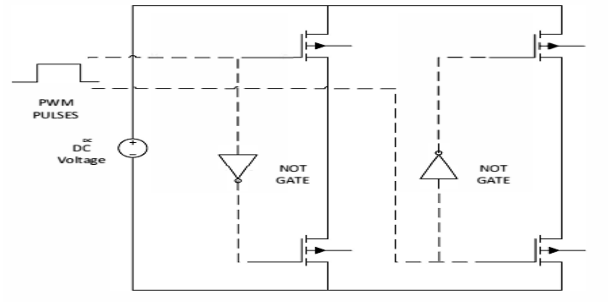
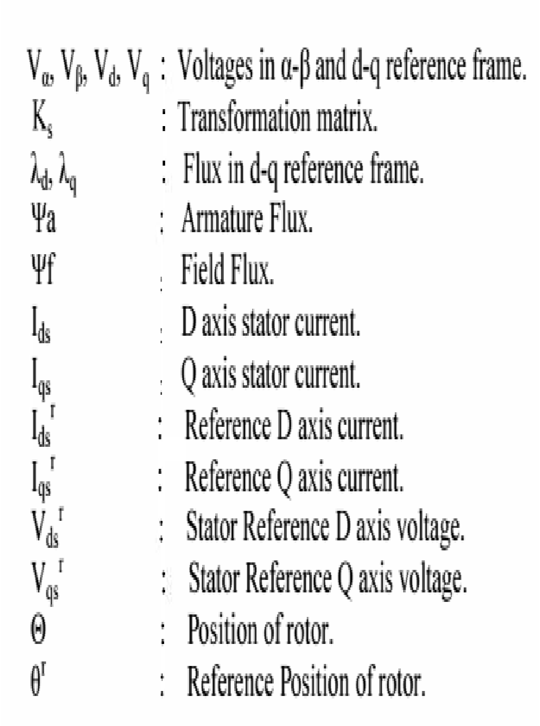


Fig 1 Single H-Bridge

A three phase five level inverter is used to control the induction motor driving a pump load. In the proposed drive scheme, Sine Pulse Width Modulation, technique is used. The multicarrier PWM technique for generating Sinusoidal Pulse Width Modulation is again subdivided into Phase Disposition techniques and Phase displacement techniques [6], [7]. Very popular Phase Disposition techniques are Phase Disposition (PD), Phase Opposition Disposition (POD) and Alternate Phase Opposition Disposition (APOD). In this paper, Alternate Phase Opposition Disposition (A POD) technique is used since it has shown better harmonic spectrum compared to PD and POD. In this technique, alternate carrier waveforms are in phase opposition with each other. In Fig 3.2 APOD Multicarrier PWM with reference sine wave is shown. The number of H bridges required per phase to produce a 5 level output is two and these H bridges are connected in cascade. Increasing no of voltage level results in reducing the voltage stress across the switching devices and as a whole overall harmonic spectrum of the system is significantly reduced.

III.INDUCTION MOTOR MODELLING NOMENCLATURE

$I_\alpha, I_\beta, I_d, I_q$: Currents in a-B and d-q reference frame.
I_A, I_B, I_C : Currents in ABC reference frame.



$V_\alpha, V_\beta, V_d, V_q$: Voltages in α-β and d-q reference frame.
K_s : Transformation matrix.
λ_d, λ_q : Flux in d-q reference frame.
Ψa : Armature Flux.
Ψf : Field Flux.
I_{ds} : D axis stator current.
I_{qs} : Q axis stator current.
I_{ds}^r : Reference D axis current.
I_{qs}^r : Reference Q axis current.
V_{ds}^r : Stator Reference D axis voltage.
V_{qs}^r : Stator Reference Q axis voltage.
Θ : Position of rotor.
θ^r : Reference Position of rotor.

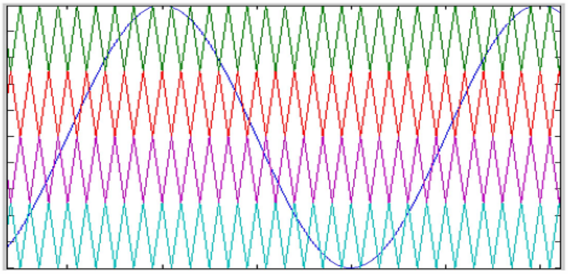


Fig 2 Alternate Phase Opposition Disposition (APOD) Multicarrier PWM

The mathematical model of induction machine is obtained in synchronously rotating reference frame [9, 10, and 11].Matrix for transforming three phase reference frame to two phase stationary reference frame α-β commonly known as Clark's Transformation is given below.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.1}$$

Matrix for transforming αβ to dq reference frame - Park's Transformation

$$V_\alpha = V_m \cos\theta \tag{3.2}$$

$$V_\beta = V_m \sin\ \theta \tag{3.3}$$

$$i_\alpha = i_m \cos(\theta - \varphi) \tag{3.4}$$

$$i_\beta = i_m \sin(\theta - \varphi) \tag{3.5}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.6}$$

Thus the matrix for transforming three-phase rotating to stationary two phase (d-q) frame can be obtained by-

$$i_{qd0s} = K_s i_{abcs} \tag{3.7}$$

$$(i_{qd0s})^T = [i_{qs} \quad i_{ds} \quad i_{0s}] \tag{3.8}$$

$$(i_{abcs})^T = [i_{as} \quad i_{bs} \quad i_{cs}] \tag{3.9}$$

$$K_s = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{3.10}$$

The machine is modeled with the following direct & quadrature axis voltage equations-

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_d \lambda_{qs} \tag{3.11}$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs} - \omega_d \lambda_{ds} \tag{3.12}$$

Eq. (3.11) and (3.12) gives the Stator voltage in D axis and Q axis. Fig. 3.3 and Fig. 3.4 shows the direct axis and quadrature axis equivalent circuit of Induction Motor respectively.

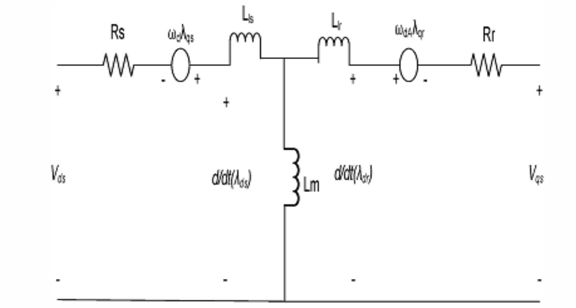


Fig 3 Direct axis equivalent Circuit of Induction Motor

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\lambda_{dr} - \omega_{dA}\lambda_{qr} \tag{3.13}$$

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\lambda_{qr} - \omega_{dA}\lambda_{dr} \tag{3.14}$$

Eq (3.13) and (3.14) gives the Rotor voltage in D axis and Q axis.

V_{ds}, V_{qs}, V_{dr} and V_{dr} are the stator and rotor voltages in DQ axes respectively. Eq. (3.15) gives the relation between flux & current for the stator and rotor in 0 and Q axis component.

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = M \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix}, \text{ where } M = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \tag{3.15}$$

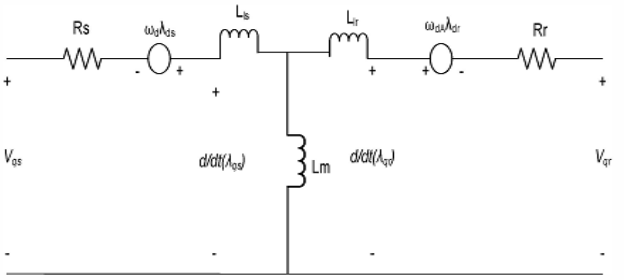


Fig 4 Quadrature axis equivalent Circuit of Induction Motor

Where, i_{ds} and i_{qs}, are the current in the d-axis and q-axis of the stator, i_{dr} and iqr are the d-axis, q-axis rotor currents. L_s is the stator inductance, L_r is the rotor inductance and L_m is the mutual inductance between stator and rotor. Thus the currents in the respective axis can be obtained as,

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \frac{1}{L_m^2 - L_r L_s} \times \left(A \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} \right) \tag{3.16}$$

where,

$$A=\begin{bmatrix} L_rR_s & \omega_{dA}L_m^2-\omega_sL_rL_s & -L_mR_r & -L_rL_m(\omega_s-\omega_{dA}) \\ -(\omega_{dA}L_m^2-\omega_sL_rL_s) & L_rR_s & L_rL_m(\omega_s-\omega_{dA}) & -L_mR_r \\ -L_mR_s & L_sL_m(\omega_s-\omega_{dA}) & L_sR_r & \omega_sL_m^2-\omega_{dA}L_rL_s \\ -L_sL_m(\omega_s-\omega_{dA}) & -L_mR_s & -(\omega_sL_m^2-\omega_{dA}L_rL_s) & L_sR_r \end{bmatrix} \tag{3.17}$$

Mechanical part is modeled with the equations below, the instantaneous electromagnetic torque is given as,

$$T_{em}=\frac{P}{2}(\lambda_{qr}i_{dr}-\lambda_{dr}i_{qr})=\frac{P}{2}L_m(i_{qs}i_{dr}-i_{ds}i_{qr}) \tag{3.18}$$

$$\frac{d}{dt}\omega_{Mech}=\frac{T_{em}-T_L}{J_{eq}}=\frac{\frac{P}{2}L_m(\lambda_{qs}i_{dr}-i_{ds}i_{qr})-T_L}{J_{eq}} \tag{3.19}$$

$$\omega_{dA}=\omega_{slip}=\omega_s-\omega_m \tag{3.20}$$

$$\omega_m=\frac{P}{2}\omega_{Mech} \tag{3.21}$$

$$L_s=L_{sl}+L_m;\ L_r=L_{rl}+L_m \tag{3.22}$$

Using inverse Park's transformation matrix P(θ_s), the following equations can be derived,

$$\begin{bmatrix}[\lambda_{s_{dq0}}]\\ [\lambda_{r_{dq0}}]\end{bmatrix}=\begin{bmatrix}[P(\theta_s)][L_s][P(\theta_s)]^T & [P(\theta_s)][M_{sr}(\theta)][P(\theta_r)]^T\\ [P(\theta_r)][M_{sr}(\theta)]^T[P(\theta_s)]^T & [P(\theta_r)][L_r][P(\theta_r)]^T\end{bmatrix}\begin{bmatrix}[i_{s_{dq0}}]\\ [i_{r_{dq_0}}]\end{bmatrix}$$

Thus the Two-axis frame can be modeled as shown below-

$$\begin{bmatrix}[\lambda_{s_{dq0}}]\\ [\lambda_{r_{dq0}}]\end{bmatrix}=\begin{bmatrix}[L_{ps}] & [M_{psr}]\\ [M_{sr}(\theta)] & [L_{pr}]\end{bmatrix}\begin{bmatrix}[i_{s_{dq0}}]\\ [i_{r_{dq_0}}]\end{bmatrix} \tag{3.25}$$

These are the equations used in the IFOC model for the determination of magnitude & flux angle [3].

IV.IFOC CONTROL

Due to the inherent coupling effect in the machin the scalar control methods of voltage-fed and current-fed inverter offer a very sluggish control response. A vector or field oriented control offers a better dynamic response. In vector control, an Induction Motor is controlled like a separately excited DC motor. In case of a separately excited DC motor, the field flux ψ_f and armature flux ψ_a is established by the respective field current I_f and armature or torque component of current I_a are independent and orthogonal in space such that when torque is controlled by I_a, the field flux is not affected which results in fast torque response. Similarly, in induction motor vector control, the synchronous reference frame currents I_{ds} and I_{qs} are analogous to I_f and I_a, respectively as shown in Fig 3.5 which is the significance of IFOC Scheme [8]. Therefore, when torque is controlled by I_{qs}, the rotor flux is not affected thus giving fast DC motor-like torque response.The drive dynamic model also becomes simple like that of a dc machine because of decoupling vector control.

In the DFOC scheme rotor speed is calculated by means of position sensors and encoders fitted in the rotor shaft so it makes the rotor bulky, costly and complicated and hence overall efficiency of the system is reduced due to the friction and vibration losses in the rotor shaft. In IFOC scheme, the speed of motor is calculated from the stator current. An error signal is generated by comparing the speed with the reference value. The error signal thus generated is then fed to a PI controller $P_2(s)$ which generates the reference torque T_e^r. The reference torque is converted to the reference Q axis current I_{qs}^r by machine equations [9]. The reference voltage V_{qs}^r is obtained from I_{qs}^r by current controller $P_4(s)$.The flux Controller $P_1(s)$ generates I_d^r which is compared with the reference flux and provided as input to current controller $P_3(s)$.that generates the voltage reference V_d^r. The input of flux controller $P_1(s)$ is error obtained between desired rotor flux and calculated flux. The reference voltages are converted back to three phase rotating reference V_{ABC}which is used as reference voltage for PWM generation.

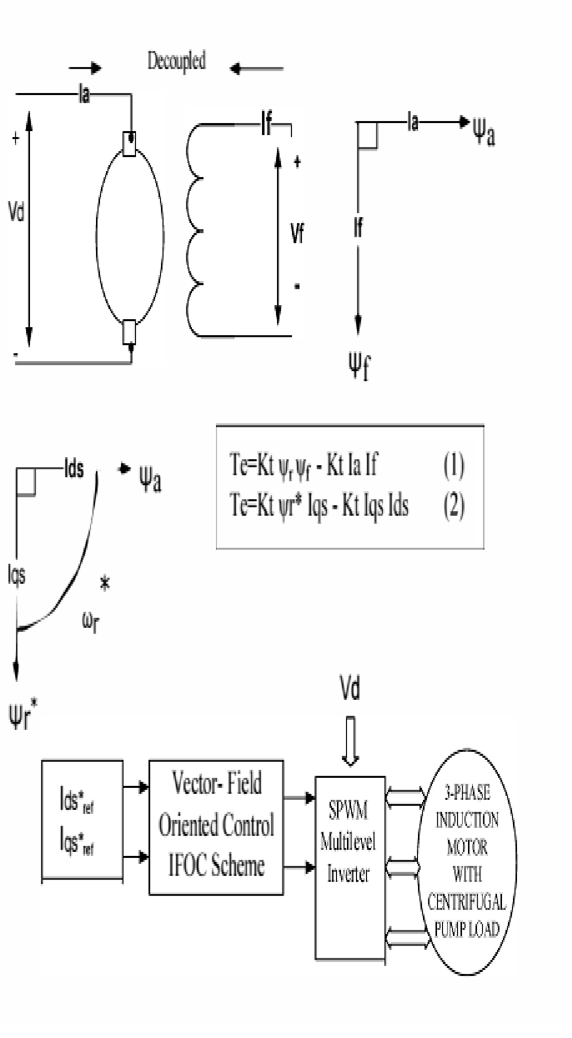


Fig 5 Significance of IFOC Scheme

Fig. 6 shows the block diagram of IFOC Scheme with Induction Motor coupled with pump load. A PI controller is used for converting the speed error into torque reference that is converted to corresponding q axis currents by the equation [3.10], [3.11].

$$i_{qs}^* = \frac{Lr}{pLm} \frac{T_{em}^*}{\lambda_r^*}$$
$$i_{ds}^* = \frac{1}{Lm} \left(T_r \frac{d\lambda_r^*}{dt} + \lambda_r^* \right) \tag{3.26}$$

The reference current is converted to reference voltage by the equation

$$\omega_s^* = \omega + \frac{L_m}{T_r} \frac{i_{qs}^*}{\lambda_r^*} \tag{3.27}$$

$$v_{ds}^* = R_s i_{ds}^* - \omega_s^* \sigma L_s i_{qs}^*$$
$$v_{qs}^* = R_s i_{qs}^* - \omega_s^* \sigma L_s i_{ds}^* \tag{3.28}$$

For flux control, the reference flux is generated using a field weakening block. In field weakening method, till the base speed is achieved the flux reference is kept constant and above base speed, the flux is weakened gradually. This was implemented using a lookup table. The flux reference is converted to the corresponding d-axis current by the above equations.

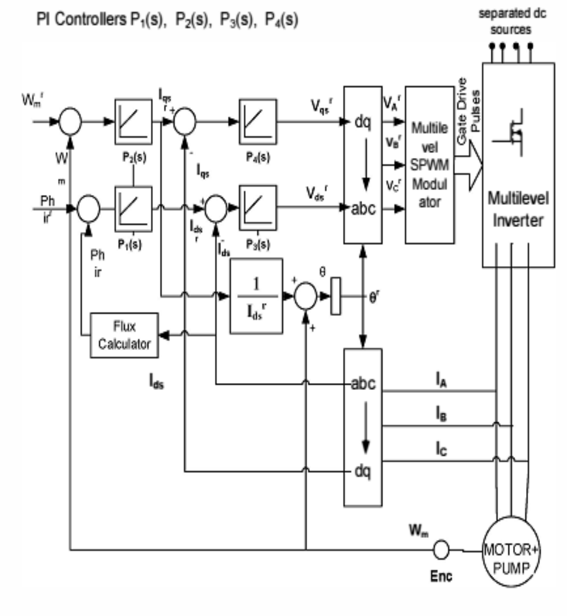


Fig 6 Block Diagram of IFOC Scheme with Induction Motor & Pump Load

V MATHEMATICAL MODEL OF CENTRIFUGAL PUMP

Centrifugal pumps are used on many industrial and commercial applications. Many of these pumps are operated at fixed speeds, but could provide energy savings through adjustable speed operation.

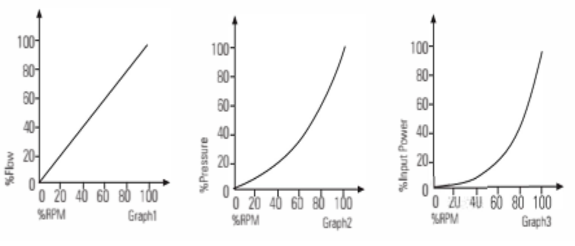


Fig 7 Affinity laws for centrifugal pump

Fig 7 graphically illustrates the physical laws of centrifugal pumping applications. The flow is directly proportional to speed; pressure is proportional to the square of the speed; and power is proportional to the cube of the speed. Theoretically, it would be possible to operate at 50% flow with only 13% of the power required at 100% flow. Since the power requirements decrease much faster than the reduction in flow, the potential exists for significant energy reduction at reduced flows. This will help in cost savings in the long run. The most important choice to be made in selecting pump drives is the decision to select a non-slip, solid-state, adjustable speed drive. Any such drive can offer dramatic energy savings by efficiently matching the energy consumed to the hydraulic load requirements at any given moment

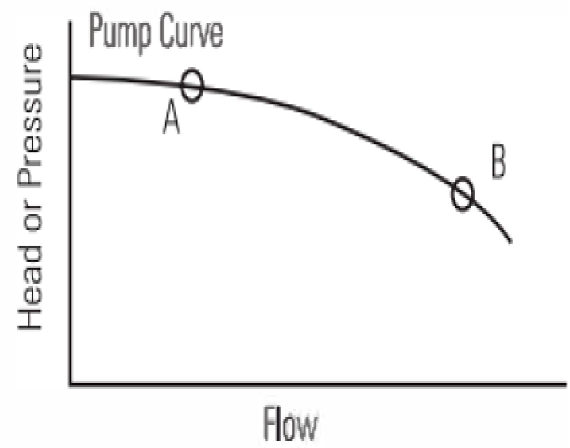


Fig 8 Pump curve describing the head v/s flow

The curve in Fig. 3.8 shows that the pump will produce limited flow if applied to a piping system in which a large pressure differential is required across the pump to lift the liquid and overcome resistance to flow(as at point A). Higher flow rates can be achieved as the required pressure differential is reduced (as at point B).

VI.MATLAB/SIMULATION RESULTS

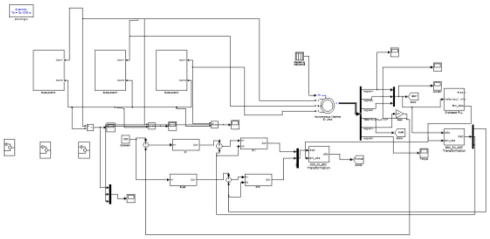


Fig 9 Matlab/simulation of IFOC Scheme with Induction Motor & Pump Load

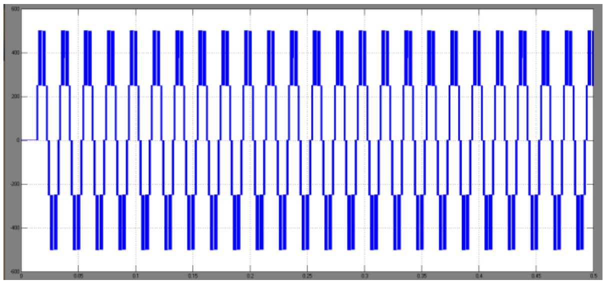


Fig 10 simulation wave form of output voltage five level inverter

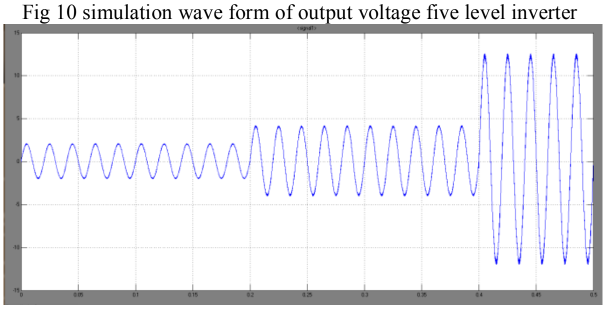


Fig 11 simulation wave form of stator current of Induction Motor

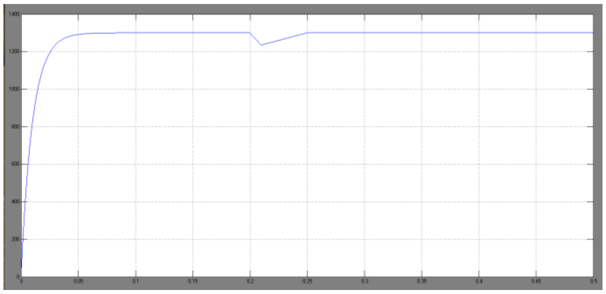


Fig 12 simulation wave form of speed of Induction Motor

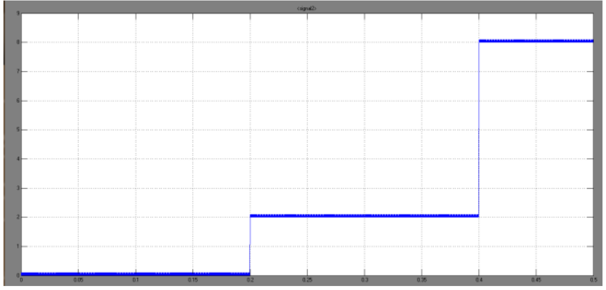


Fig 13 simulation wave form of torque of Induction Motor

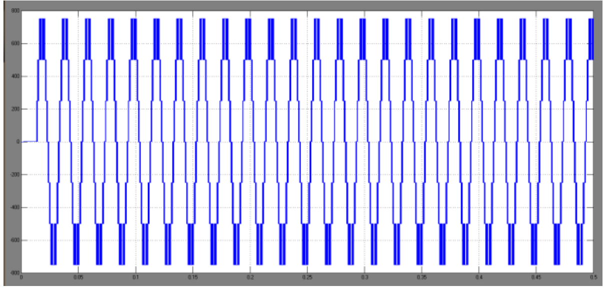


Fig 14 simulation wave form of output voltage seven level inverter.

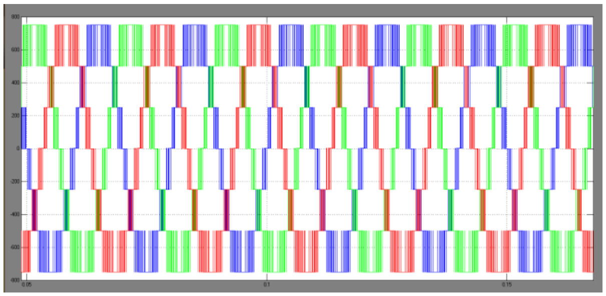


Fig 15 simulation wave form of output voltage three phase seven level inverter.

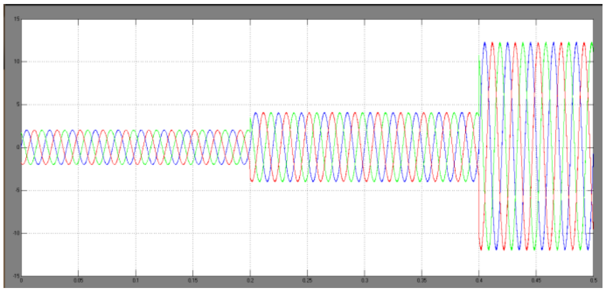


Fig 16 simulation wave form of output line current three phase seven level inverter.

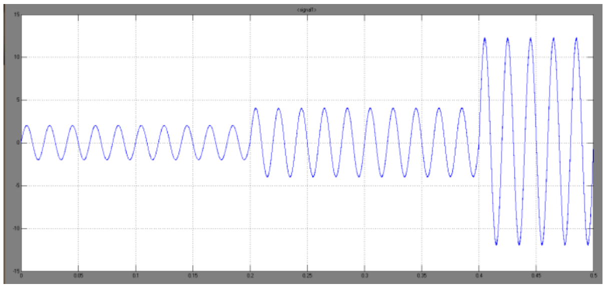


Fig 17 simulation wave form of stator current of Induction Motor of seven level inverter

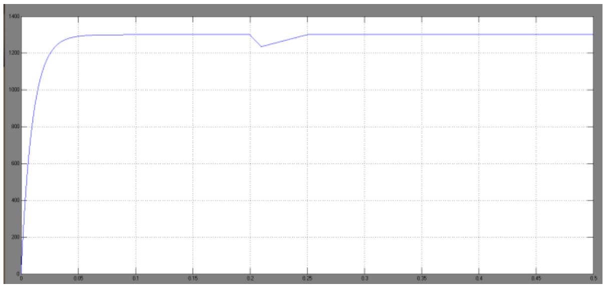


Fig 18 simulation wave form of speed of Induction Motor of seven level inverter

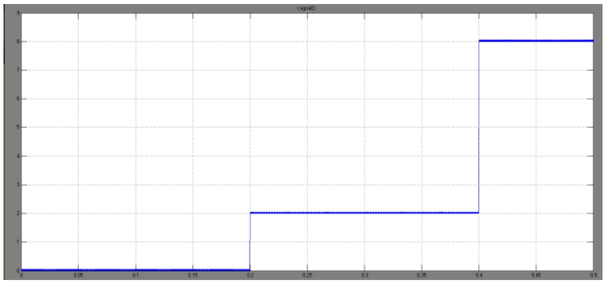


Fig 19 simulation wave form of torque of Induction Motor of seven level inverter

VII.CONCLUSION

We have analyzed the performance of Induction Motor drive with IFOC control scheme connected to pump load with level increment of inverter with Different parameters of centrifugal pump like discharge and input power is analyzed for different ratings of speed. We have found that by using variable speed drives, operations' requiring less discharge is possible with a proportional lower speed and this will lead to the much lesser power consumptions. We can compare the results obtained with that of the basic affinity laws of centrifugal pump and can see that graphs obtained are almost same. Thus by designing and implementing this variable speed drive for pumping applications overall efficiency of the drive can be improved reducing considerable cost spend for electricity.

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