Comparative Analysis of 2-Level and Multi-Level Inverter Fed Coupled IM Drives Based on V/f and DTC Techniques

Shrikant Misal[1]*, Swetha T[1], Mamta Wandalkar[2], Chang Yan Tai[3]

[1]Department of Electrical Engineering, M.S. Ramaiah University of Applied Sciences, Bangalore, India
[2]Department of Electrical Engineering, CMR Institute of Technology, Bangalore, India
[3]Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
*Corresponding Author: shrik88@gmail.com

Abstract—For industrial sectors involving coupled induction motor drives, control of speed/torque is an utmost critical issue especially in dynamic conditions. Considering this aspect, there is a dire need of a flexible and efficient control which could best fit in the scheme of coupled drive operation. In this paper an effort has been made to explore different facets of speed/toque control for coupled induction motors based on traditional scalar (Volt/Hz) and advanced vector (Direct Torque) techniques. Also in order to facilitate improvements in terms of harmonic contents and power losses, it has been proposed to replace traditional 2-Level Inverter in Induction Motor drive with an advanced Reversing Voltage Multi Level Inverter (MLI) topology providing 5-Levels of output phase voltage. Based on the simulation study for both the control strategies in MATLAB/Simulink, it has been shown that harmonic distortions present in the fundamental output voltage of a coupled drive fed by Multilevel Inverters are comparatively less when compared to its 2-Level counterpart. These reduced distortions are in-turn responsible for toning down filtering requirements at the input of motor, thereby enhancing the efficiency of drive system.

Keywords-Direct Torque Control, Multi-Level Inverter, Induction Motor, V/f control

I. INTRODUCTION

In recent years, the power demand from industrial sector has shot up drastically and it is estimated to double up in near future considering the pace at which it is progressing. At present almost 60% of the load demands are in process industries where heavy works are carried out using Induction Motor (IM) drives. To put a tab on this high power consumption, control of motors using an efficient and flexible technique with varying load pattern plays a critical role. Although it may be convenient to say that the speed or torque control can be achieved by mere variation of stator voltage and frequency of supply but in actual sense it is highly impossible to do so without sacrificing the drive efficiency. In simple terms an increase in loading proportionally decreases the efficiency of operation. Hence to account for this aspect, advanced scalar and vector control techniques [1-4][8] are coming up of late to make the process of individual or simultaneous speed/torque control quite amicable.

For load sharing applications like cranes, hoists etc. where there is a presence of coupled motor drives, the only ambiguity of control is with synchronization of different part movements. Thus in present industrial scenarios, to facilitate a precise variation in speed and torque individually, the control techniques are preferred to be independent. This type of control scheme is coherently termed as Scalar or V/f control which basically deals with steady state condition wherein only magnitude and frequency of voltage or current are controlled neglecting coupling effect in the machine. Some typical advantages of this control scheme are simple, conventional and cost effective speed control for load sharing applications. The accuracy that can be achieved using V/f Control [1] for both speed and torque control is around ±3%. But owing to constrain of individual speed/toque control circuits for coupled motors, there are healthy chances of the drive getting slowed down. This is highly undesirable from the dynamic operation point of view. On similar lines another control scheme which has garnered considerable attention in recent times is the advanced vector control technique also called as Direct Torque Control (DTC). This scheme [2] mainly deals with dynamic state of IM motor drive wherein instantaneous positions of voltage, current and flux linkage space vector can be controlled amicably by hexagonal (normally) unit space displacement. The potential advantages which work in favor of DTC [4,5] are its higher accuracy, precision, response time of around 5ms which is 10 times faster than the scalar control. These factors are certainly responsible for blessing this scheme with staggering reliability and flexibility of speed/torque control which is the foremost need of a coupled drive. The only compromise which is required here is with the complexity of control.

An extensive research has already been made in [2,3] regarding the scalar and vector control strategies with individual drive operations. Several critical issues involving stability, efficiency and reliability pertaining to open loop and closed loop operation of IM drive have been effective discussed with their probable solution. Also the Voltage Source Inverter (VSI) topology implemented for the coupled drive operation is basically a 2-Level Inverter having voltage levels $V_{dc}/3$ and $2V_{dc}/3$. Even though 2-Level VSI seems to be satisfactory for coupled drives, there will obviously a considerable presence of Total Harmonic Distortions in the phase voltage waveform responsible for dampening the system stability. Thus several MLI configurations like diode clamped, capacitor clamped, cascaded bridge, reversing voltage, hybrid etc. discussed in [6,8] have been successfully tested for single motor drive operation with Field Oriented Control (FOC). The above discussion clearly hints that there is a potential room for research in this field to explore the application of scalar and vector controls in coupled drive system which is hardly discussed in any of the referred literatures.

1. Objectives of the paper

The main scope of this paper is to propose the application of V/f and DTC techniques in coupled motor drives to achieve simultaneous torque control with a single controller and carry out their comparative analysis based on their respective performance with 2-Level and Multi-Level VSI drives.

2. Organization of the paper

V/f and DTC configurations for coupled motors are introduced in II, selection and design of induction motor parameters in III, simulation circuits and control strategies in IV, simulation results and analysis in V followed by concluding remarks in VI.

II. Configurations Of Volt/Hz And Direct Torque Controllers For Coupled IM Drives

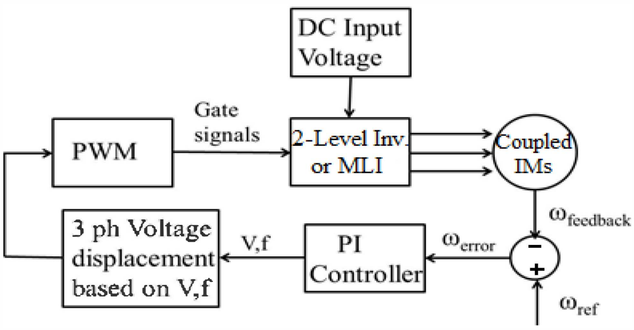


Fig. 1: Block Diagram of V/f Control

Fig.1 shows the block diagram of a coupled induction motor drive with V/f control. Here the VSI can be a 2-Level or Multi-Level depending upon the output requirements. The speed from IM is sensed and fed back to the comparator circuit wherein the reference and feedback speeds are compared and an error signal is generated. The error signal is passed through a PI controller which is responsible for fine tuning it by mitigation of overshoots. This speed voltage error is converted into 3 phase voltage signals which are 120° phase shifted with respect to each other. Based on these 3 phase voltage signals, the PWM generator gives out requisite gate pulses in order to initiate the triggering action for inverter switches. For load sharing in multiple motors, speed reference of two motors is desired to be kept same since both are driven by a common drive technology and the torque needs to be equally divided among both motors based on their ratings. This is the reason for requirement of both speed and torque control in coupled drives.

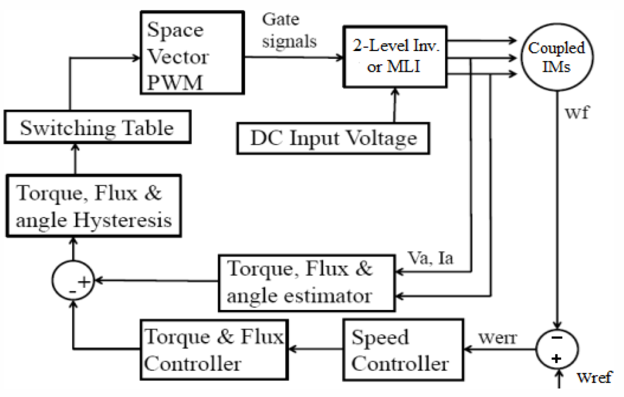


Fig. 2: Block Diagram of DTC Model

Block diagram in Fig.2 highlights the basic schematic representation of DTC. Similar to Fig.(1), VSI drive can have 2-Level or Multi-Level output. The electromagnetic torque and stator flux are calculated from primary motor inputs like stator voltage and current. The control initiates with direct selection of stator voltage vectors according to torque and flux errors. These errors are nothing but the difference between references of torque and stator flux linkage with their actual values. The optimum vector selection for inverter switching is made with an intention to restrict the torque and flux errors within pre-specified hysteresis bands. The speed controller block is nothing but a comparator circuit where the reference speed and sensed drive speed are compared to give an error signal. The error signal is processed with the help of a PI controller. From the speed output the torque and flux is estimated using the torque and flux controller.

III. Selection And Design Of Motor Parameters

1. IM Drive Selection

Consider that for the movement of heavy goods or equipments, a coupled drive has been implemented in a crane application [9]. Here the selection of coupled drive is governed by its load sharing capability to perform simultaneous different operations at a constant torque. Thus motor parameters can have a significant impact on the design of variable frequency and torque controller. In context of the given situation it is desired to meet front end high power requirements with simultaneous control of speed and torque. Taking this aspect into mind, IMs rated for 20 HP and 50HP have been selected for coupling. Detailed technical specifications of the chosen motors are as shown in Table I which will be further used in calculation of performance parameters.

2. Design of Performance Parameters for IM Drive

From specifications provided in Table I, design steps have been carried out in this section for obtaining performance parameters to be fed in simulation models. The design process in [7,10] involves calculation of losses (stator, rotor, auxiliary), calculation of motor resistances and reactances (stator, rotor, magnetizing). Table II highlights the designed parameters for 20HP and 50HP IMs respectively based on the design equations.

Table 1: Specifications of Induction Motors Used for Coupling

Power Rating	20 HP (15kW)	50HP (37kW)
Voltage (V)	415	415
Frequency (Hz)	50	50
Current (A)	27.5	63
Speed (rpm)	1470	1480
Power Factor	0.84	0.87
Efficiency @ F.L (%)	91%	94%
No. of Poles	4	4

Table 2: Designed Parameters for Induction Machine Used in Coupled Drive

IM Power Rating	20 HP = 15 kW	50 HP = 37 kW
Stator Input	16.603 kW	39.396 kW
Total Power Loss	1.494 kW	2.36376 kW
Slip	0.02	0.013
Rotor Copper Loss	306.12 W	487.3 W
Stray Loss	332.06 W	787.92 W
Friction and Windage Loss	74.7 W	118.15W
Max mum Torque	97.491 Nm	238.6 Nm
Rotor Input	15306 W	37484.615 W
Rotor Output	14925.18 W	36878.55 W
Rotor Current	24.715 A	60.36 A
Rotor Resistance	0.16725 Ω	0.0445 Ω
Stator Copper Loss	781.12 W	970.33 W
Stator Resistance	0.34429 Ω	0.08149 Ω
Stator & Rotor Reactance	0.4569 Ω	0.2383 Ω
Mutual Inductance	0.03088 H	0.0126 H

IV. SIMULATION CIRCUITS AND CONTROL STRATEGIES

1. Simulation circuit for proposed V/f control with 2-Level and Multi-Level VSI fed coupled drive system

A scheme of coupled motors implementing 3-Phase, 2-Level (basic) and 5-Level reversing voltage inverter topologies for V/f control is as shown in Fig.3.

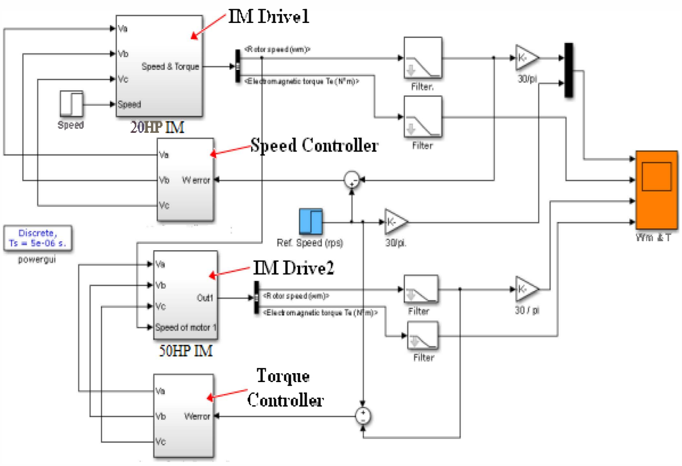


Fig. 3: Simulink Model for V/f Control of Coupled Motors

The chosen IMs are of 20HP and 50HP with a rated speed of 1470rpm. Control of speed and torque has been achieved with an individual speed and torque control scheme. Motors are coupled in such a fashion that output speed/torque of one form the driving source of other. Here switching action for VSI is initiated using a reliable Sinusoidal PWM technique.

2. Controller and drive circuits for proposed V/f coupled drive system

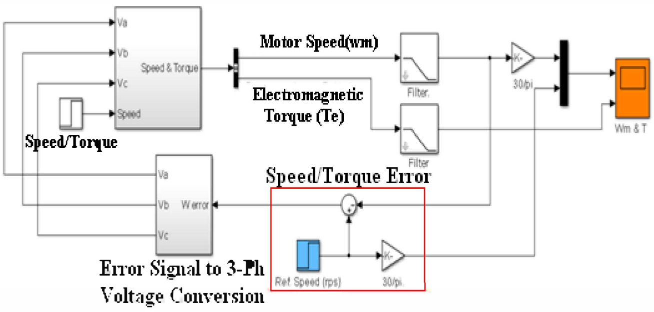


Fig. 4: Simulink Model for V/f Control of Coupled Motors

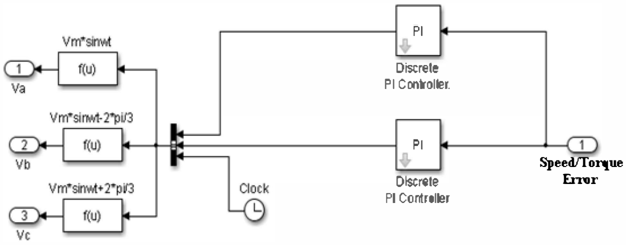


Fig. 5: Error Signal to Voltage Conversion Block

The basic schematic of control circuit typically used for speed torque variations in coupled drives is as shown in Fig.4.

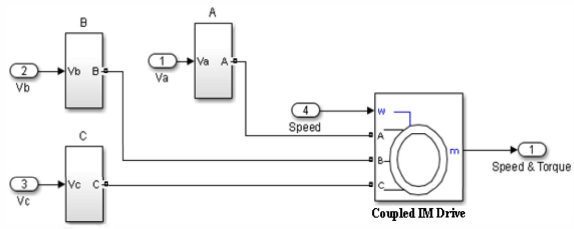


Fig. 6: VSI Fed Coupled Drive

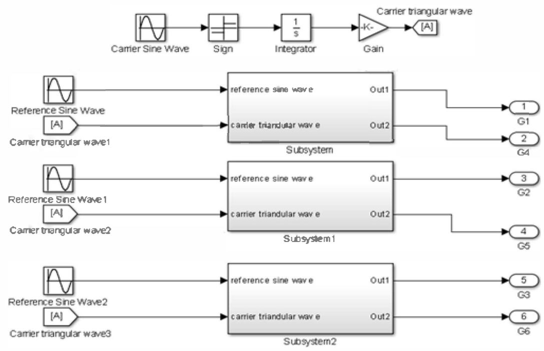


Fig. 7: Switching Scheme for 3-Ph. Reversing Voltage MLI

Based on the output speed/torque requirements, the reference signal is made to vary in steps for generating a desired error signal. As seen from Fig.5, for a chosen time instant this signal is processed through different PI controllers to dampen the overshoot that percolates into the system because of instantaneous voltage and frequency variations. Lastly the output from PI controller is passed through a voltage conversion block wherein based on the specified time instance and processed speed error, a near to perfect sinusoidal magnitude will be generated. This sine wave as evident from Fig.7 is fed as a reference signal to the control circuit of VSI for comparison with a repeating ramp signal to give out a train of PWM pulses.

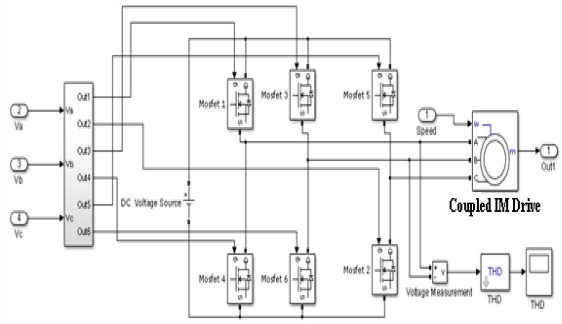


Fig. 8: Two-Level VSI with PWM Scheme for Coupled Drives

These pulses depending upon the topology of VSI have certain variations in switching patterns as seen from Figures 8 and 9. Here the choice of a particular reversing voltage topology for MLI is governed by the fact that it creates a multilevel stepped voltage half-wave with only positive values by using a simple inverter configuration having less number of DC sources. This factor particularly contributes towards improvement of system response.

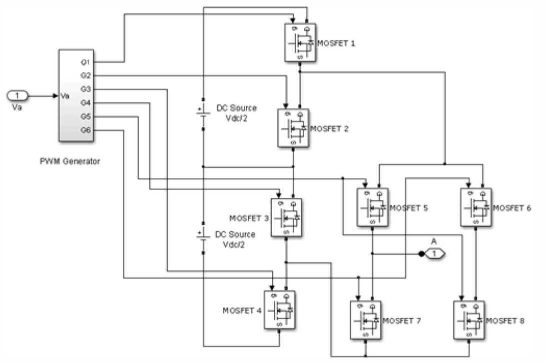


Fig. 9: Five-Level Reversing Voltage Inverter with PWM Scheme for Coupled Drives

3. Simulation circuit for proposed DTC control with 2-Level and Multi-Level VSI fed coupled drive system

A DTC basically involves connection of different subsystems working in tandem to make it capable of providing a faster and precise torque control. The sub-systems involved are speed/torque controller, torque and flux estimator, torque and flux hysteresis controller, vector switching table, switching control and sector selection.

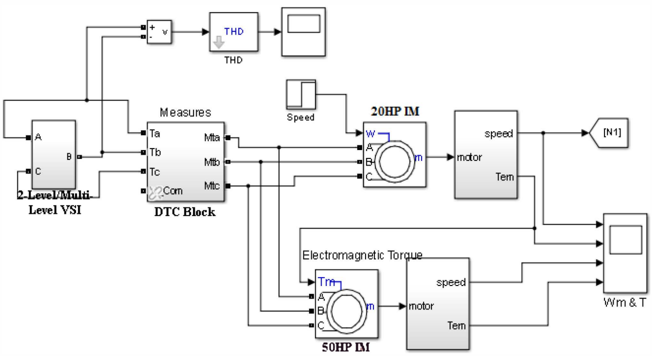


Fig. 10: Simulink Model for DTC of Coupled Motors

These components have been extensively discussed in this section for analyzing the DTC control. Fig.10 represents a generalized scheme of DTC for implementation in coupled motor drives.

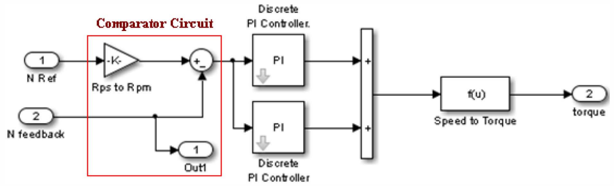


Fig. 11: Speed and Torque Controller Block

As seen from Fig.11 the functioning of speed/torque controller block resembles pretty close to that for V/f technique. Only difference observed will be the speed error signal is converted to equivalent torque value using the formula $T_{max} = \frac{974 \times kW}{N(rpm)}$. Thus the maximum torque at which the motor must be operating should be computed from speed feedback signal.

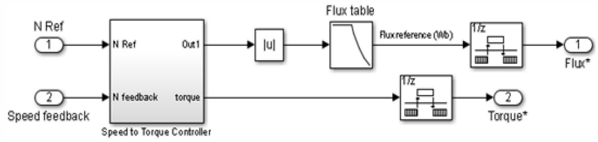


Fig. 12: Torque and Flux Controller Block

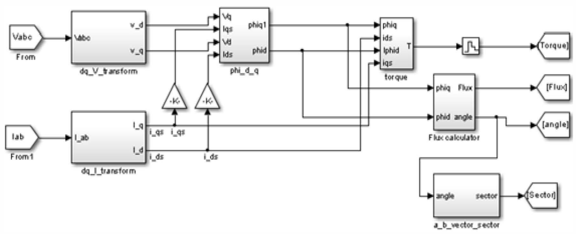


Fig. 13: Torque and Flux Estimator Block

By computation of speed feedback signal obtained from flux table, the requisite flux at which coupled motors will work can be efficiently determined with the help of scheme highlighted in Fig.12. The control of flux and torque require a certain level of feasibility and that is only possible with their pre-estimation to accomplish successive 3-phase to 2-phase transformation as shown in Fig.13.

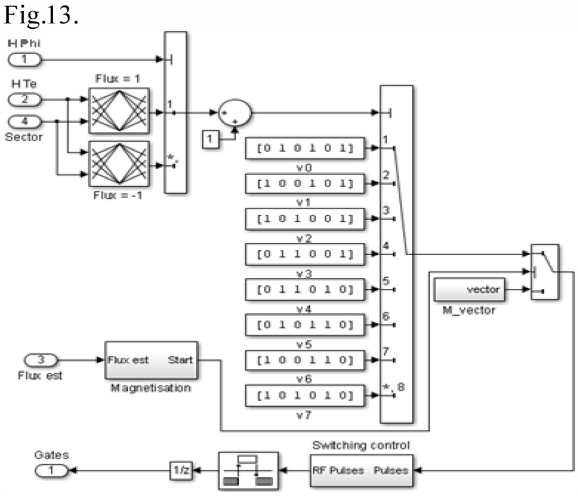


Fig. 14: Switching Control Block

The voltage and current values measured from inverter output serve as an input to Torque and Flux estimator block. These values which are sensed in 'abc' reference frame require transformation to 'dq' frame using abc to dq transformation. This step is initiated in order to express the obtained torque and flux with a two dimensional orientation as unit vectors which can possibly be controlled by initializing active switching states for VSI shown in Fig.14. The output sector is selected based on the flux angle as it forms an input to switching control block responsible for generating gate pulses.

The output sector is selected based on the flux angle as it forms an input to switching control block responsible for generating gate pulses. This block compares flux and torque, based on which switching action for VSI to compensate the torque value is initiated. Also here the precision of the torque and flux waveforms is maintained by using a flexible hysteresis controller which can vary the operating window as per requirements. The choice and switching scheme of 2-Level and Multi-Level inverters will remain the same as in V/f technique of Fig.6.

V. Simulation Results And Analysis

4. For proposed V/f control with 2-Level and Multi-Level VSI fed coupled drive system

From Fig.15 implementing a 5-Level reversing voltage inverter drive it is observed that both motors gradually start their run at an initial speed of 1380rpm until the build-up of required air-gap flux upto 1.5sec. Once the desired flux builds up of flux, there comes the need to maintain the frequency in order to avoid saturation effect. Hence by variation of supply voltage the desired stability is pitched in to attain a constant speed of 1450rpm from 1.5sec onwards. The torque at which first motor is operating is 88N-m which is slightly at a lower scale compared to the rated torque. On similar lines with speed variation, induction of V/f control enhances the torque of 20HP motor to about 92N-m which is nothing but the rated value.

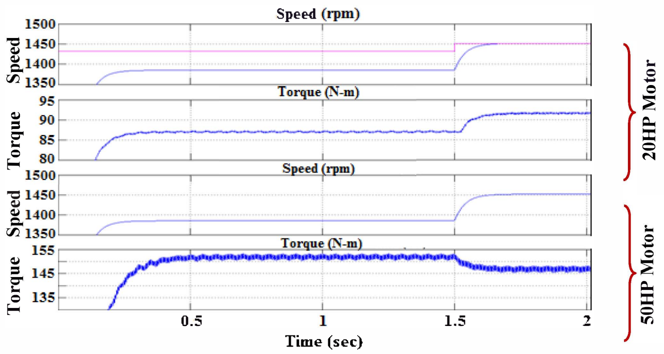


Fig. 15: Output Speed and Torque Waveforms from Two Coupled Motors using Reversing Voltage MLI

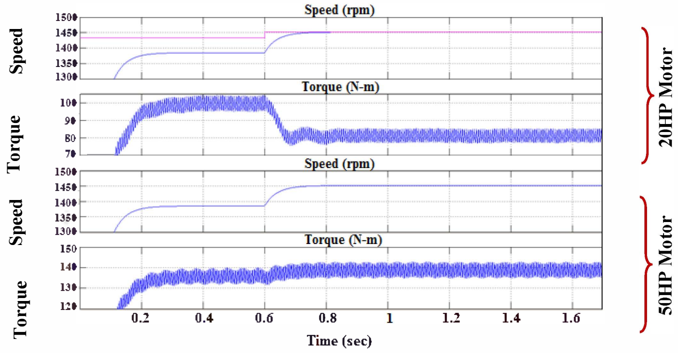


Fig. 16: Output Speed and Torque Waveforms from Two Coupled Motors using 2-Level Inverter

In this process the torque associated with coupled 50HP motor shoots up to almost 1.5 times the one obtained from first motor i.e. approximately 145N-m considering the mechanical coupling which gives the effect of a single shaft. Here the discussed operation for V/f control with MLI holds good even for a 2-Level VSI except for the few degradation in performance parameters. As seen from Fig.16 similar to previous operation, both motors are running at a speed of 1370rpm initially upto 0.6sec for initial flux build-up and thereafter from 0.6sec onwards V/f control takes over the mantle to deliver a constant speed of 1450 rpm. Similarly torque achieved for first motor is 98N-m at critical speed of 1370rpm which is slightly on a higher note than the rated one. After 0.6sec the torque of motor decreases and attains a rated value of about 83N-m. Because of single shaft sharing the net torque at which second motor should operate is around 140N-m.

Since the motor is been fed with VSI drive having either 2-Level or Multi-Level (5-Level) operation, analyzing its performance based on the magnitude of fundamental and harmonic distortions is utmost critical aspect. These parameters in-turn are responsible for determining the drive losses and hence the system efficiency. Figures 17 and 18 show the output phase voltage waveform for 3-Ph, 2-Level and 5-Level VSIs. For both the cases magnitude of voltage is maintained at 375V except for the number of steps involved. With more discretization of voltage the THD content can be potentially toned down.

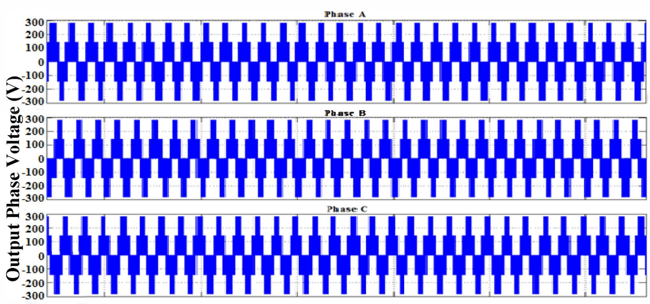


Fig. 17: 3-Ph. Output Voltage Waveforms for 2-Level Inverter

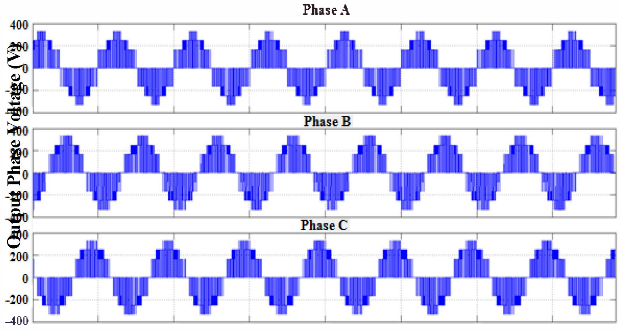
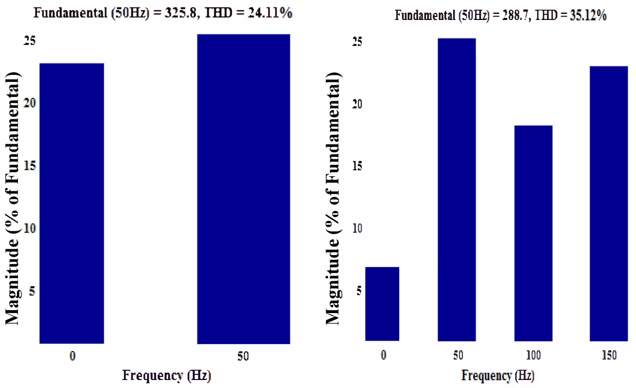


Fig. 18: 3-Ph. Output Voltage Waveforms for 5-Level Inverter



(a) (b)

Fig. 19: THD in Output Voltage for (a) Multi Level Inverter and (b) 2-Level Inverter Topologies

Fig.19 shows the percentage of THD magnitude present in the phase voltage in context of the fundamental frequency of operation. For MLI, the THD magnitude is 24.11% of the fundamental voltage as against 35.12% for 2-Level inverter which is pretty high. Another important parameter which plays a significant role in determining the overall system efficiency is determination of losses associated with switching components of VSI. Considering that the switching element used here is MOSFET, the power losses can be categorized into switching and conduction losses. Since the switching frequency used here is nothing but the supply frequency component of 50Hz, switching losses can be neglected to directly obtain conduction losses. The conduction losses for the MOSFET is calculated using the formula $P_{CM} = R_{DSON}*(I_{rms})^2$, where R_{DSon} is drain to source on state resistance and I_{rms} is RMS value of MOSFET on state current. Since ON state resistance for MOSFET is readily available in the component datasheet, it becomes convenient to obtain the conduction losses from measured RMS value of drain current. So the magnitude of conduction losses considering 6 switches (for 2-Level) and 24 switches (for 5-Level) comes out to be 312W and 1248W respectively during active state of operation. Thus knowing the drive conduction losses and motor operational losses, the overall power output of complete drive system has been amicably computed. The nature of this output power as seen from Figures 20 and 21 is a constant value of 13280W and 13090W for respective 2-Level and Multi-Level inverter fed drives only because motor torque is maintained constant.

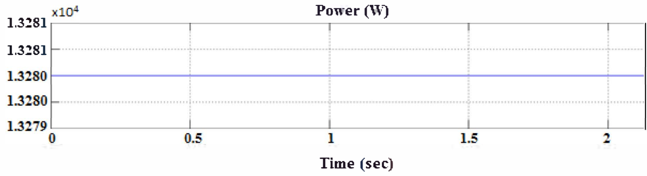


Fig. 20: Output Power of Induction Motor using V/f Control for 5-Level Reversing Voltage Inverter Topology

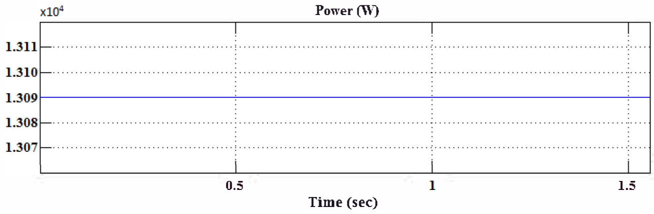


Fig. 21: Output Power of Induction Motor using V/f Control for 2-Level Inverter Topology

The data obtained from above analysis has been effectively summarized in Table III such that a comparison has been made for V/f operation based on 2-Level and 5-Level Inverter drive.

Table 3: Obtained Output Parameters for Different Inverter Topologies of V/f Control

Parameters	MLI	2 Level Inverter
THD	24.11%	35.12%
Fundamental Voltage	345 V	288 V
Conduction Losses	1248 W	312 W
Power Output	13280 W	13090 W
Efficiency	89%	87%

5. For proposed DTC control with 2-Level and Multi-Level VSI fed coupled drive system

As discussed in V/f control, DTC also deals with the control of IM torque by varying frequency of operation, ultimately to have a tab on the speed of motor. This is achieved by requisite estimation of motor's magnetic flux and torque in terms of measured voltage and current quantities as discussed in Section IV.

As seen from Figures 22 and 23, the behavior of torque speed curve for DTC remains the same as with V/f control technique but a prominent difference which separates them is the speed of operation. The transient period is comparatively reduced in this control scheme from 1.5sec to 0.5sec for MLI operation and from 0.6sec to 0.5sec for 2-Level Inverter operation.

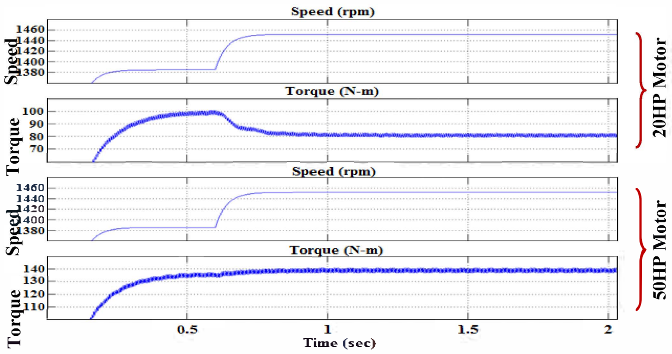


Fig. 22: Output Speed and Torque Waveforms from Two Coupled Motors using Reversing Voltage MLI

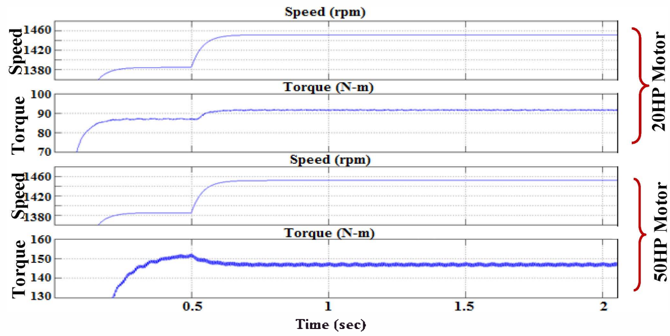
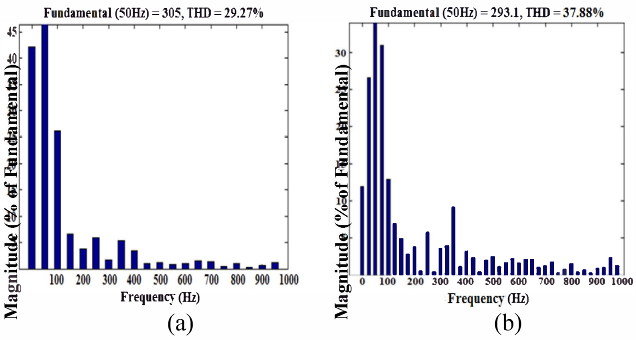


Fig. 23: Output Speed and Torque Waveforms from Two Coupled Motors using 2-Level Inverter

The nature of phase voltage will be unchanged for the chosen inverter topologies except for the magnitude 305V and 293V respectively. For the change in fundamental output voltage, the THD content is bound to change with 29.27% and 37.88% magnitudes as shown in Fig.24. It must also be noted that for the increased feasibility of output power capability upto 13860W, the drive has to compensate with increased filtering requirements since hysteretic current controller may induce some flux errors. Even then the superiority of this control scheme is justified by the fact that overall system efficiency gets a considerable boost with same losses as with V/f control. Table IV summarizes the obtained parameters.



(a) (b)

Fig. 24: THD in Output Voltage for (a) Multi Level Inverter and (b) 2-Level Inverter Topologies

Table 4: Obtained Output Parameters for Different Inverter Topologies of DTC Control

Parameters	MLI	2 Level Inverter
THD	29.27%	37.88%
Fundamental Voltage	305V	293V
Conduction Losses	1248 W	312 W
Power Output	13860 W	13000 W
Efficiency	92.89%	87.13%

VI. Conclusion

The suggested V/f and Direct Torque control techniques for coupled IM drives with 2-Level/Multi-Level Inverter have been implemented and analyzed in MATLAB Simulink. From the obtained simulation results an extensive comparative study has been carried out for the two schemes based on performance parameters. The comparative analysis clearly depicts that choice of VSI for coupled motor drive has a tremendous influence on its harmonic distortions and output efficiency. Even though a 2-Level Inverter performs decently for coupled drive operation but it is over-shadowed by the superior performance of 5-Level Inverter where improvements in THD by 11%, fundamental magnitude by 57V, output efficiency by 2% in case of V/f control and THD by 9%, fundamental magnitude by 12V, output efficiency by 6% for Direct Torque Control have been achieved. From the compared magnitudes of performance parameters it is pretty much evident that MLI forms the best choice for implementation in coupled drives with both V/f and Direct Torque controls. Also another aspect which has been brought to fore is regarding the choice of control. It is clear from the simulation study that even though DTC offers 2% (with 2-Level Inverter) and 3% (with 5-Level Inverter) slightly more THD as compared to V/f control but it potentially lifts up the overall system efficiency by almost 3% with corresponding improvement of 60% in transient response time. Thus it is very critical for a designer to strike an efficient balance between the choice of VSI and control strategy keeping in mind the system abnormalities. This simulation study intends to aid control designer in selection of appropriate inverter drive for coupled induction motors to maximize reliability and flexibility of the chosen crane application.

Acknowledgment

Authors would like to sincerely thank respective Managements of MSRUAS, CMRIT and HK PolyU for providing all facilities required to carry out this research work.

References

[1] M. Amiri, M. Feyzi and H. Saberi, "A Modified Torque Control Approach for Load Sharing Application using V/F Induction Motor Drives", Proc. IEEE Power Electronics, Drive Systems and Technologies Conference (PEDSTC) Conference, pp.1-6, Feb.2013.

[2] D. Casadei, F. Profumo, G. Serra, A. Tani, "FOC and DTC: Two Viable Schemes for Induction Motors Torque Control", IEEE Transaction on Power Electronics, vol.17, no.5, pp.779-787, Nov. 2002.

[3] Iyer J., Tabarraee K., Chiniforoosh S. and Jatskevich J., "An Improved V/f Control Scheme for Symmetric Load Sharing of Multi-Machine Conference on Electrical and Computer Engineering (CCECE), pp.1487-1490, May.2011.

[4] Aarniovuori L., Laurila L., Niemela, M., Pyrhonen, J., "Measurements and Simulation of DTC Voltage Source Converter and Induction Motor Losses", IEEE Transaction on Industrial Electronics, vol.59, no.5, pp.2277-2287, May 2012.

[5] Mishra R., Singh S., Singh B., Kumar D., "Investigation of Transient Performance of VSI fed Induction motor Drives Using Volt/Hz and Vector Control Techniques", Proc. IEEE Power, Control and Embedded Systems Conference (ICPCES), pp.1-6, Dec.2012.

[6] Baby T., Sabah V., Lall K., Chitra A., "Multi-level Inverter Fed Induction Motor Drive for Pumping Application", Proc. IEEE Int. (TAP Energy), pp.85-92, June 2015.

[7] Curiac R., Li H., "Specific Design Considerations for AC Induction Motors Connected to Adjustable Frequency Drives", Proc. IEEE Pulp6, June 2010.

[8] H. Joshi, P. N. Tekwani, A. Hinduja, "Multilevel Inverter for Induction Motor Drives: Implementation using Reversing Voltage Topology", Proc. IEEE Industrial Power Electronics Conference (IPEC), pp.181-186, Oct 2010.

[9] D. Hartanto, G.H. Vaupel, W. Gansel, G. L. Fischer, "Comparison of Conventional and Frequency Converter Driven Overhead Bridge Crane Control Systems", Proc.

IEEE Power Electronics and Motion Control Conference (PEMCC), pp.940-945, Aug.2000.
[10] I. Daut, K. Anayet, M. Irwanto, N. Gomesh, M. Muzhar and M. Asri, Syatirah, “Parameters Calculation of 5 HP AC Induction Motor”, Proc. International Conference on Applications and Design in Mechanical Engineering (ICADME), pp.12B1-12B5, Oct. 2009.