A Novel Optimal PI Parameter Tuning Strategy to Improve Constant Switching Performance of Direct Torque Control

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A Novel Optimal PI Parameter Tuning Strategy to Improve Constant Switching Performance of Direct Torque Control

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ABSTRACT

This paper presents a novel method of optimal Propotional-Intergral (PI) controller's parameter tuning strategy in-order to improve the constant switching performance of 3-phase direct torque control (DTC) shceme. The DTC sheme is acknowledged to provide fast decoupled control over the torque output and stator flux via a simple control structure. However, DTC sheme has two major downsides, which are the inconsistent inverter switching frequency and high torque output ripple. The main reason that contributes to these tribulations is the usage of hysteresis comparators in order to control the output torque. The realization of PI based controller method as replacement of hyterisis controller in DTC system able to provide significant solutions to over come the fall back while retaining the simple control structure of conventional DTC. The combination usage of higher sampling controller DS1004 and also 3-level cascaded H-bridge multilevel inverters (CHMI) in this system can further minimize the output torque ripple by providing higher resolution with lower digital error and greater number of vectors. This paper presents detail explanation and calculation of optimal PI parameter tuning strategy consecutively to enhance the performance of 3-level DTC system. In order to verify the feasibility of the proposed method experimentation, the proposed method is compared with convention DTC system via simulation and experiment results.

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1. INTRODUCTION

There are two most general ac drives control schemes that are being commonly researched. One of it is field oriented control (FOC) which was proposed by F. Blaschke and the following is direct torque control (DTC) which was proposed by I. Takahashi and T. Noguchi [1, 2]. There are two major downsides of FOC compared to the DTC. Those drawbacks are the torque output is controlled indirectly and necessity of the pulse encoder [3]. FOC scheme controls the torque indirectly because controller gives priority to the flux vector. FOC scheme requires the pulse encoder in order to acquire the speed and position of the rotor. These make the DTC as an alternative scheme in which gained the interest of numerous researchers recently. This is because of its simple structure by exclusion of pulse encoder and simple algorithm with lesser dependence on motor parameters (only requires value of stator resistance R_s and phase current) [1, 4]. Recently, the utilization of multilevel inverter topology in DTC scheme has gained popularity mainly in the medium and high voltage applications. In general, there are three types of multilevel inverter 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 accessibility of larger number of voltage vectors in which allows the selection of most optimal and suitable voltage vectors in order to control flux and torque by reducing the slope magnitude of the flux and torque. Moreover, this features also contributes towards optimum switching strategies in which increases the 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 of the torque output and power switches 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 appropriate voltage vectors that is the most tangential to the stator flux gives higher rate of torque change compare to less tangential voltage vector [3]. It can be asserted 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, while the two suitable vectors become less tangential and switch more often when the flux vector travels around the middle of sectors(i.e. the rate of torque increment is lesser). 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 occurrences majorly contribute to the inconsistent switching frequency in DTC scheme. The realization of constant switching method can overcome the inconsistent switching problems in DTC scheme [3, 4, 5]. Earlier the constant frequency torque controller (CFTC) method was proposed by [3] in order to reduce the output torque ripple. In this approach, two triangular carrier waves were injected after the torque error node and two comparators were used to generate torque status. The low frequency torque error oscillations still exist even though this method reduced the torque ripple. 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.

This paper reviews the implementation of CFTC in minimizing the output torque ripple with a constant switching frequency as proposed in [3]. Some extensions of the work in utilizing CFTC are done by adding 3-level cascaded CHMI and also increase the sampling frequency of the DSpace DS1004 by utilizing C programming language. By utilizing this method, it is possible to further increase the efficiency of DTC scheme by providing constant switching, eliminating the low frequency torque error oscillation, and optimizing the voltage vector selection based on the torque demand. The detailed explanation regarding the impact of voltage vector selection in influencing the minimization in torque ripple and switching frequency are also given in this paper.

2. PRINCIPLE OF BASIC THREE PHASE DTC SHEME

The basic principles of DTC system are based on the estimations of electromagnetic torque and stator flux in d-q axis. Both of the values are estimated using the information of applied voltage vector and phase current. The behavior of three phase induction machines in DTC drives can be described in terms of space vectors by the equations that are written in stator stationary reference frame as shown below:

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

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

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

$$T_e = \frac{3}{2} P(\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd}) \tag{4}$$

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

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

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 writtenin d-q axis components. Voltage vectors for the switching patterns of the voltage source inverter S_a, S_b, and S_c (can be either 0 or 1), obtained by using d-q transfomation equation are given below:

$$v_{sd} = \frac{1}{3} V_{dc}[2S_a - S_b - S_c] \quad (7)$$

$$v_{sq} = \frac{1}{\sqrt{3}} V_{dc}[S_b - S_c] \quad (8)$$

Figure 1(a) illustrates the 3-phase inverter connected to the star winding of 3-phase machine. There are 6 switches in total where 3 upper switches and 3 lower switches. The upper switches are complementary with lower switches. When the upper switch is in ON (1) position, lower switch will be in OFF (0) position. The switching state is corresponds to [S_a, S_b, S_c]. The combinations of this switching states produces 6 non-zero active voltage vectors and two zero voltage vectors. Figure 2 (a) shows the voltage vector produce by the 2-level voltage source inverter (VSI) shown in Figure 1.

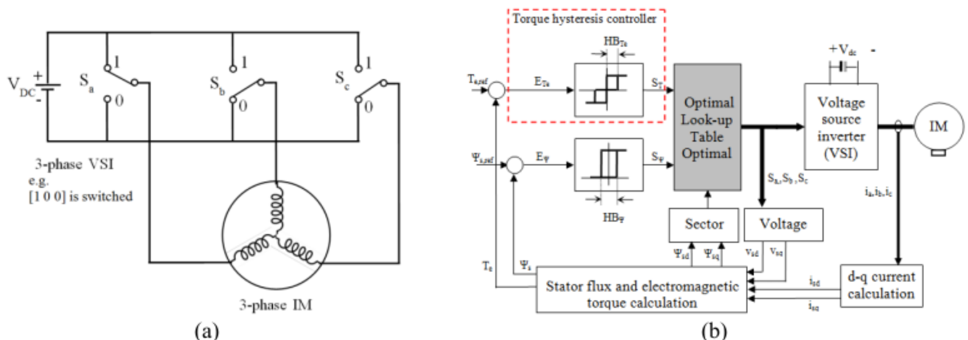


Figure 1. (a) shows Three-phase VSI connected to 3-phase machine and (b) Basic structure of DTC-hysteresis based motor drive system

Figure 1(b) shows the Basic structure of DTC-hysteresis based motor drive system as initially proposed by [1]. The voltage vector and output stator voltage are applied based on the look-up table selection of the switching states (Sa, Sb, Sc). The voltage vectors are selected based on the torque, stator flux demand and the stator flux position in d-q plane. The decisions as to whether increase or decrease the torque and/or the flux are made by their respective hysteresis comparators.

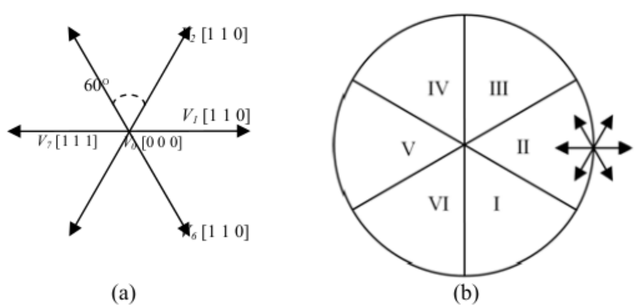


Figure 2. The selection of appropriate voltage vector (a) voltage vectors of 2-level VSI with corresponding switching combinations, and (b) 3-phase sector definition

3. IMPLEMENTATION OF CFTC CONTROLLER IN 3-LEVEL DTC SCHEME

The CFTC was implemented in DTC system in order to reduce the output torque ripple while maintaining a constant switching frequency as proposed in [3]. This is done by injecting two triangular carrier waves at the torque error node and the resultant signal are passed through two comparators. These comparators are used to generate the torque error status signal (Tstat). The CFTC (shown in Figure 3) was used to replace the torque hysteresis controller as shown in Figure 1(the area marked with red dotted line).

Figure 3(b) shows the CFTC which was modified for the purpose of implementing it in 3-level CHMI DTC system. The modified CFTC consists of six triangular generators, six comparators and a proportional-integral (PI) controller. In principle, the torque error status signal (T_{stat}) generated from the modified CFTC is similar to a 7-level hysteresis comparator, which can be in one of three states; −3,-2,-1, 0, 1, 2 or 3. There is no modification of the original look-up table is required. As a result, the simple control structure of hysteresis-based DTC can be retained. The T_{stat} signal generated by the comparators in Figure 3(b) can be described by the following equation:

$$T_{stat} = \begin{cases} 3, & \text{for Carrier } 1 \le E_{pi} \\ 2, & \text{for Carrier } 2 \le E_{pi} < Carrier\ 1 \\ 1, & \text{for Carrier } 3 \le E_{pi} < Carrier\ 2 \\ 0, & \text{for Carrier } 4 \le E_{pi} < Carrier\ 3 \\ -1, & \text{for Carrier } 5 \le E_{pi} < Carrier\ 4 \\ -2, & \text{for Carrier } 6 \le E_{pi} < Carrier\ 5 \\ -3, & \text{for Carrier } 6 > E_{pi} \end{cases} \quad (9)$$

The T_{stat} signal generated by the CFTC block will be used by the lookup table block in order to choose appropriate voltage vector according to the instantaneous torque demand. The rate of T_{stat} alternation (frequency) from increase to decrease torque demand will be same as the frequency of the carrier waves. The frequency (6.25kHz) and peak-to-peak magnitude ($Tri_{p\text{-}p}$) value of each triangle wave (the six carrier waves) was set to a same value but the carrier waveforms were offset by the magnitude of $Tri_{p\text{-}p}$. This phenomena is clearly describe by the Figure 4 where it shows relationship between the PI compensated torque error (E_{pi}), six carrier waves and T_{stat} signal which is involved in equation 9. In this simulation the E_{pi} is regulating around carrier 2 (C2) where corresponding T_{stat} signal for medium voltage vector will be generated.

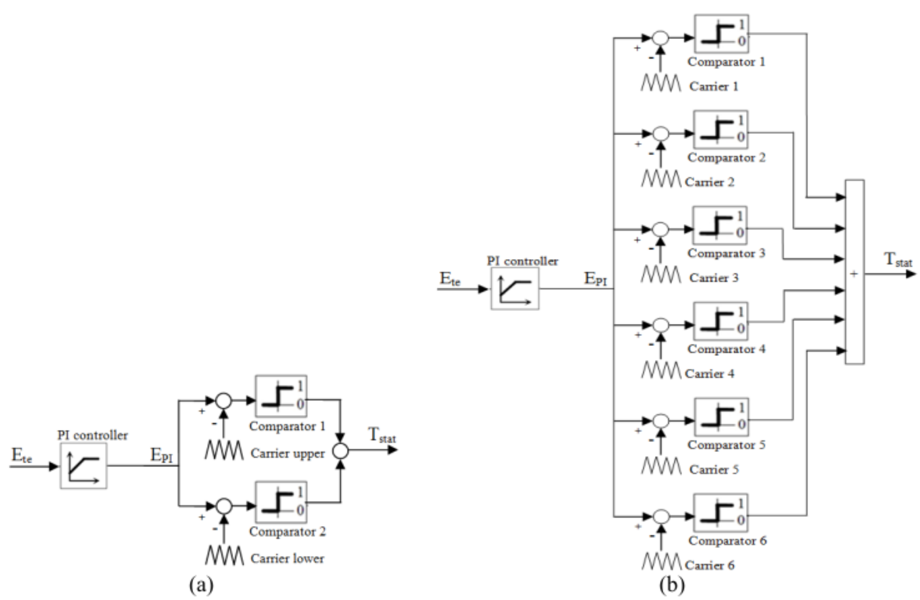


Figure 3. (a) shows the original structure of Constant Frequency Torque Controller (CFTC) and (b) shows the modified structure Constant Frequency Torque Controller (CFTC) for 3-level DTC sheme.

The selection of the optimal voltage vector depends on the demand needed in order to regulate the estimated torque according to the reference torque value. Voltage vector with higher magnitude can support higher torque demand and highspeed operation whereas voltage vector with lower magnitude can support low torque demand and low speed operation. Smaller torque slope will reduce inverter switching frequency. This advantage will contribute in minimizing the torque ripple and switching losses. For example in the case of forward torque operation, Carrier 1 will generate longest magnitude of voltage vector (high speed operation) in which followed by Carrier 2 for medium vector (medium speed operation) and Carrier 3 for lowest vector (low speed operation).

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:

$$K_{tp}^{+} \leq \frac{2\, f_{t\_tri} C_{p-p}}{-A\tau_e + Bv_s^{\Psi s} \;\; + K_t\left(\frac{\omega_e}{d} - \omega_r\right)} \tag{9}$$

and also

$$K_{tp}^{-} \leq \frac{2\, f_{t\_tri} C_{p-p}}{|-A\tau_e - K_t\omega_r|} \tag{10}$$

The K_{tp}^{+} is positive slope equation and theK_{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).

$$TF_{DTC} = \frac{Bv_s^{\Psi s}}{s + A} \tag{11}$$

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

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

$$\sigma = 1 - \frac{{L_m}^2}{L_s L_r} \tag{14}$$

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

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. Induction Machine and control parameters

Induction Machine	
Parameter	**Value**
Rated power, P	1.1 kW
Rated speed, $\omega_{m\ rated}$	2800 rpm
Stator resistance, R_s	6.1 Ω
Rotor resistance, R_r	6.2293 Ω
Stator self inductance, L_s	0.47979 mH
Rotor self inductance, L_r	0.47979 mH
Mutual inductance, L_m	0.4634 mH
Numbers of pole pairs, P	2

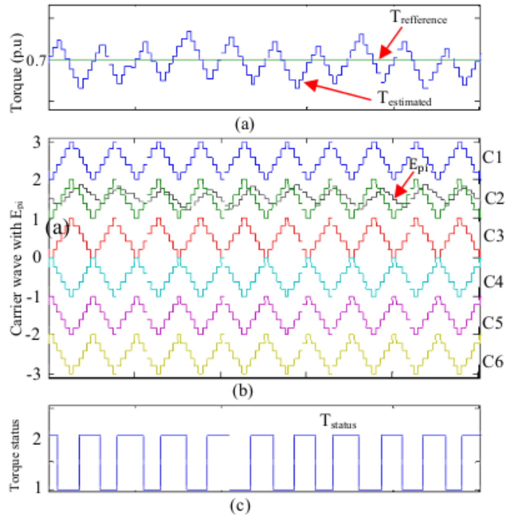


Figure 4. Simulation result using 6-level carrier wave with corresponding output signal. (a) reference torque with estimated torque output, (b) 6-level carrier wave with the PI compensated torque error signal (E_{pi}), (c) 7-levelequivalent torque demand status (Tstat) generated by the modified CFTC block

4. PROPOSED METHOD OF HIGH SAMPLING APPLICATION IN 3-LEVEL CFTC

For the proposed method, the CFTC controller was implemented in 3-level DTC system of 3-phase induction machine with higher sampling frequency and studies the effect of sampling time. Since the limitation of hardware only provides digital sampling option, there is an inevitable presents of digital sampling error. In general, digital error can be classified in two parts, which is sampling and resolution. The sampling is a process converts a continuous time signal to a discrete time signal with a defined time resolution in which is known as the sampling rate, usually expressing in Hertz (Hz) or samples per second.The sampling rate important for the reproduction of the signal depends on the sharpness of the fluctuations of the signal being sampled and processed in a controller. Figure 5 shows an illustration of a sine wave with the frequency of 8 Hz that is sampled at 100 Hz 25Hz and 10Hz. As shown the 100Hz sampling able to reproduce the original sine wave better than the other two samples.

Undersampling is known as aliasing where the original sine wave is distorted to the point unrecognizable. Aliasing can be over come by the Nyquist sampling rule where it states that the sampling rate must be at least twice the frequency of the sine wave ($f<fs/2$). More the higher sampling time, better the result will be produced. The hardware experiment was carried out using the DSpace DS1004 where it is generally use the matlab simulink model block of simulation to run as the algorithm of the DS1004 controller. A simulink model with basic 3level DTC algorithm can only run up to 22.222 kHz (45µs sample time). The 3-level CFTC based DTC simulink model only able to run upto 50µs sample time. Increase in sampling time interval will cause the controller to lack of accuracy and more prone to have overshoot or undershoot problems. The numbers of bits involve in the ADC conversion and length of the algorithm of simulink model cannot be reduced due to accuracy and reliability problems. So in order to increase the sampling frequency, the only option left is to convert the entire simulink block in to simpler C programming language. The command prompt will be used to upload the C programming file into the DS1004 controller. There are total 3 files require in order to upload program which are the .c file, .trc file and .sdf file. The C programming option will able to simplify the total algorithm without many unnecessary predefine values as the simulink model. This advantage contributes to the sampling speed of the DS10004 controller in which can run up to 50 kHz (20µs sample time).

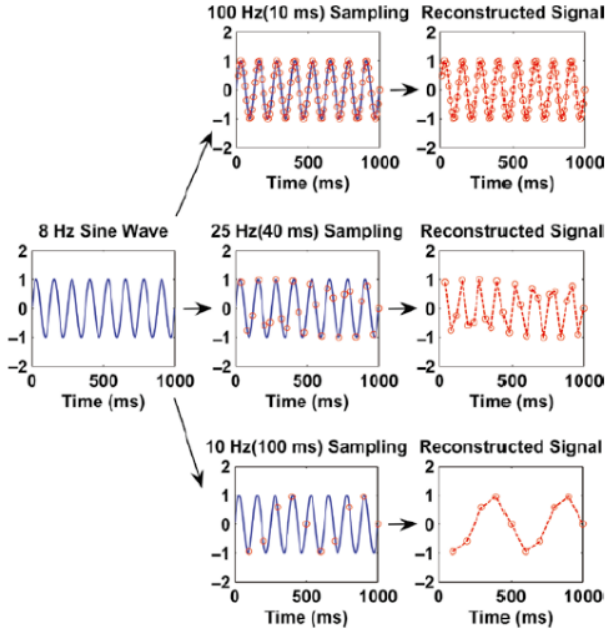


Figure 5. Simulation result shows effect of different sampling time compare to the original signal

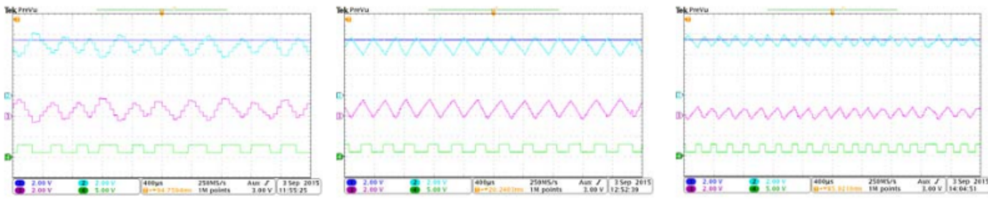
Previously there was only one set of kp and ki is used for 2-level DTC system because there is only single magnitude of voltage vector was used throughout the operation. Since the 3-level DTC system provides 3-level magnitude of voltage vector, there should be 3 set ok kp and ki to be used in 3 different 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 obtained using the parameters and equation given previously.

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

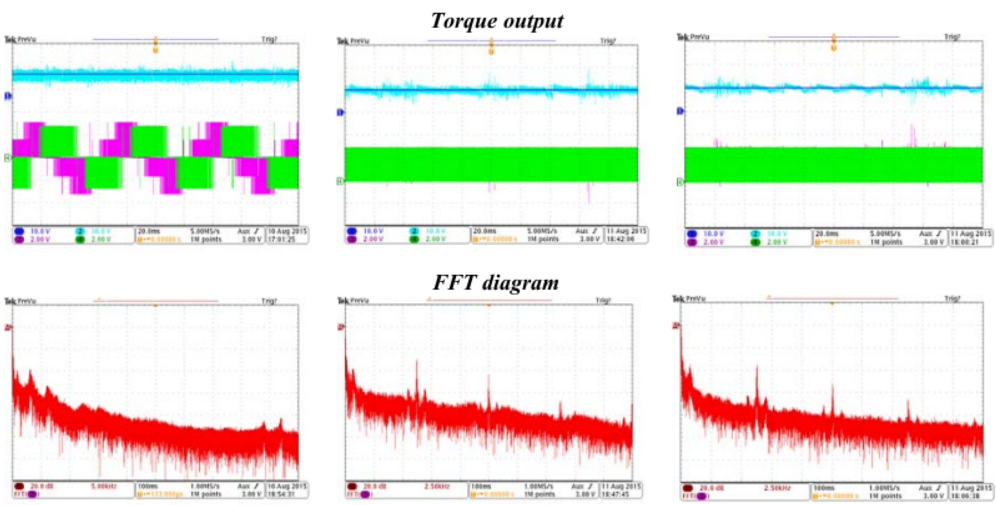
5. SIMULATION AND EXPERIMENTAL RESULT

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 1.1 HP, two-pole induction motor. The control algorithm is implemented on DSPACE 1104 with sampling period of 20 µs. Figure .6 shows the experimental result of different sampling time of 3level DTC with the torque output ripple of (a)16.45%, (b)13.71%, and (c)10.97%. This shows that the torque out ripple able to reduce by increasing the sampling frequency of the controller.



(a) (b) (c)

Figure 6. Experimental result of 3-level DTC with sampling time of (a) 50µs, (b) 20µs, and (c) 20µs with reduced bandwith



(a) (b) (c)

Figure 7. Experimental result of torque output and FFT diagram of stator current (a) 2-level DTC, (b) 2-level CFTC based DTC, and (c) proposed method of 3-level CFTC based DTC
This experiment result was carried out using 20µs sampling time

Figure 7 shows the experimental result of output torque ripple and the FFT diagram ofof the stator current in order to analysis harmonics and switching frequency between the conventional DTC and CFTC based DTC. The upper result (i) show torque ripples of (a) 17.13%, (b) 14.02%, and (c) 7.79%. The upper result (ii) shows the FFT diagram, where the switching frequency 2-level conventional DTC was not uniform and have higher THD compare to CFTC controller based DTC where both 2-level and 3-level have same switching frequency and lesser THD. Implementation of CFTC controller in DTC sheme shows significant improvement in reducing the torque ripple and also by providing constant switching frequency based on the carrier frequency.

6. 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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R. Sundram was born in 1989 in Penang, Malaysia. He received the B.Eng. degree (Hons) in Electrical Engineering from Universiti Teknikal Malaysia Melaka, Malaysia in 2012 and now he is currently pursuing the M.Sc degree in Power Electronics and Drive. His areas of research interest include Direct Torque Control of Multi Phase System and Power Electronics.

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Tole Sutikno is an expert in the field of power electronics, industrial electronics & informatics, embedded systems and electric drives. Since 2001 he has been a lecturer in Electrical Engineering Department, Universitas Ahmad Dahlan (UAD), Indonesia. He is an Associate Professor at the above University since 2008. He received his B.Eng., M.Eng. and Ph.D. degree in Electrical Engineering from Diponegoro University, Gadjah Mada University and Universiti Teknologi Malaysia, respectively. He is an Editor-in-Chief of TELKOMNIKA Telecommunication Computing Electronics and Control, and also acts as an Editor in some international journals in electrical and computer engineering, power electronics, motor drive systems and FPGA applications areas.

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