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Improved Torque Control Performance in Direct Torque Control using Optimal Switching Vectors

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ABSTRACT

This paper presents the significant improvement of Direct Torque Control (DTC) of 3-phases induction machine using a Cascaded H-Bidge Multilevel Inverter (CHMI). The largest torque ripple and variable switching frequency are known as the major problem founded in DTC of induction motor. As a result, it can diminish the performance induction motor control. Therefore, the conventional 2-level inverter has been replaced with CHMI the in order to increase the performance of the motor either in dynamic or steady-state condition. By using the multilevel inverter, it can produce a more selection of the voltage vectors. Besides that, it can minimize the torque ripple output as well as increase the efficiency by reducing the switching frequency of the inverter. The simulation model of the proposed method has been developed and tested by using Matlab software. Its improvements were also verified via experimental results.

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1. INTRODUCTION

In the middle 1980's, a simple control strategy to enhance performance of induction motor was proposed by Takahashi and Noguchi. The control strategy is popularly known as Direct Torque Control (DTC) [1]. This method gradually replacing the traditional method of Field Oriented Control (FOC) proposed by F.Blaskhe [2]. At early stages, the FOC was extensivey used to established the control of AC quantities of stator flux, currents and voltages by using vector control approach. However, this scheme is complicated due to the existence of frame transformation, current controller and requires knowledge of machine parameters. In DTC, the torque and flux are controlled independently, in which their demands are satisfied simultaneously by choosing suitable voltage vectors according to the digitized status produced from hysteresis controllers. Unlike the FOC, the torque and flux are controlled based on producing the current components (d-q axis component of stator current referring to excitation reference frame) which results in complex mathematical equations.

Despite the DTC simplicity, it is known to have two major problems, namely variable switching frequency and large torque ripple. These problems that have arisen due to the unpredictable torque and flux control behavior for various operating conditions in hysteresis operation. Obviously, many researchers have extensively proposed some/minor adjustments to minimize the problems. Space vector modulation technique is one of the popular methods to overcome the problem. This way is widely used by researchers in order to achieve greater performance motor as was reported in [3]. The major different between DTC hysteresis based and DTC-SVM is the how to generate the stator voltage reference. In DTC-SVM, the stator voltage reference can be produced by calculating within a sampling time[4, 5]. By doing so, it can produce the constant switching as opposed the DTC-hysteresis based. However, to generate the stator voltage references involve the complex calculation and burden the processor device. Another improvement used is a variable hysteresis band. Basically, when reduce the bandwidth hysteresis band, the torque ripple has also become minimize. Even so, the possibility to select the reverse voltage vector can be occurred whenever the torque changes rapidly at the extreme conditions (i.e. at very low speeds). This mean, overshoot and undershoot of torque to vary outside the hysteresis bands might be happened. As a result, the extreme torque ripple is produced due to the inappropriate selection voltage vector. To improve the switching frequency, the dithering method is used [6, 7]. This method was applied with injecting the high switching frequency of the error component for flux and torque. However, it still also not maintains the switching frequency. Furthermore, many kinds of technique were adopted in DTC drives in order to overcome the problem as well as enhance the excellent performance of motor drives such as [8, 9].

In recent years, the researches on DTC drives utilizing multilevel inverter become the hot topic for providing the more excellent and precision of selection voltage vector to improve DTC performance[10-12]. In general, multilevel inverter can be categorized in three layouts, namely, CHMI, neutral point capacitor multilevel inverter and flying capacitor multilevel inverter as was reported [13, 14] . The all kinds of multilevel have different configurations, number of switching devices, switching states/vectors and arrangements. Multilevel inverter can offer significant advantages to improve DTC performance, especially for medium and high-power voltage application. Furthermore, it also can operate at high voltage and produce lower harmonic (i.e. slope of voltage changed dv/dt)[15].

In this paper, the DTC performances, in terms of torque ripple, harmonics distortion and switching frequency were improved by applying appropriate selection of voltage vectors offered in CHMI topology. The selection of the appropriate vectors depends on the motor operating conditions which inherently determined by the output status of 7-level of torque hysteresis comparator. The application of simple DTC structure and fast instantaneous control with high control bandwidth offered in hysteresis based DTC can be retained. This paper is organized by section as followed; Section II described about the concept of DTC-hysteresis based, Section III presents the topology and switching vectors available in CHMI topology, Section IV discusses the proposed selection of vectors in DTC-CHMI; Section VI presents the simulation results to show the improvements offered and finally Section VII gives the conclusion.

2. CONCEPT OF DTC-HYSTERESIS BASED

DTC has a simple structure configuration as shown in Figure 1, yet it is superior to enhance torque and flux control, in terms of fast dynamic and reliable control due to the hysteresis operation. By doing so, the appropriate selection of voltage vectors can independently control both torque and flux. Therefore, it can offer a faster instantaneous control of torque and flux based. Selection voltage vector or switching state can be obtained from the look-up table as was tabulated in Table I. Where, in the switching table contains three main components, namely the status of torque, flux and status flux orientation for selecting the appropriate switching state. The switching states are choosing based on the requirement of torque and stator flux, either to increase or decrease and also stator flux sector. In order to make the decision either to increase or decrease can be obtained from the 3-level and 2-level hysteresis of torque and stator flux, respectively. Besides that, the estimated value of flux and torque can be produce from the calculation of voltage and current component. In power circuits, the voltage source inverter is performed by IGBT device. The schematic diagram of 3-phase voltage source inverter is realized in Figure 2. According to these figures, the inverter has contained six switch modes to operate in the 3-phase induction machine. Therefore, it can generate eight voltage space vectors, as illustrated in Figure 3. Each voltage space vector, has a three switching state, [Sa,Sb,Sc]. Six active voltage vector ($\overline{v}_1$ to $\overline{v}_6$) and two non-active or zero voltage vector ($\overline{v}_0$ and $\overline{v}_7$) corresponding to [0 0

0] and [1 1 1], respectively. Each switching device must be complementing each other for (upper and lower switch) to avoid short circuit conditions.

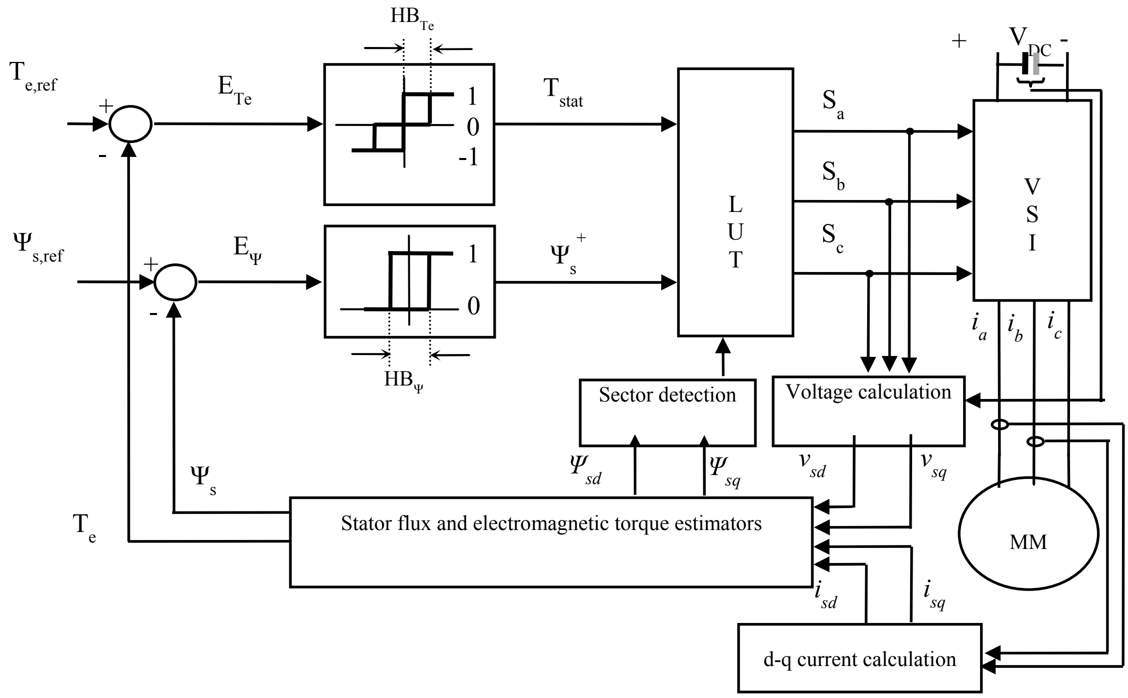


Figure 1. Complete structure of DTC-Hysteresis Based

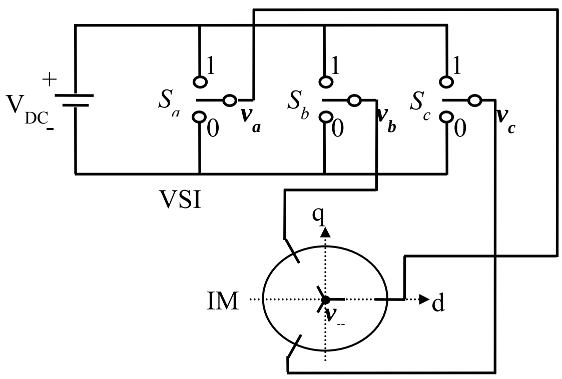


Figure 2. Schematic diagram of VSI

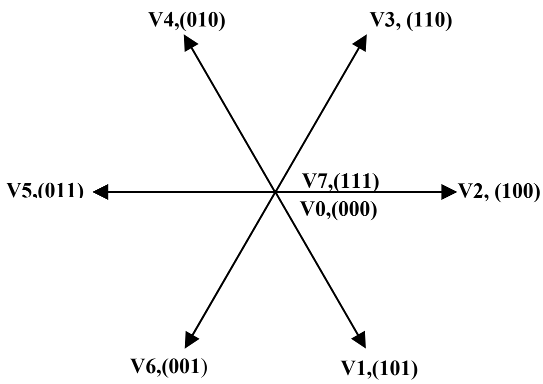


Figure 3. Voltage vectors are generated by VSI

Table 1. Look-up table

Stator flux error status, Ψ_s^+	Torque error status, T_{stat}	Sec I	Sec II	Sec III	Sec IV	Sec V	Sec VI
1	1	[100]	[110]	[010]	[011]	[001]	[101]
	0	[000]	[111]	[111]	[000]	[000]	[111]
	-1	[001]	[101]	[100]	[110]	[010]	[011]
0	1	[110]	[010]	[011]	[001]	[101]	[100]
	0	[111]	[000]	[000]	[111]	[111]	[000]
	-1	[011]	[001]	[101]	[100]	[110]	[101]

3. CASCADED H-BRIDGE MULTILEVEL INVERTER (CHMI)

CHMI is one of the popular power circuit topologies used in high-power medium voltage. These names were given because, it uses multiple units of power cells connected in a series to operate in medium or high voltage as well as to generate lower harmonic ripple. A few isolated DC sources are required for this inverter to synthesize an output voltage waveform. The structure of this inverter is shown in Figure 4, which each phase consists of two H-Bridge. Each cell has single DC-link source to fed the induction motor with connected individually. So, for three phases motor required three isolated DC-links. Four switches off the device (Sa+, Sa-, Sb+ and Sb-) are operating when they receive the signal from the gate drives. By four switches of the inverter to trigger, can produce three discrete output Vab with the level $+V_{dc}$ for (S1 and S4 switch is ON), $-V_{dc}$ for (S2 and S3 switch is ON) and 0V for (all switch OFF). The number of voltage level, L for CHMI can be defined by L=2m+1, where m, for numbers of H-bridge cell per phases. For a 3-level CHMI, the voltage vector can generate 3^3= 27 different voltage vectors and 3L (L - 1) +1= 19 voltage vectors practices used in CHMI topology. Figure 5 shows the voltage vector available as shown in CHMI on a d-q axis . It can be seen that, the outer hexagon which contains 12 voltage vectors with single switching state combination, while for inner hexagon which contains 6 voltage vectors are produced with two combination switching state. Therefore, when increase the level of multilevel inverter, more voltage vectors will be produced. So that, the voltage vectors can be categorized in three conditions (i.e: low speed, medium and high) according the speedy operation. As a result, the total number of switching state become increase, and it offered the many possibilities to improve control strategies of induction motor.

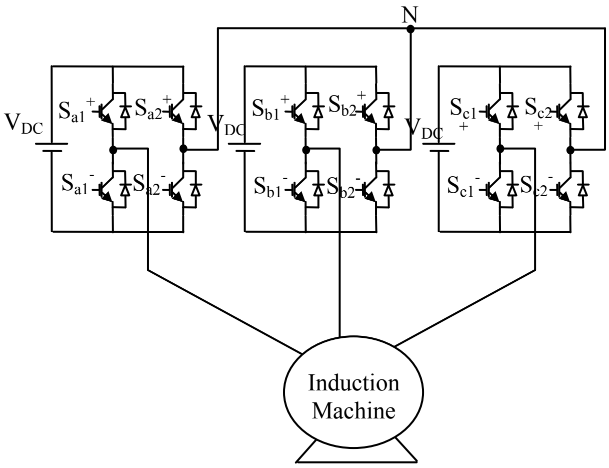


Figure 4. 3-Level CHMI connected to 3-phase induction machine.

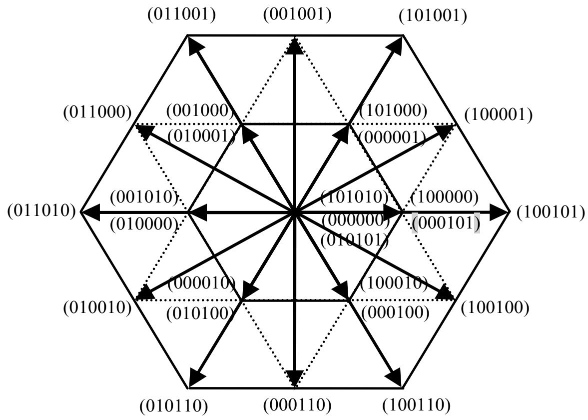


Figure 5. Voltage vector generated by the 3-level CHMI on d-q plane.

4. PROPOSED SWITCHING STRATEGY

In the proposed strategy, a new block modification of torque error status is introduced in the DTC structure by implementing the CHMI topology, is called “Optimum Status Detection or OSD”. This block is responsible to modify the torque error status (T_{stat}), which produces new torque status ($T_{stat,new}$) for selecting the optimum switching vectors. Figure 6 shows the complete structure of the DTC-CHMI with inclusion of OSD block (gray color). From the figure, it can be noticed that, some different parts as compared with the DTC conventional. These include the definition of the stator flux plane, calculation of voltage phase for d and q component, and modified the look-up-table for DTC-CHMI. The following subsections discuss the functions or equations used to model the parts.

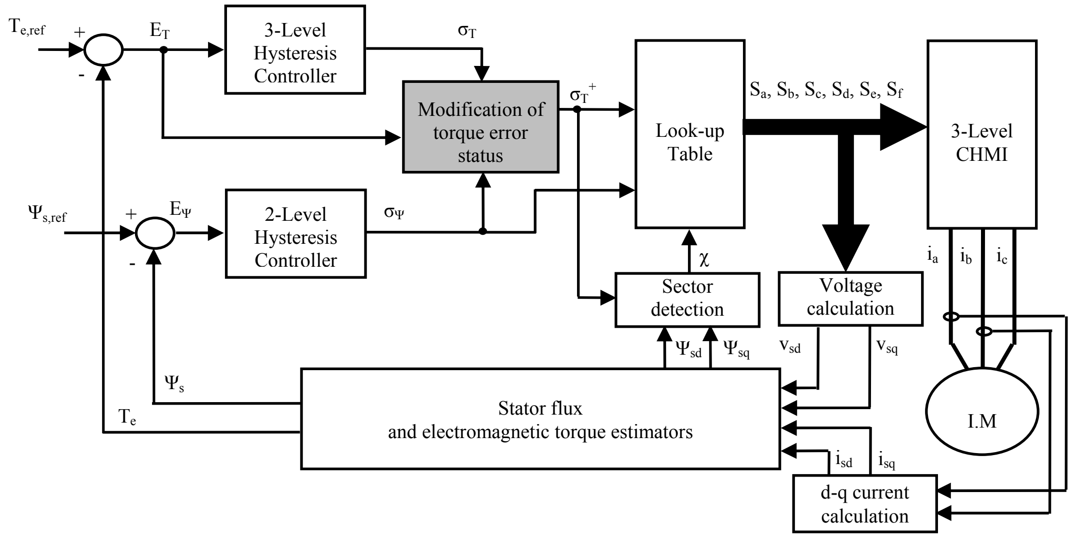
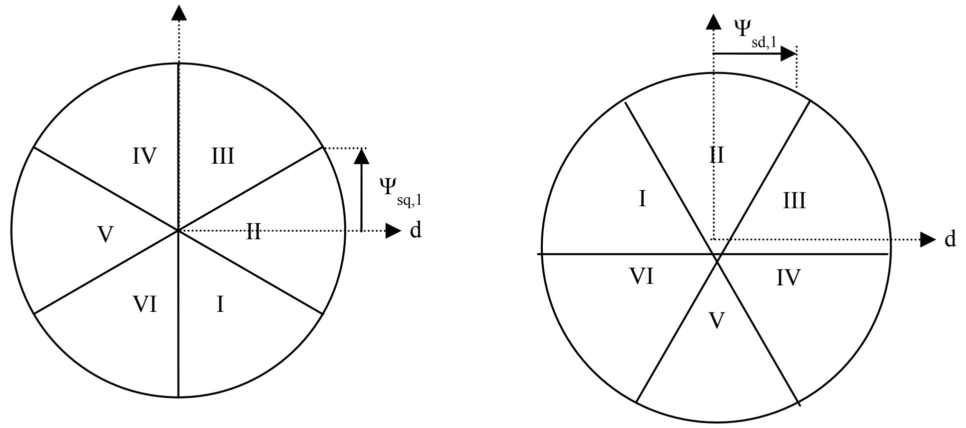


Figure 6 Structure of DTC-hysteresis based induction machine with the proposed modification of flux error status

(i) Definition of sector flux plane

A sector definition of stator flux plane in proposed method is split into two different sequences and angle between sectors is maintained to 60 degrees. It is because, in implementing the CHMI topology produces more voltage vector and the number of switching state also increases. Figure 7. is showing a two different definition of the stator flux plane to apply in this research. Figure 7(i) is shown the definition of stator flux plane for middle speed operation. In this case, the middle voltage vector amplitude is chosen to increase and decrease the flux. While for low and high speed, the sector definition of the stator flux plane as in Figure 7 (ii) is used either to increase or decrease flux. The threshold value for both of the definition stator flux plane can be determined using this equation;

$$\chi = \begin{cases} \vartheta, \text{ if } \sigma_T^+ = 0, 1 \text{ or } 3 \\ \vartheta', \text{ if } \sigma_T^+ = 2 \end{cases} \quad (1)$$



(i) For low and high speed conditions (ii) For middle speed condition

Figure 7. Difference sector definition

(ii) Calculation of d and q component

By applying this topology; the voltage component can be obtained from the switching pattern of the 3-phase voltage source inverter as follows

$$V_d = \frac{V_{dc}}{3}(2S_{a1} - 2S_{a2} - S_{b1} + S_{b2} - S_{c1} + S_{c2}) \quad (2)$$

$$V_q = \frac{V_{dc}}{\sqrt{3}}(S_{b1} - S_{b2} - S_{c1} + S_{c2}) \quad (3)$$

(iii) Modified Look-Up-Table

As a shown the previous section, look up table is an important part in DTC drives. In the look-up-table have three conditions must be satisfied to choose the appropriate switching state, i.e. torque status, flux status and sector. In look-up table with a proposed structure consist of voltage vectors with three difference amplitudes, (i.e. Short, medium and long). The selection of voltage vectors depends on the torque error status. For example, when the high speed condition mode, the torque error status is selected 3 to indicate is high speed as well as is choosing the longest voltage vector. For the medium speed, the torque error is select the status 2 is shown the motor in middle speed mode. Finally, at low speed operation, the shortest amplitude voltage vector is selected. The labeling the voltage vector based on the speed operation as shown in Figure 9 and Table II shows the look-up table of DTC with proposed structure and strategy.

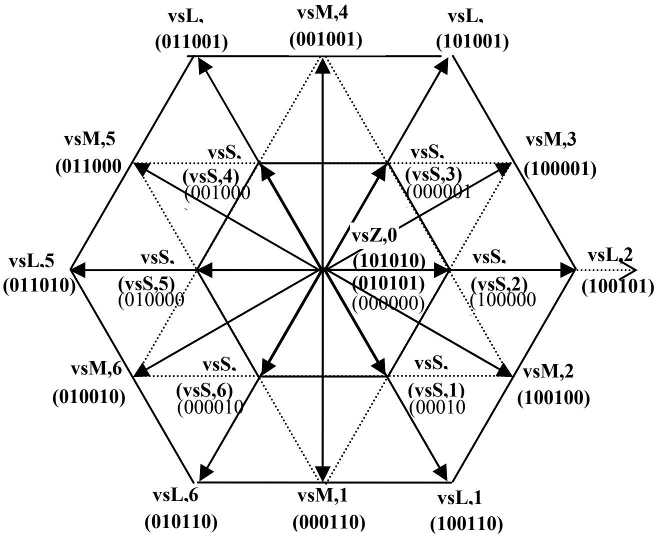


Figure 9. Voltage Vector available in CHMI

Table 2. The Look-Up Table For DTC drives by applied

Stator flux error status, Ψ_s^+	Torque error status, T_{stat}	Sector I	Sector II	Sector III	Sector IV	Sector V	Sector VI
	3	vsL,2	vsL,3	vsL,4	vsL,5	vsL,6	vsL,1
	2	vsM,6	vsM,5	vsM,4	vsM,3	vsM,2	vsM,1
	1	vsS,2	vsS,3	vsS,4	vsS,5	vsS,6	vsS,1
1	0	vsZ,0	vsZ,0	vsZ,0	vsZ,0	vsZ,0	vsZ,0
	-1	vsS,6	vsS,1	vsS,2	vsS,3	vsS,4	vsS,5
	-2	vsM,4	vsM,3	vsM,2	vsM,1	vsM,6	vsM,5
	-3	vsL,6	vsL,1	vsL,2	vsL,3	vsL,4	vsL,5
	3	vsL,3	vsL,4	vsL,5	vsL,6	vsL,1	vsL,2
	2	vsM,1	vsM,6	vsM,5	vsM,4	vsM,3	vsM,2
	1	vsS,3	vsS,4	vsS,5	vsS,6	vsS,1	vsS,2
0	0	vsZ,0	vsZ,0	vsZ,0	vsZ,0	vsZ,0	vsZ,0
	-1	vsS,5	vsS,6	vsS,1	vsS,2	vsS,3	vsS,4
	-2	vsM,3	vsM,2	vsM,1	vsM,6	vsM,5	vsM,4
	-3	vsL,5	vsL,6	vsL,1	vsL,2	vsL,3	vsL,4

A description of the optimal selection based on the operating speed is determined from the behavior of error status (flux and torque) and torque error as follows:

1) Selection of the longest voltage vector happened, when the switching frequency of torque status is less than the switching flux status (Tstat < Fstat) during the torque demands or high speed operation.
2) Selection of the medium of the vector is active when the switching frequency of torque status is slightly higher than that of flux status.
3) The shortest amplitude voltage vector is chosen when the switching frequency of torque status is higher that flux status (Tstat > Fstat). This case occurring during at low speed operation and negative torque demand.

5. EXPERIMENTAL SETUP

The feasibility of the DTC of implementing CHMI topology in reduced the torque ripple output and constant switching frequency has been realized with a complete drive system. In the experimental test, the proposed algorithm switching strategy has conducted by dSPACE ds1104. To interface in real time between hardware and software system, the Control Desk has been provided in order to easily control the parameter.

The control Desk application is very friendly user to configure the layout experiment to monitor the experimental result. For FPGA device, the algorithm blanking times for 3-level CHMI is constructed in proper for preventing the short circuit at power device circuit (IGBT). This device is responsible to achieve the proposed strategy in smooth and successful. The sampling period in this system is set 50us with same the simulation sampling time. Figure 10 shows the complete hardware setup has been done. Three units of the DC-Link is set 120V for testing DTC-CHMI and for DTC conventional inverter is set 240V. The motor parameters are determined based on the blocked rotor and no load test. The motor parameter as tabulated in Table III. In the experiment, induction motor is coupled to a DC motor as a load. To control the load is by applying the voltage supply at the armature winding in the DC motor. The DC motor was manufactured by LO RENZO and the power rating is 1.1kW.

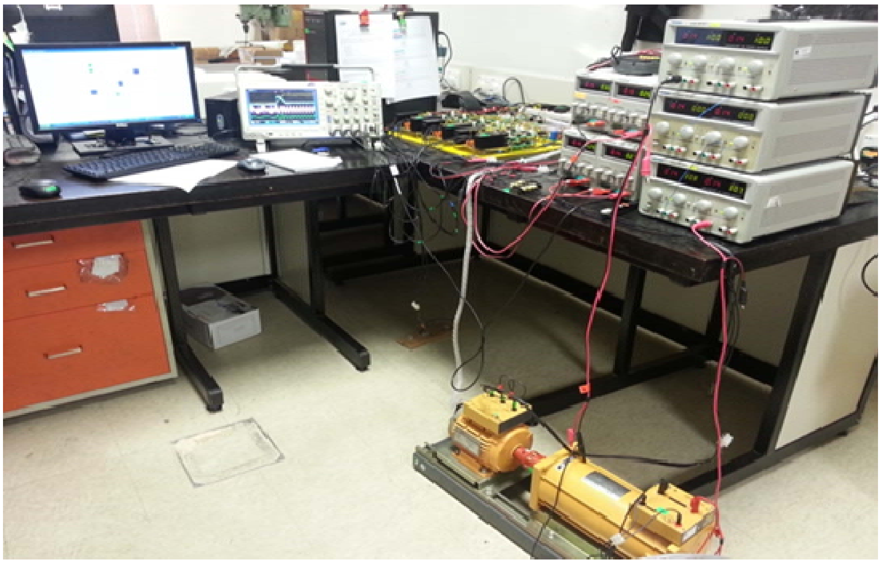


Figure 10. Complete experimental setup

Table 3. Motor parameters

Induction motor parameters	
Rated power, P	1.1 kW
Rated voltage, V_s	380 V
Rated current, $i_{s,rated}$	2.7 A
Rated speed, ω_m	2800 rpm
Stator resistance, R_s	6.1 Ω
Rotor resistance, R_r	4.51 Ω
Stator self inductance, L_s	306.5 mH
Rotor self inductance, L_r	306.5 mH
Mutual inductance, L_m	291.9 mH
Combined inertia, J	0.0565 kg-m^2
Combined viscous friction, B	0.0245 N.m.s
Number of pole pairs, P	2

6. IMPLEMENTATION AND EXPERIMENTAL RESULTS

These sections present the experimental results of significant improvement by using CHMI configuration. Before to the algorithm conducted at hardware testing, the simulation has been simulated to make sure the proposed strategy can achieve the excellent performance of DTC drives via CHMI. Matlab R2011a version is used as a tool to confirm that a strategy. Then, the proposed switching strategy was verified through experimental test. Some test conditions were conducted on DTC-drives control schemes to evaluate the performances. The two different topologies of inverter and control scheme used in these evaluations are conducted as follows;

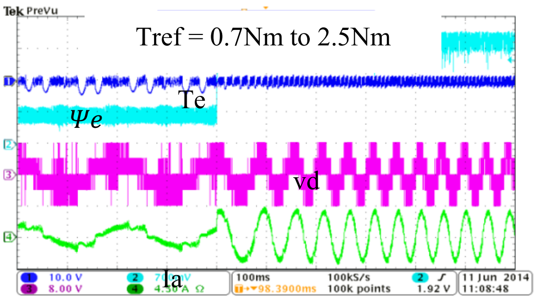
i. Control of DTC-Hysteresis based on the 2-level conventional inverter.
ii. Control of DTC based on the 3-level CHMI using proposed switching strategy.

Each test was performed under the same condition in order to have fair comparisons for both of inverter topology as tabulated in Table 4.

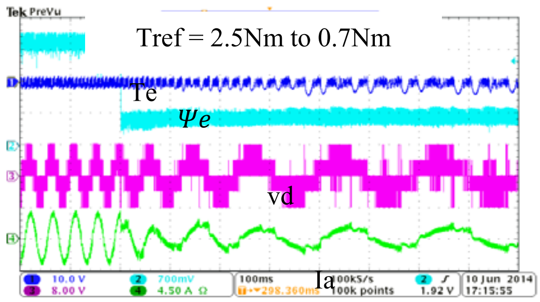
Table 4. Comparison between the conventional and proposed method

Control Parameters		Inverter topology	
		(a) 2-Level Conventional Inverter	(c) 3-Level CHMI
Torque reference Change	Low to High	0.7 Nm – 2.5 Nm	
	High to Low	2.5 Nm – 0.7 Nm	
Sampling time, T_s		50 µs	
Torque hysteresis bandwidth, HB_T		0.36 Nm	
Flux hysteresis bandwidth, HB_i		0.02 Wb	
Torque limit, T_{limit}		4 Nm	

The torque, flux, voltage phases and current waveform result for both of inverter topology are shown in Figure 11. Two different references of torque have been applied for both of the inverter. The significant improvement in term torque ripple and switching pattern can be obtained by applying the proposed switching strategy. A step change of reference torque (T_{ref}) was applied from 0.7 Nm to 2.5 Nm at t=0.4s as shown in Figure 11(i) and (iii) and 2.5Nm to 0.7Nm as shown in Figure 11(ii) and (iv) for both of the inverter . In initially, the stator flux angular velocity as well as motor speed is slower. So, in this condition, the torque error status is selected between S_t=0 and S_t=1 in order to choose the lower amplitude of voltage vector. When the torque reference suddenly changed to 2.5Nm, it can be seen that, the torque error status S_t=2 momentarily for very short of time response during torque transient was occurring. This is show that, when have a new demand, the longest amplitude voltage vector is applied to produce the faster dynamic torque response to increase. Based on the observation of the experimental results, it can be seen that when the torque reference change to lower the magnitude, suddenly the negative longest reverse voltage is chosen. That means, the torque error status is selected S_t=-3 in order to quick response to reach the demand of the motor. Therefore, it shows the torque error status St gradually changes from S_T=3↔2 to S_T=2↔1 and finally to S_T=1↔0 for decreasing the output voltage in satisfying the torque demand as the stator flux angular velocity reduce. The effects of torque ripple and switching frequency by applying proposed switching strategy can be clearly seen in the magnified image of Figure 12. By observing the proposed switching strategy, it can be seen that, the waveform for voltage phase is to show the length of slope when torque reference is applied. This is indicated the longest voltage vector is chosen when suddenly torque reference changed either for forward or reverse condition operation.

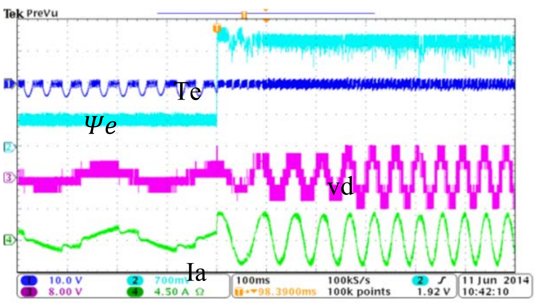


(i)

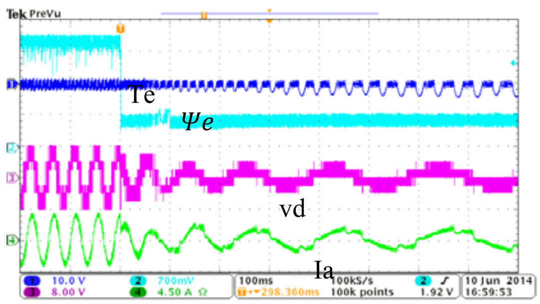


(ii)

(a) Conventional inverter



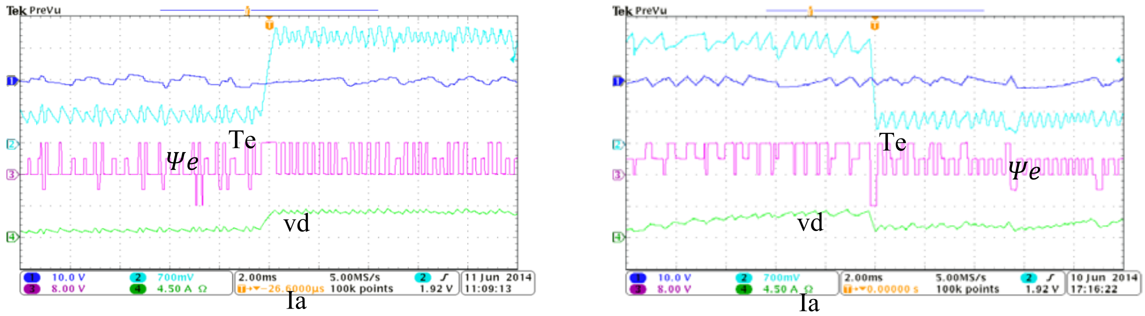
(iii)



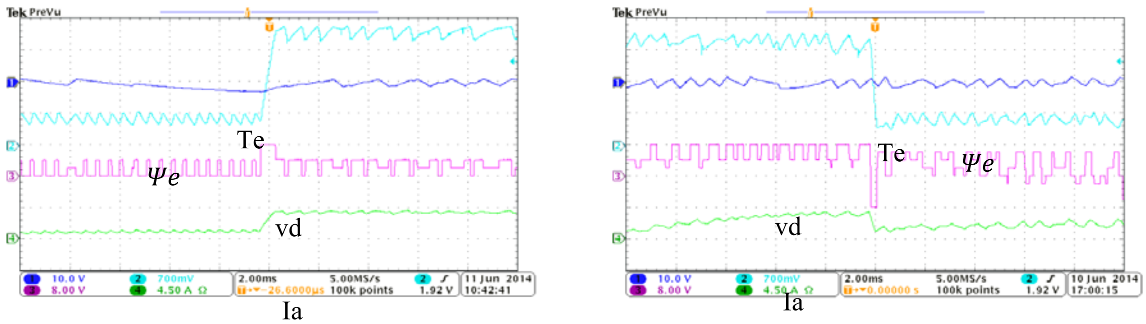
(iv)

(b) Proposed strategy

Figure 11. Experimental result for torque referecene was applied for condition



(a) Conventional inverter



(b) Proposed Strategy

Figure12 Magnified image for all experimental results

7. CONCLUSION

This paper presented a simple implementation by introducing the block modification on DTC of induction motor fed by 3-level CHMI topology. This multilevel can generate more voltage vectors as well as increase the number of switching states. Besides that, the appropriate voltage vector was selected based on the status generated from the modified OSD block. By increasing the number of voltage vectors, it can improve the DTC performances in term torque ripples, switching frequency and dynamic response. Besides that, by employing the CHMI topology, the extreme torque slope can be prevented by applying the lower amplitude vector during at low speed as well as the rate change of voltage can also minimize (dv/dt). Whereas, in condition at high speed operation, the longest vector is chosen in order to improve torque control capability in satisfying its demand.

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