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Comparative Analysis of VSI & 7 Level MLI Fed Induction Motor Drive with IFOC Scheme and Pump Load

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ABSTRACT

Induction Motor are named as workhouse of Industries. Three phase induction motors are widely used in Industrial drives because of their ruggedness, reliability and simplicity in construction. The Induction Motor is fed by a cascaded H-Bridge 7 Level MLI and is controlled by Indirect Field Oriented Control (IFOC) technique. In the current paper, Multi Carrier PWM techniques like PD, POD and APOD are used for switching of multilevel inverters due to their simplicity, flexibility and reduced computational requirements compared to Space Vector Modulation (SVPWM). Dynamic performance of the Induction Motor is analyzed for various carrier based PWM methods. Mathematical model of Pump Load is designed and the performance of the Induction Motor Drive with Pump Load is analyzed using simulation results obtained.

***Keywords* -** Centrifugal Pump, CHBMLI-Cascaded H-Bridge Multilevel Inverter, Induction Motor, IFOC-Indirect Field Oriented Control, Multicarrier PWM Technique.

I. INTRODUCTION

Induction motor has achieved popularity in motoring application due to its low cost, reliability, low maintenance, no brushes to wear out, very simple rotor assembly and no magnets to add to the cost. Squirrel cage induction machine when operated constant line voltage (50Hz) it operates at constant speed. However in industries we have variable speed applications of Induction motors. This can be achieved by Induction motor drives [1]. Main application of Induction Motor drives are Fans, blowers, Compressor, Pumps [2], 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. Centrifugal pumps are more economical to operate and require lesser maintenance than other types of pumps. In this Paper our objective is to analyze the MLI Fed Induction Motor drive with IFOC [3] for pump application. There are several control schemes devised for the control Induction motor both in open loop as well as closed loop vector control of Induction motor is widely accepted control scheme due to its better dynamic response. Vector control scheme is more popular due to its better dynamic performance. In IFOC [3] scheme speed and position are not directly measurable. Speed and position are estimated by measuring other parameters such as phase voltages and currents which are directly measured. 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. Multi level inverters can be used to replace the two level inverters. For a particular switching frequency, compared with a two level inverter, the harmonic content is less in case of MLI [4,5].Multi Level Inverter topologies have been widely used in the drives industry to run induction machines for high power configurations. Three major topologies are available for MLI namely: Cascaded H Bridge, Diode clamped, Flying Capacitor. The Cascaded H Bridge MLI is probably the only kind of multi level inverter wherein the inputs can be individual isolated energy sources (capacitors, batteries, PV arrays, etc) and is best suited for renewable energy systems.

A feedback closed loop Induction motor connected pump load is analyzed in this paper as pump load contributes to a major Industrial load. In case of pump load torque increases with the square of the change in rotational speed of the motor. The mechanical load on the motor will change with approximately the cube of the change in rotational speed. Many of the applications are controlled with throttles, mechanical dampers and bypasses. This paper also analyses a dynamic control scheme for pump connected load enabling a complete AC drive system.

II. CASCADED H BRIDGE MLI

The basic block diagram of a cascaded H bridge MLI [4, 5] for is shown in Fig 2.1. Here 4 switches are used 2 switches in first leg (S1, S4) & 2 in second leg (S2, S3) and NOT gate IC is connected to switches (S3,S4) as no two switches should conduct simultaneously in the same leg since it is voltage source so there will be a chance of short-circuit.

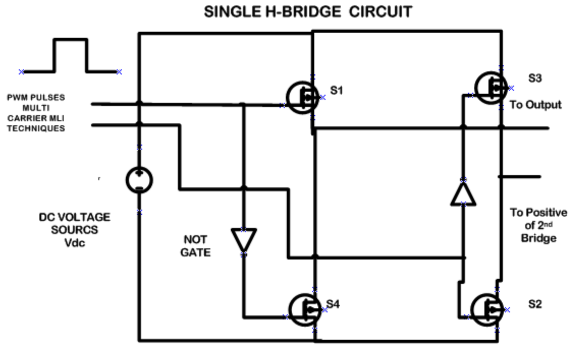


Fig 2.1: Single H-Bridge Circuit Diagram

A three phase 7 level inverter is used to control the induction motor driving a pump load. Fig shows the topology of the Multilevel Inverter [5] used .Three H Bridges are present in each phase of the Multilevel Inverter. Four switches supplied from a separate DC source contribute a single H bridge. Output voltage of each H bridge will be: Vdc, 0,-Vdc. H bridges are provided by gate pulses which are generated by Pulse Width Modulation techniques. There are several PWM techniques like Selective harmonic elimination, Space vector Pulse Width Modulation, Sine Pulse Width Modulation, etc. In the proposed drive scheme, Sine Pulse Width Modulation, technique is used. The multicarrier PWM technique [6, 7] for generating Sinusoidal Pulse Width Modulation is again subdivided into Phase Disposition techniques and Phase displacement techniques. 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 (APOD) technique is used. In this technique, all the carrier waveforms are in phase opposition with each other. In open loop sine wave generator provides the reference sine wave for PWM pulse where as in closed loop it is generated by the controller. In Fig 2.2 (APOD) Multicarrier PWM is shown with reference sine wave & multicarrier APOD [6, 7] pulses. The below fig is having 4 switching pulses to be given to 4 different switches.

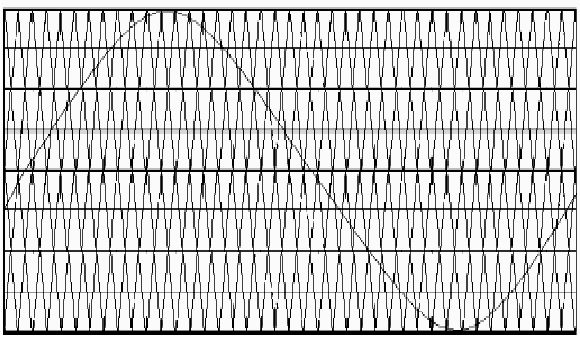


Fig 2.2: Alternate Phase Opposition Disposition (APOD) Multicarrier PWM

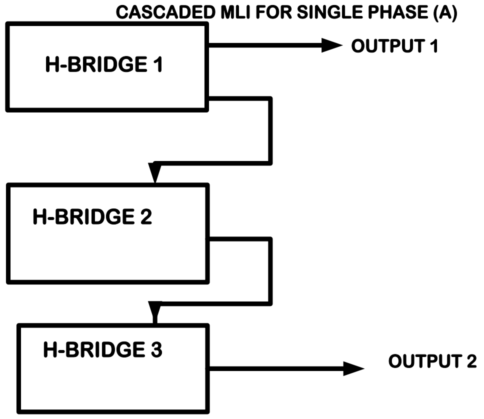


Fig 2.3: Basic Block Diagram of 3 H-Bridge Structures

The Basic Block Diagram of 3 H-Bridge Cascaded Structure is shown in Fig 2.3. From H-Bridge 1 & 3 output is taken from the MLI and H-Bridge 2 acts as intermediate bridge structure connected in series with H-Bridges 1 and 3. As there are 3 H-Bridges so MLI output voltage profile for single phase (A) is increased, similarly for the phases B and C. So 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. It is seen that 40-50% of losses is the switching losses so if switching stress is low then the efficiency of the system can be enhanced.

III. MLI INDUCTION MOTOR DRIVE WITH IFOC

NOMENCLATURE

Iα, Iβ, Id, Iq - Currents in α-β and d-q reference frame.
IA, IB, IC - Currents in ABC reference frame.
Vα, Vβ, Vd, Vq -Voltages in α-β and d-q reference frame.
Ks- Transformation matrix.
λd , λq -Flux in d-q reference frame.
ψa - Armature Flux.

ψf - Field Flux.
Ids- D axis stator current.
Iqs- Q axis stator current.
Idsr - Reference D axis current.
Iqsr - Reference Q axis current.
Vdsr- Stator Reference D axis voltage.
Vqsr- Stator Reference Q axis voltage.
θ- Position of rotor.
θr- Reference Position of rotor.

Because of inherent coupling effect in the machine the scalar control methods of VSI and CSI offer a very sluggish control response. A vector or field oriented control as explained in this figure offers a better dynamic response. In vector control method, an induction Motor is controlled like a separately excited dc motor. In case of a separately excited dc motor, the field flux ψf and armature flux ψa, established by the respective field current If and armature or torque component of current Ia, are independent and orthogonal in space such that when torque is controlled by Ia, the field flux is not affected which results in fast torque response. Similarly, in induction motor vector control [8], the synchronous reference frame currents Ids and Iqs are analogous to If and Ia, respectively as shown in Fig 3.1 which is the significance of IFOC Scheme. Therefore, when torque is controlled by Iqs, 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.

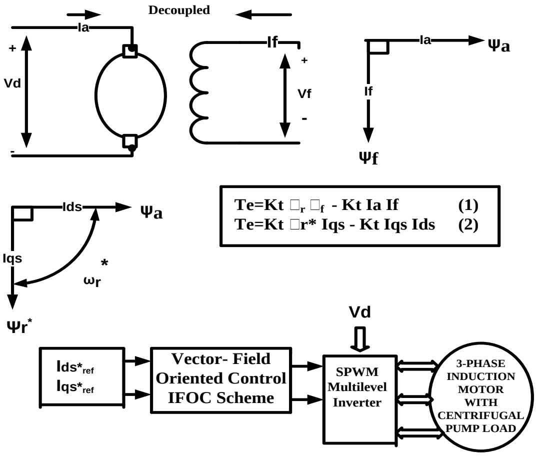


Fig 3.1: Significance of IFOC Scheme

In the Direct FOC 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 whereas in IFOC scheme which is implemented here, 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 toque is converted to the reference Q axis current I_{qs}^r by machine equations. 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.

In the Fig 3.2 it shows the block diagram of IFOC Scheme with Induction Motor coupled with Pump Load. As we have implemented 7 Level MLI i.e. n=7, so there will be (n-1) PWM pulses i.e. 6 Multicarrier PWM pulses should be given to the switches in each of the three phases.

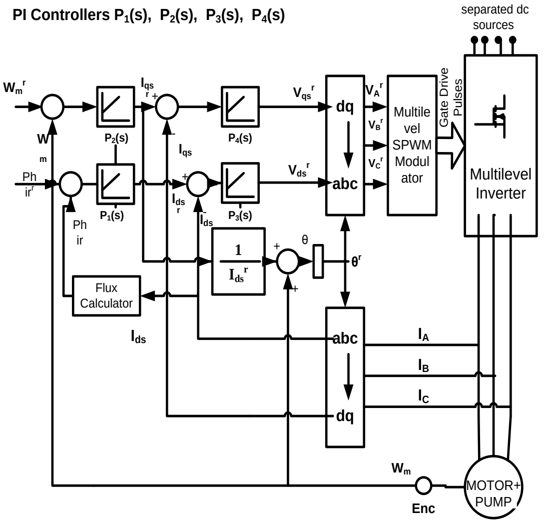


Fig 3.2: Block Diagram of IFOC (Indirect) Scheme with Induction Motor & Pump Load

IV. MATHEMATICAL MODEL OF CENTRIFUGAL PUMP

Centrifugal Pump [2] is designed in simulink as shown in the figure given below with the following Parameters and equations-

T (Torque) in N-m
ωn= Speed in rad/s
$g=9.81m^2/s$ (Specific Gravity)
Q= Water Flow Discharge Rate (in ltr/s)
$\rho= 1000\ Kg/m^3$ (Water Volumic Mass)
H=Manometric Head of Well (in m) = 10m, 20m, 30m (specified in simulation)
$P_H = \rho gQH$ (Hydraulic Power) eq.(4.1)
$T_L = g/\omega$ (in N-m) eq.(4.2)
$Q= (T\ \omega)/ (gH*1000)$ eq. (4.3)

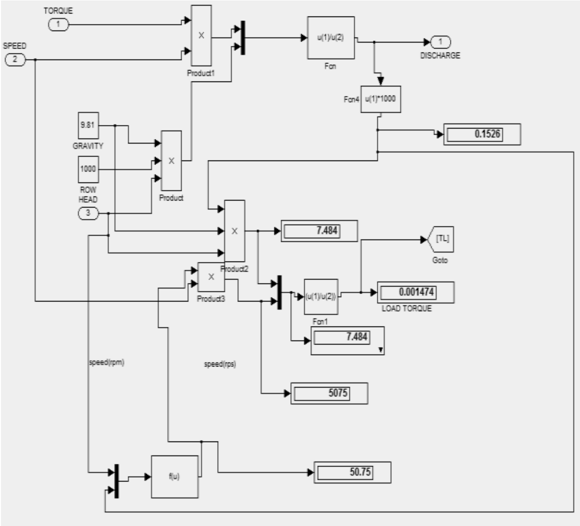


Fig 4.1: Matlab /Simulink Model of Centrifugal Pump

The Fig 4.1 shows the Matlab /Simulink Model of Centrifugal Pump where Torque and speed is multiplied by product block to give the numerator of discharge similarly specific gravity, density of water, total row head is multiplied by product block to give the denominator of discharge. In this way Discharge i.e. water flow rate through the pump is calculated.

V. RESULTS & DISCUSSION

The above mentioned setup is simulated with Phase Disposition (PD) as well as Alternate Phase Opposition Disposition (APOD) in closed loop with pump load and it is found that steady state error & torque ripples are less and discharge is more i.e. Closed Loop Performance Analysis with Multicarrier PWM. So we have implemented the APOD Multicarrier PWM technique for our proposed system. In Field-Oriented Control (FOC) technique the flux & torque components are decoupled by means of a decoupler & hence torque and flux are independent of each other. For different values of torque, stator and rotor flux remains constant & the rotor flux is maintained at 0.9 wb as shown in below simulated rotor flux waveform in fig 5.3. Our simulation setup is in full accordance with flux control.

CASE I: Variable Speed (80-100 rad/s) in 3s & constant load torque T_L=7 Nm, H=20m

TABLE I

COMPARISION OF PARAMETERS	VSI	7-Level MLI With APOD Multi-Carrier Technique
Discharge Water Flow Rate Q in (ltr / s)	3.488	4.782
Electromagnetic Torque Te (Nm)	6.843	9.382
THDv	0.8916	0.6388
Hydraulic Power of Pump PH(in W/hp)	684.3/0.917 hp	938.3/1.257 hp
Steady State Error in Speed ess in (%)	0.0023	0.0005
Torque Ripples (%)	4.4	3.8
Settling Time Ts in (s)	0.38	0.156

CASE II: Variable load torque (0-7 Nm) in 3s & constant speed 100 rad/s, H=20m

TABLE II

COMPARISION	VSI	7-Level MLI
Discharge Water Flow Rate Q in (ltr / s)	3.469	4.711
Electromagnetic Torque Te (Nm)	6.806	9.242
THDv	0.8815	0.6465
Hydraulic Power of Pump PH(in W)	680.6/0.912 hp	924.2/1.238 hp
Maximum Peak Overshoot Mp (%)	1.17	1.5
Steady State Error in Speed ess in (%)	0.0015	0.0002
Torque Ripples (%)	5.4	4.2
Settling Time Ts in (s)	0.4	0.144

Simulated Waveforms for 7-Level MLI-

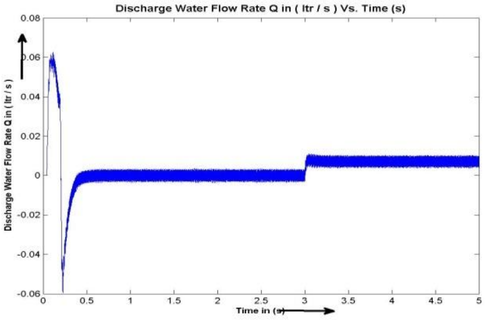


Fig 5.1: Discharge Rate Vs Time

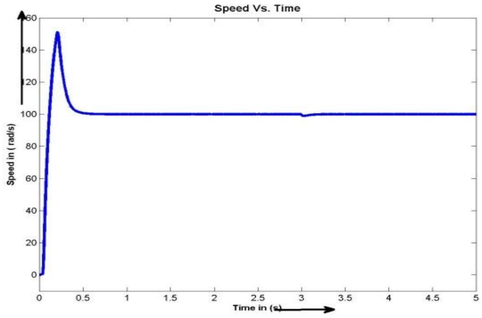


Fig 5.2: Speed Vs Time

For Variable load application load torque varies from (0-7 Nm) in 3s & at constant speed of 100 rad/s, H=20m it is seen that electromagnetic torque Te (Nm) developed & discharge is comparatively high , Torque Ripples are reduced & Settling Time Ts gets improved.

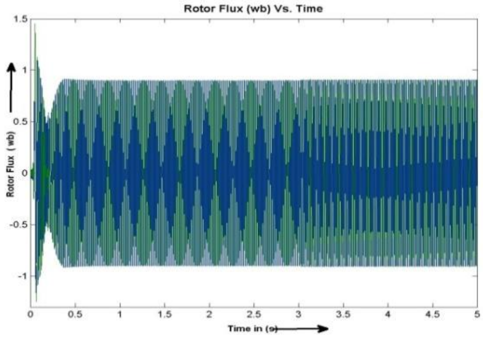


Fig 5.3: Rotor Flux Vs Time

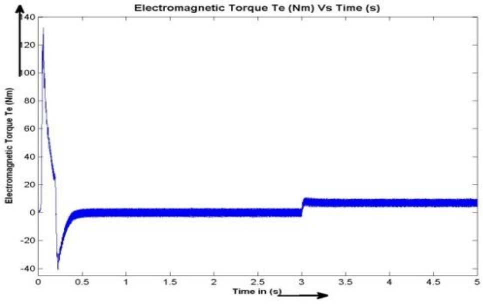
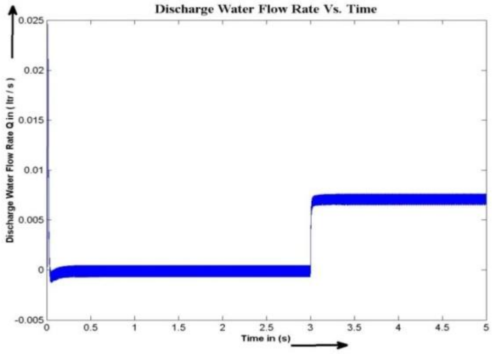
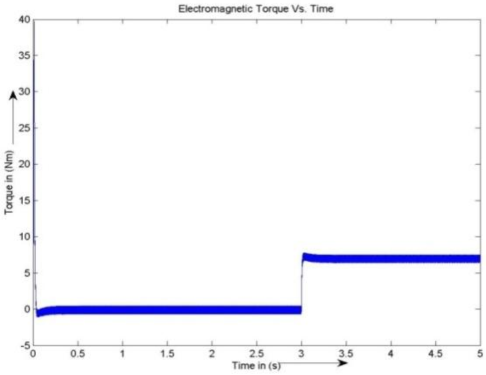


Fig 5.4: Electromagnetic Torque Te (Nm) Vs Time

Simulated Waveforms for VSI





 # Variable load torque (0-7 Nm) in 3s & constant speed 100 rad/s, H=10m

TABLE III

COMPARISION	**VSI**	**7-Level MLI**
Discharge Water Flow Rate Q in (ltr / s)	6.937	9.421
Electromagnetic Torque Te (Nm)	6.806	9.242
THDv	0.8815	0.6465
Hydraulic Power of Pump PH (in W)	680.51/0.9122 hp	924.2/1.238 hp
Maximum Peak Overshoot Mp (%)	1.17	1.5
Steady State Error in Speed ess in (%)	0.0015	0.0002
Torque Ripples (%)	5.4	4.2

TABLE IV

Speed wn =100 rad / s	**H=10m, Electromagnetic Torque Te (Nm)= 9.242**		**H=20m, Electromagnetic Torque Te (Nm)= 9.242**		**H=30m, Electromagnetic Torque Te (Nm)= 9.242**	
	Discharge Water Flow Rate Q in (ltr / s)	Hydraulic Power of Pump PH (in W)	Discharge Water Flow Rate Q in (ltr / s)	Hydraulic Power of Pump PH (in W)	Discharge Water Flow Rate Q in (ltr / s)	Hydraulic Power of Pump PH (in W)
0.75 wn	7.065	693.07	3.532	692.9	2.355	693.07
0.85 wn	8.007	785.4	4.003	785.3	2.669	785.4
wn	9.421	924.2	4.711	924.34	3.145	925.5
1.1 wn	10.363	1016.61	5.181	1016.52	3.454	1016.7

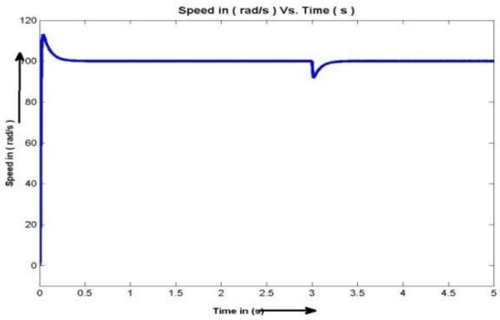


Fig 5.5: Rotor Speed Vs Time

Analyzing Table IV confirmed that as head increases from 10m to 30m discharge gets reduced from 9.421 ltr/s to 3.145 ltrs/s at full rated speed. Also on the other hand for constant head operation (H=10m) as speed increase from 75% of rated value to more than rated 110% discharge increases from 7.065 ltr/s to 10.363 ltr/s

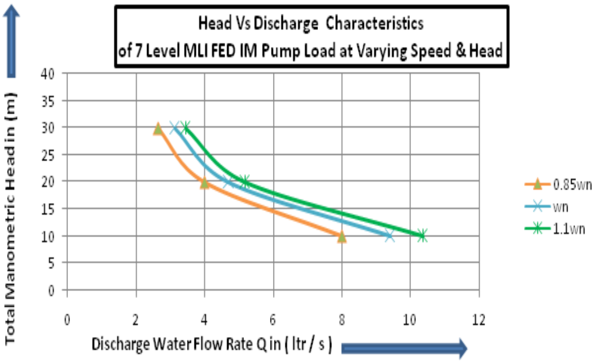


Fig 5.6: Head (H) Vs Discharge (Q) Characteristics at varying rotor speed & head.

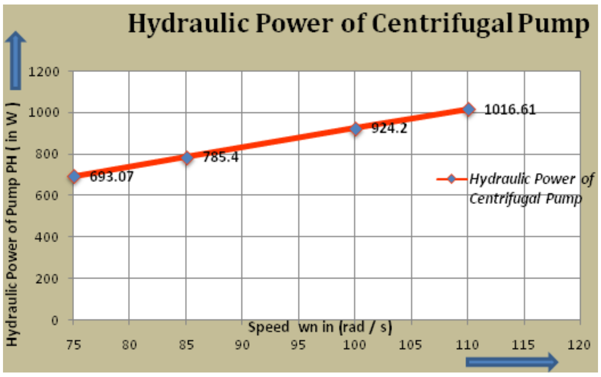


Fig 5.7: Hydraulic Power of Pump PH (in W) Vs Speed wn in (rad/s)

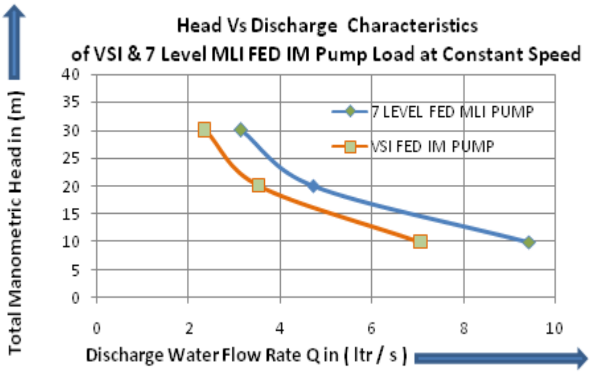


Fig 5.8: Head (H) Vs Discharge (Q) Characteristics at constant rotor speed .

The above fig 5.8. shows the nature of curve for total manometric head Vs discharge obtained by VSI & 7 Level MLI Fed drive at constant rotor speed.

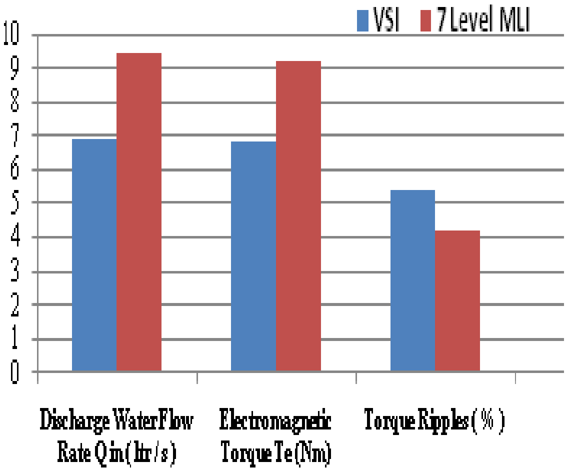


Fig 5.9: Chart comparing between VSI & 7 Level MLI for various parameters Q, Te, % Ripples.

VI. CONCLUSION

In this paper we analyzed the performance of Induction Motor [1] drive connected with pump load [2] and found that for the same head (say 20m) & Electromagnetic Torque Te as the rotor speed varies from 75% of rated to 110%, discharge Water Flow Rate Q in (ltr / s) quantitavely increases from 3.532 ltr/s to 5.181 ltr/s.

Also for 7 Level MLI fed drive THD in voltage is considerably less compared to VSI fed as ripples in electromagnetic torque effectively reduced, level of voltage magnitude is increased making output nearly sinusoidal thereby decreasing electrical stress across the switching devices as a whole the voltage profile of complete drive gets improved & efficiency of the closed loop feedback system is increased.

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APPENDIX
Squirrel Cage Induction Motor Parameters
3-Ø, 415v

Stator Resistance	Rs=6.03 Ω
Rotor Resistance	R_r=6.085 Ω
Magnetizing Inductance	Lm=0.4893 H
Base Frequency f	50 Hz
Number Of Poles	P=6
Synchronous Speed Ns	1000 rpm
Moment Of Inertia	J=0.011787
Magnetic flux Density	B=0.0027 Wb/m^2
Rotor & Stator Inductance	Lr=0.5192 H Ls=0.5192 H