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Improvise 3-Level DTC of Induction Machine using Constant Switching Frequency Method by Utilizing Multiband Carrier

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ABSTRACT

This paper presents the advantage of using optimal PI parameter tuning strategy of constant switching method in the three phase Direct torque control (DTC) scheme. The DTC system is known to offer fast decoupled control of torque and flux via a simple control structure. Nevertheless, DTC system has two major drawbacks, which are the variable inverter switching frequency and high torque output ripple. The major factorthat contributes to these problems the usage of hysteresis based comparators to control the output torque. The implementation of PI based constant switching method in DTC able to solve these problems while retaining the simple control structure of conventional DTC. The combination usage of 3-level CHMI in this system can further minimize the output torque ripple by providing greater number of vectors. This paper presents detail explanation and calculationof optimal PI parameter tuning strategy consecutively to enhance the performance of 3-level DTC system. In order to validate the feasibility, the proposed method compared with convention DTC system via simulation and experiment results.

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1. INTRODUCTION

There are two most common ac drives control schemes that are being widely researched. One of it is Field Oriented Control (FOC) which was proposed by F. Blaschke. Second scheme is Direct Torque Control (DTC) which was proposed by I. Takahashi and T. Noguchi [1, 2]. There are two major drawbacks of FOC compared to the DTC which are torque is controlled indirectly and requirement of the pulse encoder [3]. FOC method controls the torque indirectly because its control priority is flux vector. FOC needs the pulse encoder in order to obtain the speed and position of the rotor. This makes the DTC system as an alternative and gained the attention of many researchers lately due to its simple structure by elimination of pulse encoder and simple algorithm with lesser dependency on motor parameters (only requires value of stator resistance R_s and phase current) [1,4]. Over the past years, the utilization of multilevel inverter topology in the DTC system has gained popularity for the medium and high voltage applications. Typically, there are three types of multilevel inverters topologies. Those types are the Neutral Point Clamped (NPC), Flying Capacitor (FC) and Cascaded H-bridge Multilevel Inverters (CHMI) [6]. The benefit of using multilevel inverter is its availability of greater number of voltage vectors that will contribute in selecting suitable and optimal voltage vector to control flux and torque by reducing the slope magnitude of the torque and flux. Moreover, this features also contributes towards optimum switching for high-efficiency by reducing the switching frequency and also improve the output voltage quality (by reducing the rate of change of phase voltage, dV/dt) [6].

In conventional DTC, the variable switching frequency is inevitable due to the nonlinear effects of applied voltage vectors on torque and flux variations, in restricting the variations within hysteresis bands. As the stator flux space vector forms a circular locus, one of the two suitable voltage vectors that has the most tangential to the stator flux gives higher rate of torque change compare to less tangential voltage vector [3]. It can be shown that the application of this vector is dominant (i.e. longer time application) when the flux moves closer to the sector border in the stator flux plane, on the other hands, the two suitable vectors become less tangential and switch more often when the flux vector travels around the middle of sectors. So the torque switching (or flux switching) is more frequent in the border (or middle) of the sector compare to the middle (or border) of the sector. These phenomena majorly contribute to the variable switching frequency in DTC. The implementation of constant switching method can overcome the irregular switching problems in DTC [3, 4, 5]. Previously the constant frequency torque controller (CFTC) method was proposed by [3] in order to reduce the output torque ripple with a constant switching frequency. In this approach, two triangular carrier waves were injected at the torque error node and then two comparators were used to generate torque status. Although this method reduced the torque ripple but still has low frequency torque error oscillation. This is due to the stator flux hysteresis based controller in which used to regulate flux around its reference value. This error is less significant and negligible if the PI parameter is calculated correctly.

2. IMPLEMENTATION OF CONSTANT FREQUENCY TORQUE CONTROLLER (CFTC) IN 2-LEVEL DTC SYSTEM

The constant frequency torque controller (CFTC) was implemented in 2-level DTC system in order to reduce the output torque ripple while maintaining a constant switching frequency compared to the conventional DTC method [3]. The switching frequency of conventional DTC system varies based on operating condition of the system. This is due to the hysteresis based controller is used to control the flux and torque of the conventional DTC system. The hysteresis based controller controls the magnitude of torque (or flux) within the prefixed bandwidth (error tolerance). The rate of change of the torque (or flux) is directly proportional to the frequency of torque (or flux) error signal. Higher rate of change of thetorque produce higher frequency torque error status frequency and vice versa. It these phenomena occur when the flux locus enters and leaves a sector of d-q plane flux locus. The conventional DTC system of 3-phase induction machine has the total of 6 sectors with 30^o angle difference between each sector. The 3-phase conventional DTC system has 6 active and 2 zero voltage vectors (as shown in Figure 1). For the decrement of the torque status, a zero voltage vector will be selectedalways in which the rate of change of torque is constant throughout every operating condition. But for the increment of the torque status, there will be an active vector selected between two most tangential vectors in the direction of flux locus in which rotate in circular motion. The selection of the suitable voltage vector effected by the flux error signal produce by the flux hysteresis controller either to increase or decrease flux locus magnitude along the flux reference signal.

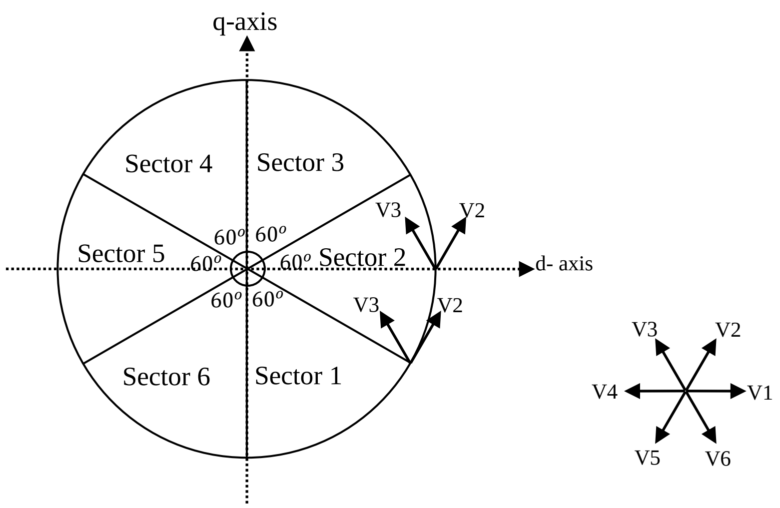


Figure 1. Basic sector definition and 2-level voltage vector of 3-phase DTC system

For example in sector 2, the voltage vector V3 and V2 will be chosen for the anti-clockwise stator flux rotation in d-q plane. At the beginning of sector 2 for anti-clockwise rotation, vector V2 will be most tangential to the flux locus compare to V3. The direction of flux locus vector is contributed by the direction of applied voltage vector. The V2 (most tangential to flux locus) will be selected dominantly at the beginning of sector 2 because its less contribute to the increment of the stator flux. In the other hand V2 will give highest torque increment since it has highest tangential component. As a result, the rate of changes of torque error status (frequency) will be higher at the beginning of sector. When the flux locus travel pass the middle of sector, the both vector V2 and V3 have equal tangential component in where both vectors will be selected more frequently to maintain the flux regulation. But the both vectors have lower tangential component compare to the V2's tangential component at the beginning of the sector. This makes the both vector will to produce lower rate of change of torque. Consequently, the rate of changes of torque error status (frequency) will be lesser after the middle of sector. This scenario is clearly describe by the Figure 2(a) in which it shows the relationships between torque, hysteresis band, torque status error, andthe angle of stator flux locus in d-q plane. For the anti-clockwise rotation, angle -30^o is the beginning of the sector 2 and 30^o is the middle. Even the increment of the torque slope differs according to the angle of stator flux locus, but the decrement of the torque slope is same (because only zero vectors are used). This alternation of torque (and flux) switching frequency contributes to the alternation of inverter (IGBT) switching frequency.

Figure 2(a) and Figure 2(b) show the theoretical illustration comparison of the conventional DTC system versus the CFTC implemented DTC system. From the comparison, the variation of the torque frequency for the both cases can be observed clearly. For the conventional DTC system the torque status switching frequency varies along the sector 2. However for the CFTC implemented DTC system, the torque status switching frequency remain constant but only changes in the duty ratio corresponding to the torque demand needed to regulate the torque around the reference. In order to verify the feasibility of the CFTC method over the conventional method, the simulation testing was done using Matlab software with the given parameter. The FFT analysis is done on the torque output to verify the frequency spectrum. The result analysis is shown in Figure 3. The DTC have wide rage switching frequency involved. Where as in CFTC method, the entire frequency spectrum were eliminated except for the frequency of carrier wave in which 6250Hz.

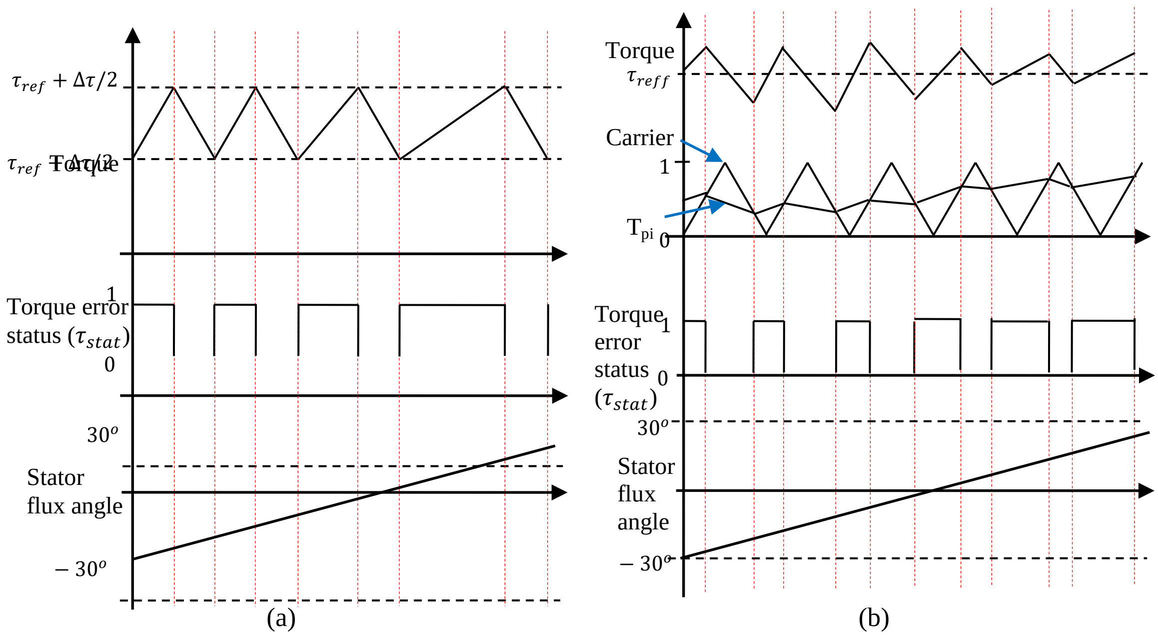
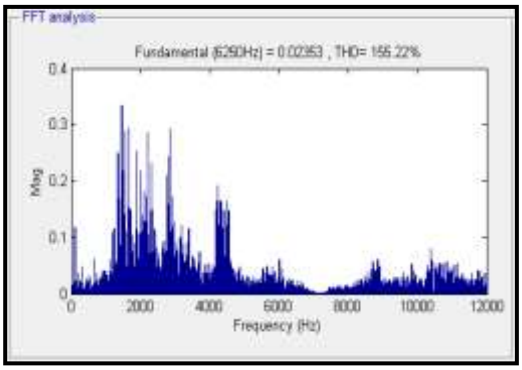
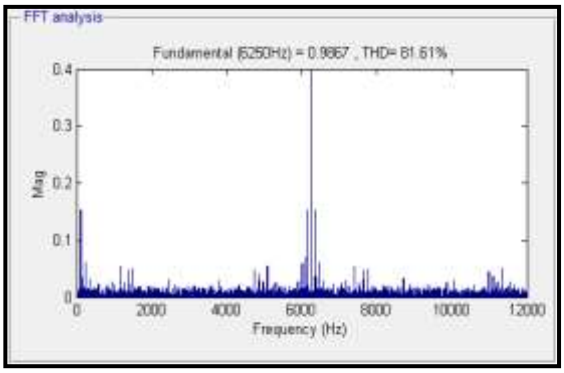


Figure 2. Illustration Comparison of (a) Basic DTC System and (b) The CFTC System in Term of The Torque, Controller, Torque Error Status, and Stator Flux Angle (Degree).



(a)



(b)

Figure 3. FFT result for output torque of (a) basic DTC system and (b) the CFTC system in which simulated in same operating condition

The theoretical behavior of DTC system if 3 phase induction machines can be described in terms of space vectors by the equations that are written in stator stationary reference frame as below:

$$Vs = r_s i_s + \frac{d\Psi_s}{dt} \tag{1}$$

$$\Psi_s = L_s i_s + L_m i_r \tag{2}$$

$$\Psi_r = L_r i_r + L_m i_s \tag{3}$$

$$T_e = \frac{3}{2} P|\Psi_s||i_s|\sin\delta \tag{4}$$

$$\Psi_{sd} = \int (v_{sd} - i_{sd} r_s) dt \tag{5}$$

$$\Psi_{sq} = \int (v_{sq} - i_{sq} r_s) dt \tag{6}$$

where P is the number of pole pairs; Ls (stator inductance), Lr (rotor inductance), and Lm (mutual inductance) are the inductances of the motor, Ψ_s and Ψ_r are the stator and rotor flux and δ is the angular difference between stator flux linkage and i_s stator current space vector . As in equation 5 and 6, the stator flux vector is written in d-q axis components. The electromagnetic torque given in equation 4 can be rewritten in d-q coordinates shown in equation 7. This equation also shows the relationship of tangential component over the torque output.

$$T_e = \frac{3}{2} P(\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd}) \tag{7}$$

Even though variation of switching status of torque and flux effect the inverter switching frequency, thus the torque status (T_{stat}) frequency give a high impact compare to the flux. This is because averagely the torque status switching is higher than compare to the flux status switching. As a simple solution, the constant frequency torque controller (CFTC) can be used to reduce the output torque ripple while maintaining a constant switching frequency compared to the conventional DTC method. This is done by injecting two high frequency triangular carrier waves at the torque error node and then the resultant signal were passed through two comparators in order to generate the torque error status signal (T_{stat}) equivalent to the conventional 2-level DTC. The CFTC block (shown in Figure 4) was used to replace the torque hysteresis controller as shown in Figure 5 (the area marked with red dotted line). The T_{stat} signal generated can be described by the following equation 8.

$$T_{stat} = \begin{cases} 1, & \text{for } C_{upper} \le E_{pi} \\ 0, & \text{for } C_{lower} < E_{pi} < C_{upper} \\ -1, & \text{for } C_{lower} \ge E_{pi} \end{cases} \quad (8)$$

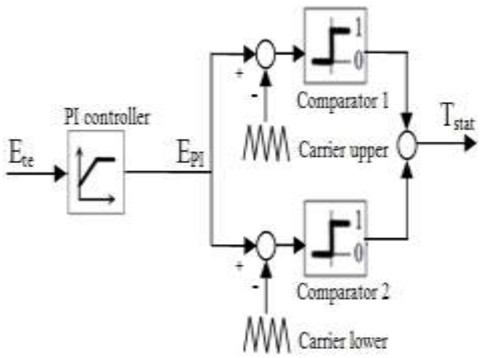


Figure 4. The Constant Frequency Torque Controller (CFTC)

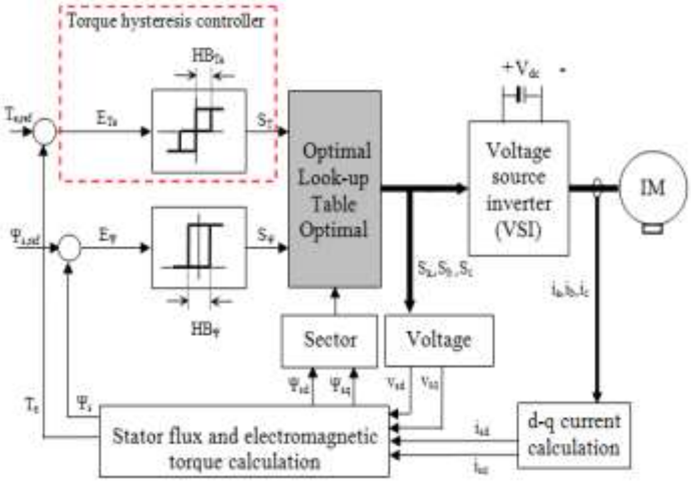


Figure 5. Basic structure of DTC-hysteresis based motor drive system

The absolute slope value of T_{pi} signal must be lesser than the absolute slope value of the carrier in order to regulate the torque output along the reference value. This is possible by the proportional gain of the PI controller. To archive the above condition, the following equation must be fulfilled:

$$K_{tp}^{+} \le \frac{2\, f_{t\_tri} C_{p-p}}{-A\tau_e + B v_s^{\Psi s} + K_t\left(\frac{\omega_e}{d} - \omega_r\right)} \quad (9)$$

and also

$$K_{tp}^{-} \le \frac{2\, f_{t\_tri} C_{p-p}}{|-A\tau_e - K_t \omega_r|} \quad (10)$$

The K_{tp}^{+} is positive slope equation and the K_{tp}^{-} is negative slope equation. The selection of optimal K_{tp} value is based on the smallest value produced the equation (9) and (10). The supporting equations in order to solve the above equation are given by the (11) until (15).

$$TF_{DTC} = \frac{B v_s^{\Psi s}}{s + A} \quad (11)$$

$$A = \frac{1}{\sigma \tau_{sr}} = \frac{1}{\sigma}\left(\frac{R_s}{L_s} + \frac{R_r}{L_r}\right) \quad (12)$$

$$A = \frac{1}{\sigma}\left(\frac{R_s}{L_s} + \frac{R_r}{L_r}\right) \quad (13)$$

$$\sigma = 1 - \frac{{L_m}^2}{L_s L_r} \quad (14)$$

$$B = \frac{3p}{4}\left(\frac{L_m}{\sigma L_s L_r}\right) \Psi_s \quad (15)$$

The minimum sampling period can be obtain in the experimental setup by using DSPACE interface card DS1104 is 20μs. The sampling time of the Matlab simulation is set to 20μs. The minimum sampling required to make low resolution triangle wave carrier is 8. The 8 step per-cycle with 20μs sample will produce carrier frequency of 6250Hz. The Table 1 shows the parameter of 3-phase induction machine used in simulation and experiment.

Table 1. Parameters of 3-Phase Induction Machine Parameters and Experimental Set-up Data

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	306.5mH
Rotor self inductance, L_r	306.5mH
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*	1
Inverter's Voltage Supply	240V

3. PROPOSED OPTIMAL PI PARAMETER TUNING STRATEGY

For the proposed method, the CFTC controller was implemented in 3-level DTC system of 3-phase induction machine. The principle of applying the CFTC controller in multilevel DTC is to increase efficiency of the DTC system by selecting most optimal voltage vector at every operating condition. This is possible because the 3-level inverter provide 18 active voltage vectors in which more than conventional system. As result, the optimal voltage vector selection willcontribute to more the reduction of torque ripple and lower harmonic. Figure 6 shows the constant frequency torque controller (CFTC) which was modified for the purpose to be implemented in conventional 3-level DTC system. The modified CFTC consists of six triangular carrier wave, six hysteresis comparators and single proportional-integral (PI) controller. In theory, the torque error status signal (T_{stat}) produced from the modifiedCFTC is similar to a 7-level hysteresis controller, which can be in one of seven states; −3, -2, -1, 0, 1, 2 or 3. There is no modification of the original (3-level) look-up Table is required. As a result, the simple control structure of hysteresis-based DTC can be maintained in which the decouple control structure of flux and torque output.

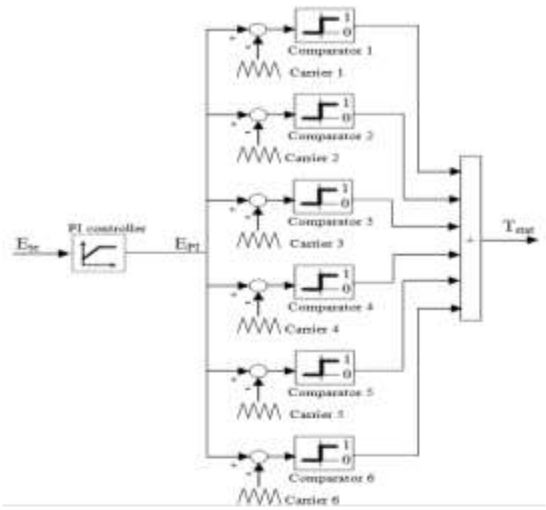


Figure 6. The modified Constant Frequency Torque Controller (CFTC)

The submission of T_{stat} signal generated by the comparators in Figure 6 can be described by the following equation:

$$T_{stat} = \begin{cases} 3, & \text{for Carrier } 1 \le E_{pi} \\ 2, & \text{for Carrier } 2 \le E_{pi} < Carrier\ 1 \\ 1, & \text{for Carrier } 3 \le E_{pi} < Carrier\ 2 \\ 0, & \text{for Carrier } 4 \le E_{pi} < Carrier\ 3 \\ -1, & \text{for Carrier } 5 \le E_{pi} < Carrier\ 4 \\ -2, & \text{for Carrier } 6 \le E_{pi} < Carrier\ 5 \\ -3, & \text{for Carrier } 6 > E_{pi} \end{cases} \quad (16)$$

Previously there was only one set of kp and ki is used for 2-level DTC system because there is only single magnitude of voltage vector was used throughout the operation. Since the 3-level DTC system provides 3-level magnitude of voltage vector, there should be 3 set ok kp and ki to be used in 3 different operating condition in order to provide better torque regulation at every point of operating condition. For every operation condition there will be 3 different optimal torque error statuses will be selected to reduce the torque ripple. First, which is low-speed operation where torque 1-0 will be selected. Second, which is Medium-speed operation where torque 2-1 will be selected. Last will be high-speed operation where torque 3-1 will be selected. The Table 2 shows the parameter of CFTC controller for 3-level DTC system using the parameters and equation given previously. Simulation result using 6-level carrier wave with corresponding output signal. (a) reference torque with estimated torque output, (b) 6-level carrier wave with the PI compensated torque error signal (E_{pi}), (c) 7-level equivalent torque demand status (Tstat) generated by the modified CFTC block as shown in Figure 7.

Table 2. Parameters of CFTC Controller for 3-Level DTC System

Induction motor parameters	
A	382660
B	38004
σ	0.0672
K	33257
K_{tp} (low speed)	0.0031
K_{ti} (low speed)	1181.5
K_{tp} (medium speed)	0.00052794
K_{ti} (medium speed)	202.0211
K_{tp} (high speed)	0.00039613
K_{ti} (high speed)	151.581

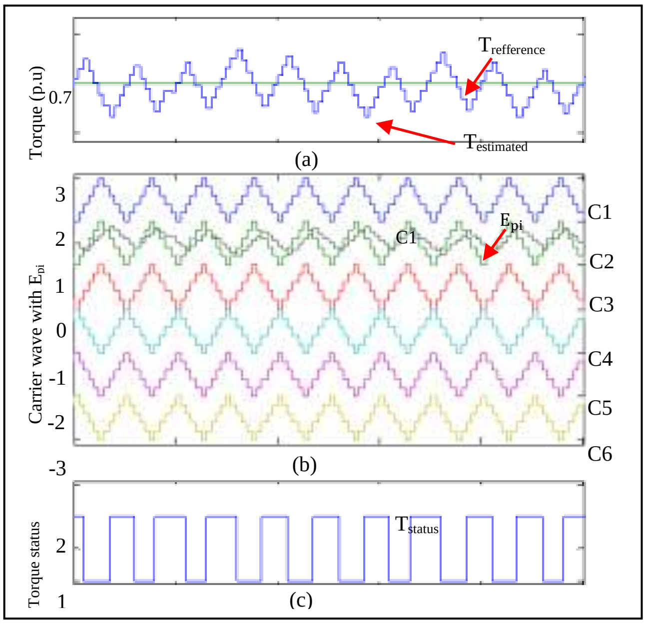
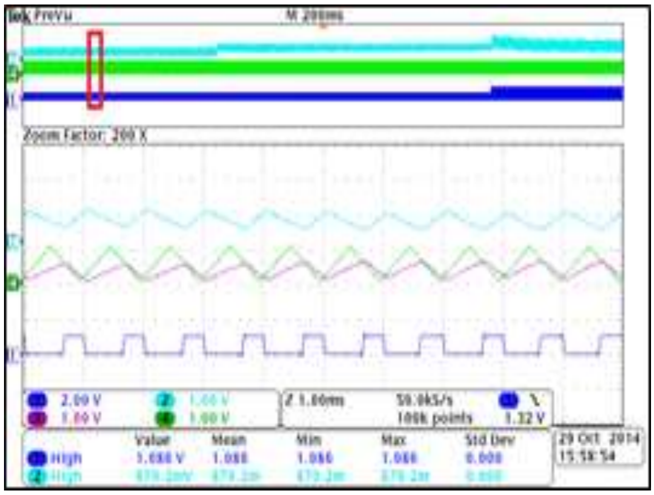


Figure 7. Simulation result using 6-level carrier wave with corresponding output signal. (a) reference torque with estimated torque output, (b) 6-level carrier wave with the PI compensated torque error signal (E_{pi}), (c) 7-level equivalent torque demand status (Tstat) generated by the modified CFTC block.

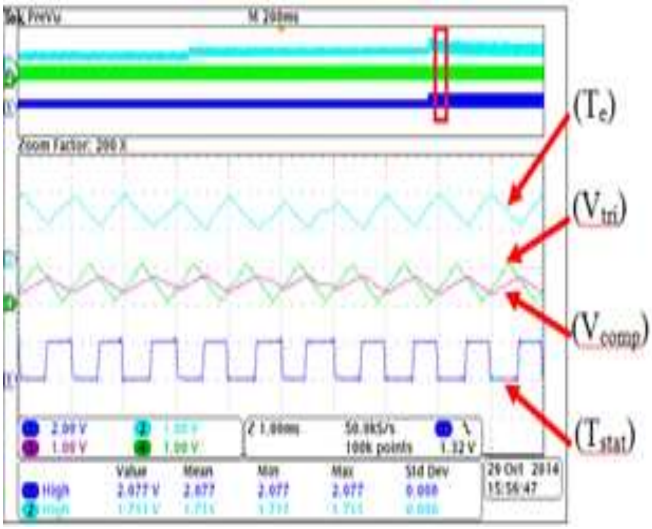
4. SIMULATION AND EXPERIMENTAL RESULT

The simulation of proposed method had been performed by using Matlab/Simulink 2011. Figure .8 shows the simulation result of the proposed method. The simulation was done in using the 3-phase induction machine model. As result of the simulation the CFTC controller was able establish in 3-level DTC system with a proper regulation of torque along the reference value. The switching frequency of the torque error status was constant (same frequency as the carrier) regardless the operation condition. The 3-level CFTC controller able to generate optimal torque status signal according to the torque demands (high, medium, and low speed).

A complete experimental set-up has been realized to verify the feasibility of the proposed method in terms of hardware implementation. The experimental set-up consists of DSPACE 1104 controller, hardware setup of 3-level CHMI and a 2 HP, two-pole induction motor. The Table 1 shows the induction motor parameter that used for both simulation and experimental setup. The control algorithm is implemented on DSPACE 1104 with sampling period of 20 µs. Figure 8 shows the experimental result of proposed method in two different operating conditions which is the high speed and low speed.



(a)



(b)

Figure 8. Experimental result of proposed method two different operating conditions which is (a) the high speed and (b) low speed. (Te) is the estimated torque ripple waveform, (Vtri) is the triangle shape carrier waveform, (Vcomp) is the compensated signal before feed in to the comparator, (Tstat) is the torque status demand signal produce by PI controller.

The lower section waveform shows zoomed view of the red square from the upper waveform with 200 times zoom factor. The torque waveform (T_e) regulate along the torque reference. It is noticeable that the gradient for both increase and decrease torque not abrupteven at high and low speed operating condition. The lower gradient of torque slopes is contributed by the 3-level CHMI topology by choosing optimal voltage vector magnitude according to the torque demand status (as shown by waveform T_{stat}). For example, the higher magnitude voltage vector is chosen for high speed operation (in Figure 8(b)) and vice versa for (in Figure 8(a)). The compensated signal (V_{comp}) is compare with triangular carrier (V_{tri}) to produce appropriate torque demand signal (T_{stat}). The selection of 3-level voltage vector is proportional to themagnitude of T_{stat}.The torque demand status (T_{stat}) in both results clearly shows the characteristic of constant in frequency (on/off period) regardless to the magnitude of torque status. As conclusion, the experimental and simulation results of proposed method able to optimized DTC performance by producing constant switching.

5. CONCLUSION

This paper has presented the implementation of constant switching method in conventional the 3-level DTC system. This system has total number of 18 active and 2 zero voltage vectors. The proposed scheme was simulated and compared with CFTC and conventional method using Matlab/Simulink. The proposed method was also tested and verified its feasibility using a complete experimental set-up.

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