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Practice article

The optimization of torque ripple reduction by using DTC-multilevel inverter

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ABSTRACT

Direct Torque Control (DTC) scheme introduces a robust and simple control of electrical drive. However, its shortcomings such as broad torque ripple and variable switching frequency have offered several improvements like Space Vector Modulation (SVM) strategy, multilevel inverter (MLI) topology, etc. The conventional DTC which is fed by the two-level inverter has limited voltage vector, results in some difficulties to optimize the operation, especially at low operating speed. In contrast to MLI, the abundant of voltage vector has provided various amplitudes and angles that can overcome the problem of conventional DTC. Thus, this paper introduces the selected optimal voltage vector obtained from five-level Cascaded H-Bridge (CHB) inverter that employs in DTC hysteresis-based to achieve better optimization that similar to the DTC-SVM. Initially, the research work begins with an investigation on the performance comparison between a DTC hysteresis-based between two-level inverter (conventional method) and a five-level CHB inverter (proposed method). Here, a DC generator acted as a load is employed to control the operating speed instead of the speed controller (speed controller is negligible). Hence, the DTC method is optimized by minimizing the torque ripple as well as retaining the torque control capability at constant torque region on several operating speed. The selected optimal vector from the look-up table DTC of five-level CHB inverter must be dynamically appropriate to any change of torque (increased or decreased torque). For simplicity, this paper will only discuss the experimental results for both topologies of drive system. From the experimental results, it is verified that the torque ripples by the proposed method have achieved 10% and 50% reduction at high and low operating speed respectively. It is found that the DTC hysteresis-based result simpler control method than DTC-SVM while maintaining similar output performance.

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1. Introduction

In the past several years, adjustable speed drive (ASD) applies widely vector control which often classified into two [1,2]; (1) Field Oriented Control (FOC), (2) Direct Torque Control (DTC). FOC is the first establishment of vector control that introduces the flux vector decomposition technique to optimize the dynamic performance of the induction motor [3]. FOC employs the PI controller to control the d and q current components which represent for the flux and torque demand respectively [3, 4]. Hence, Pulse Width Modulation (PWM) of current regulation, frame transformer and machine parameters knowledge are the essential elements to complete the FOC scheme. Although it performs an excellent in dynamic performance, speed response and accuracy, but it suffers due to the requirement of instantaneous

position information on the coordinate transformation to select the appropriate voltage space vector [5,6].

Alternatively, DTC gains a lot of attraction in ASD due to its superior attributes such as robust control, fast torque response and simple structure rather than FOC [7]. DTC employs the hysteresis controller, commonly termed as DTC hysteresis-based achieve the regulatory scheme of torque and stator flux [8]. Despite of the method, several shortcomings have appeared such as variable switching frequency, large torque ripple and extensive sampling time, particularly in the digital system. Besides, the degradation of DTC performance may drop at low operating speed due to the utilization of conventional (two-level) inverter. There are various developments of DTC have been suggested such as stator flux improvement [9], harmonic reduction [10], linearization [11], artificial intelligent [12–14], but the well-known strategy is space vector modulation (SVM) [15–17]. DTC-SVM applies a different technique to produce the stator voltage compared to the DTC-hysteresis based. Initially, the DTC-SVM will create the stator voltage reference vector obtained from the reference of torque

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and stator flux which is further to be calculated within a sampling period. Eventually, the space vector modulator is applied to synthesize the stator voltage.

In contrast to the DTC-hysteresis based, the hysteresis controller will produce the required status obtained from the torque and stator flux reference before manipulated in the look-up table. Hence, the look-up table will create the voltage vector or switching state for the inverter. The symmetrical switching generated by DTC-SVM enables to achieve the constant switching frequency compared to the DTC-hysteresis based. Several DTC-SVM strategies have established the optimization of DTC performance which most of them focus on the method of voltage reference estimation that apply to the SVM modulator. Some of them employ the PI controller, artificial intelligence and linearization control [17–20]. The excellent performance is achieved, such as fast response, high power and torque capability of DTC. Nevertheless, the shortcomings appear such as degraded precision and consistency due to the sophisticated structure employed by the strategies as mentioned earlier.

Multilevel inverter (MLI) is also well-recognized in the DTC application as it acquires the abundant of voltage vector as proposed in [21–27]. In the conventional DTC, the stator flux and torque are controlled by the limited voltage vector that contains eight vectors produced by the two-level inverter. Oppose to MLI, the amount of voltage vector keeps increasing as the level of inverter increases. The classical MLI applied in DTC can be categorized into three types [28]: (1) Flying capacitor (FC), (2) Neutral point clamped (NPC), (3) Cascaded H-bridge (CHB). FC and NPC apply single DC-link supply while CHB applies the several isolated DC-link supply. FC has less interest in the DTC application due to the requirement of high switching frequency to balance the capacitor voltage. NPC has been dominant in DTC since it is pleasant in the high switching application, but it has to deal with the voltage balancing problem. The unbalance voltage occurred because the current has flown from/to the neutral point of the inverter. Alternatively, there are average studies of CHB in DTC application. CHB is mostly built in the modular structure and prefers in the high-level design of inverter. It can be designed either in symmetrical or asymmetrical topology, but the system must require adequate space to place the isolated DC-link supply. Most of the MLI mentioned previously is applied in the DTC-hysteresis based. Furthermore, DTC MLI has improved by using artificial control [29–31] and duty cycle control strategy [32,33]. It can also be utilized in DTC-SVM as proposed in [34–38], but its computational burden in the digital signal processing increases due to the additional voltage vector of MLI.

As for the inspiration, this paper will focus on the optimization of torque ripple reduction. It is optimized by selecting the optimal voltage vector that is appropriate in the specific speed which can produce the lowest torque ripple as well as maintain the torque capability at constant torque region or steady-state operation. The implementation is done by analyzing the DTC hysteresis-based between two-level inverter (conventional method) and five-level CHB inverter (proposed method). Here, the speed controller is ignored, but the motor load is applied to tune the speed according to the selected optimal voltage vector. It is noted that each optimal vector must be practical to the adjustment of the motor load to operate in the particular speed. The variation of voltage vectors will play an important role for the increased or decreased torque which they can be selected from the look-up table of DTC. Therefore, the DTC hysteresis-based fed by five-level CHB inverter can maintain the simple structure of DTC and minimize the complexity method compared to the DTC-SVM. Also, it enables to perform well at the low-speed region and reduce the torque ripple compared to the DTC hysteresis-based two-level inverter. In Section 2 of this paper, the brief of DTC

Table 1

The look-up table of conventional DTC scheme [8].

$\sigma_{\varphi_{stat}}$	$\sigma_{T_{stat}}$	θ_n					
		I	II	III	IV	V	VI
+1	+1	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_1$
	0	$\bar{v}_0$	$\bar{v}_7$	$\bar{v}_0$	$\bar{v}_7$	$\bar{v}_0$	$\bar{v}_7$
	−1	$\bar{v}_6$	$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$
0	+1	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_1$	$\bar{v}_2$
	0	$\bar{v}_7$	$\bar{v}_0$	$\bar{v}_7$	$\bar{v}_0$	$\bar{v}_7$	$\bar{v}_0$
	−1	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$

principle by using a two-level inverter as well as five-level CHB inverter are presented. It is followed by Section 3 that discusses the improvement of torque ripple through the comparison of DTC-SVM and DTC-hysteresis based. Then, Section 4 will explain the proposed method of torque ripple optimization for every operating speed with the selected optimal voltage vector. Further, the experimental result of both methods is discussed in Section 5. Finally, the paper is concluded in Section 6.

2. DTC basic for two-level inverter fed IM

2.1. Principal of DTC fed IM

The dynamic behavior of induction motor by referring to the stationary reference frame is stated in the space vector form as follows.

$$\bar{v}_s = R_s \bar{i}_s + \frac{d\bar{\varphi}_s}{dt} + j\omega_s \bar{\varphi}_s \quad (1)$$

$$\bar{v}_r = R_r \bar{i}_r + \frac{d\bar{\varphi}_r}{dt} - j\omega_r \bar{\varphi}_r \quad (2)$$

$$\bar{\varphi}_s = L_s \bar{i}_s + L_m \bar{i}_r \quad (3)$$

$$\bar{\varphi}_r = L_r \bar{i}_r + L_m \bar{i}_s \quad (4)$$

$$T_e = \frac{3}{2} P \bar{\varphi}_s \times \bar{i}_s \quad (5)$$

where $\bar{v}_s$ is the stator voltage vector, $\bar{\varphi}_s$ is the stator flux vector, $\bar{i}_s$ and $\bar{i}_r$ are the rotor and stator current vector respectively. Furthermore, R_s and R_r are the stator and rotor resistance respectively, while L_s , L_r and L_m are the stator, rotor and mutual inductance correspondingly. P is the number of pole pairs, whereas J is the total moment of inertia. Stator and rotor angular speed in rad/s are represented by ω_s and ω_r . The complete structure of conventional DTC is illustrated in Fig. 1. It consists of torque and flux estimators, a coupled of hysteresis comparators (three-level hysteresis torque comparator and two-level hysteresis flux comparator), look-up table, two-level inverter (Voltage Source Inverter) and three-phase induction motor.

At the beginning of studying the principal of DTC, the basic structure of conventional inverter (two-level inverter) is constructed by a single DC power source, V_{dc} and six switches which are performed as a coupled on three legs as shown in Fig. 2. The mapping voltage vector of two-level inverter consists of eight voltage vectors with their respective switching states shown in Fig. 3. The voltage vector in the look-up Table 1 is tabulated according to the principle of tangential vector to the flux component that may give the fast torque response in DTC-hysteresis based as mentioned in [8]. In the table, the voltage vectors are mapped into stator flux error status, $\sigma_{\varphi_{stat}}$, torque error status, $\sigma_{T_{stat}}$ and sector, θ_n .

2.2. Look-up table of five-level (CHB) inverter

The conventional DTC is modified by replacing the two-level inverter with a five-level Cascaded H-Bridge (CHB) inverter, as

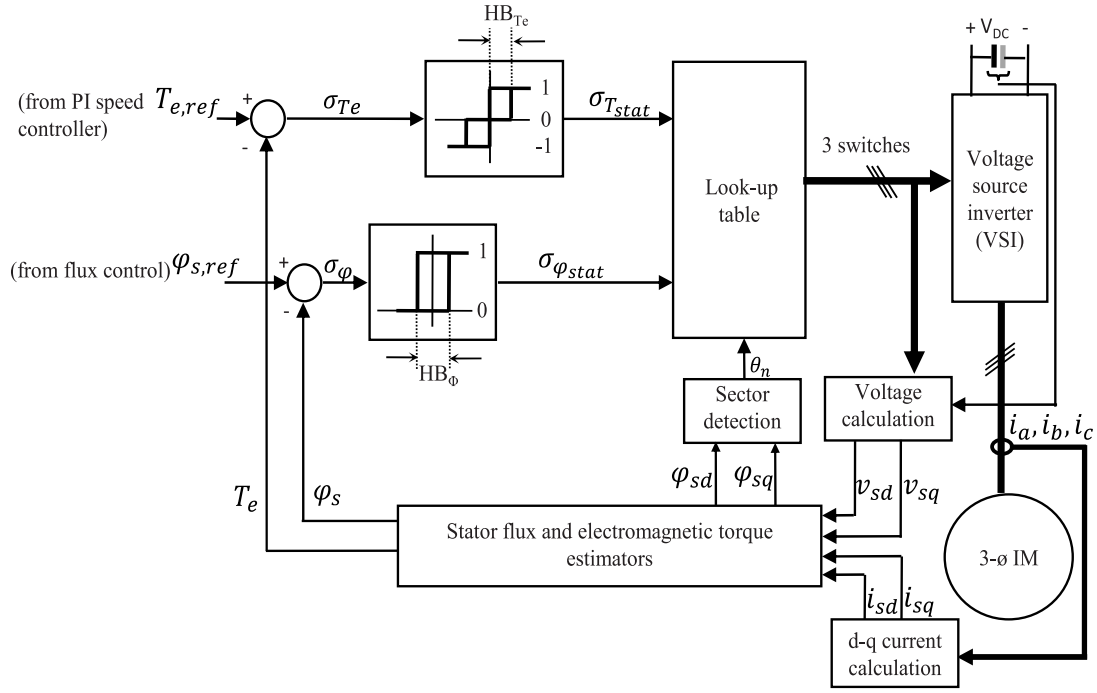


Fig. 1. The configuration of conventional DTC [8].

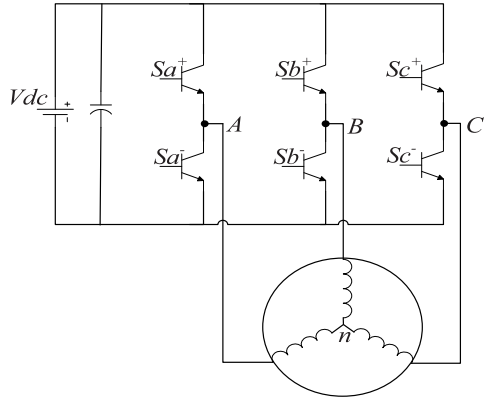


Fig. 2. Two-level inverter schematic circuit [8].

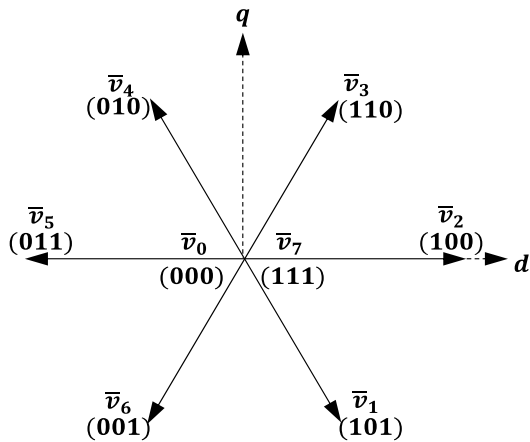


Fig. 3. The mapping voltage vector of two-level inverter circuit [8].

Table 2

The look-up table of DTC fed by five-level CHB inverter.

$\sigma_{\psi_{stat}}$	$\sigma_{T_{stat}}$	θ_n					
		I	II	III	IV	V	VI
+1	+6	$\bar{v}_{37}$	$\bar{v}_{41}$	$\bar{v}_{45}$	$\bar{v}_{49}$	$\bar{v}_{53}$	$\bar{v}_{57}$
	+5	$\bar{v}_{51}$	$\bar{v}_{47}$	$\bar{v}_{43}$	$\bar{v}_{39}$	$\bar{v}_{59}$	$\bar{v}_{55}$
	+4	$\bar{v}_{19}$	$\bar{v}_{22}$	$\bar{v}_{25}$	$\bar{v}_{28}$	$\bar{v}_{31}$	$\bar{v}_{34}$
	+3	$\bar{v}_7$	$\bar{v}_9$	$\bar{v}_{11}$	$\bar{v}_{13}$	$\bar{v}_{15}$	$\bar{v}_{17}$
	+2	$\bar{v}_{14}$	$\bar{v}_{12}$	$\bar{v}_{10}$	$\bar{v}_8$	$\bar{v}_{18}$	$\bar{v}_{16}$
	+1	$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$
	0	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$
	-1	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$
	-2	$\bar{v}_{10}$	$\bar{v}_8$	$\bar{v}_{18}$	$\bar{v}_{16}$	$\bar{v}_{14}$	$\bar{v}_{12}$
	-3	$\bar{v}_{15}$	$\bar{v}_{17}$	$\bar{v}_7$	$\bar{v}_9$	$\bar{v}_{11}$	$\bar{v}_{13}$
	-4	$\bar{v}_{31}$	$\bar{v}_{34}$	$\bar{v}_{19}$	$\bar{v}_{22}$	$\bar{v}_{25}$	$\bar{v}_{28}$
	-5	$\bar{v}_{43}$	$\bar{v}_{39}$	$\bar{v}_{59}$	$\bar{v}_{55}$	$\bar{v}_{51}$	$\bar{v}_{47}$
	-6	$\bar{v}_{53}$	$\bar{v}_{57}$	$\bar{v}_{37}$	$\bar{v}_{41}$	$\bar{v}_{45}$	$\bar{v}_{49}$
0	+6	$\bar{v}_{41}$	$\bar{v}_{45}$	$\bar{v}_{49}$	$\bar{v}_{53}$	$\bar{v}_{57}$	$\bar{v}_{37}$
	+5	$\bar{v}_{55}$	$\bar{v}_{51}$	$\bar{v}_{47}$	$\bar{v}_{43}$	$\bar{v}_{39}$	$\bar{v}_{59}$
	+4	$\bar{v}_{22}$	$\bar{v}_{25}$	$\bar{v}_{28}$	$\bar{v}_{31}$	$\bar{v}_{34}$	$\bar{v}_{19}$
	+3	$\bar{v}_9$	$\bar{v}_{11}$	$\bar{v}_{13}$	$\bar{v}_{15}$	$\bar{v}_{17}$	$\bar{v}_7$
	+2	$\bar{v}_{16}$	$\bar{v}_{14}$	$\bar{v}_{12}$	$\bar{v}_{10}$	$\bar{v}_8$	$\bar{v}_{18}$
	+1	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_1$
	0	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$	$\bar{v}_0$
	-1	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$
	-2	$\bar{v}_8$	$\bar{v}_{18}$	$\bar{v}_{16}$	$\bar{v}_{14}$	$\bar{v}_{12}$	$\bar{v}_{10}$
	-3	$\bar{v}_{13}$	$\bar{v}_{15}$	$\bar{v}_{17}$	$\bar{v}_7$	$\bar{v}_9$	$\bar{v}_{11}$
	-4	$\bar{v}_{28}$	$\bar{v}_{31}$	$\bar{v}_{34}$	$\bar{v}_{19}$	$\bar{v}_{22}$	$\bar{v}_{25}$
	-5	$\bar{v}_{39}$	$\bar{v}_{59}$	$\bar{v}_{55}$	$\bar{v}_{51}$	$\bar{v}_{47}$	$\bar{v}_{43}$
	-6	$\bar{v}_{49}$	$\bar{v}_{53}$	$\bar{v}_{57}$	$\bar{v}_{37}$	$\bar{v}_{41}$	$\bar{v}_{45}$

shown in Fig. 4. Meanwhile, Fig. 5 illustrates the mapping voltage vector of five-level CHB inverter. The total voltage vectors are supposed to produce 512 but, due to the overlapping, it reduces into 61 vectors. By using the earlier principle, the red highlighted voltage vector on the mapping vector is selected further tabulated into the look-up Table 2.

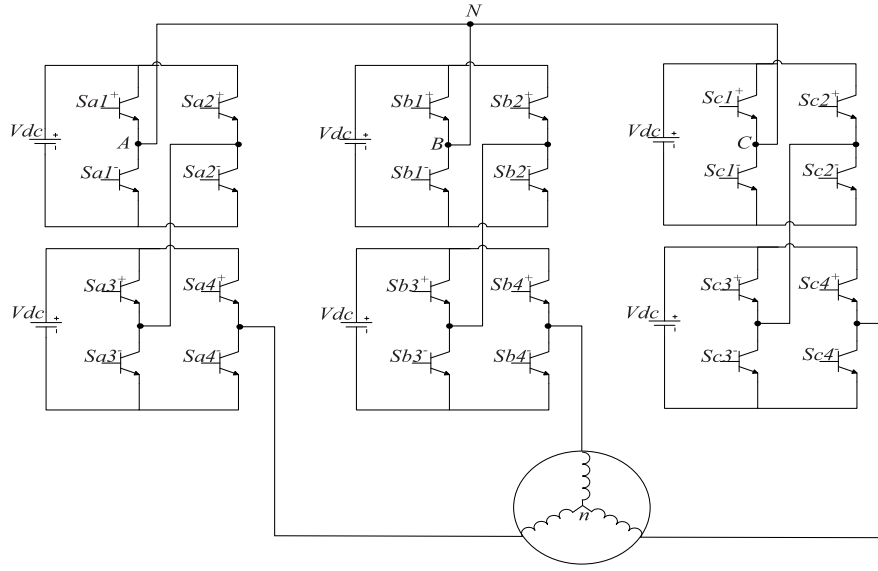


Fig. 4. The configuration circuit of five-level CHB inverter.

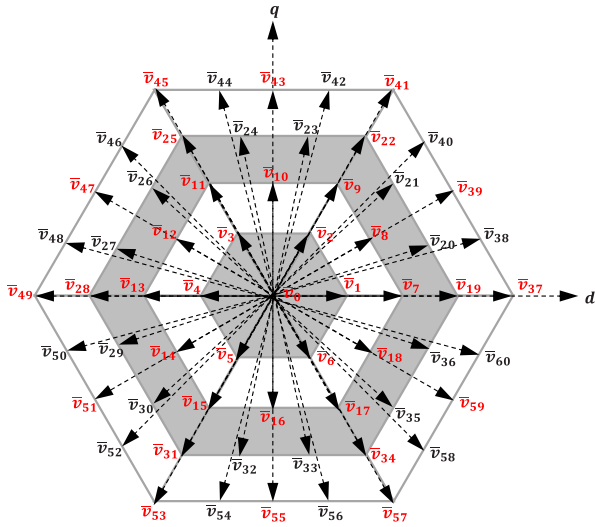


Fig. 5. The mapping vector of five-level CHB inverter.

3. The comparison of torque ripple between DTC-SVM and DTC hysteresis-based

In the DTC application, the high torque ripple occurs mainly caused by the inconsistency of switching frequency in the hysteresis comparators i.e., torque comparator [39,40]. On the basis, the slope of torque contains several variables, such as stator voltage, speed, stator flux, and rotor flux. Furthermore, the uncontrollable operating speed may contribute to the unpredictable switching frequency, thus difficult to optimize the DTC performance [6]. In DTC-SVM, the torque ripple can be reduced and optimized by synthesizing the desired voltage based on the subdivided voltage vector switching period in the space vector. In contrast to the hysteresis based-DTC, the principle of the synthesized voltage vector is neglected. However, the torque ripple can be improved by selecting the appropriate voltage vector provided by various voltage vectors available in MLI [41,42].

3.1. SVM strategy applied in DTC

SVM strategy to reduce the torque ripple in DTC is widely used in [15–20,34–38]. The DTC-SVM strategy is employed by controlling the decouple of electromagnetic torque and stator flux by using the PI controller to produce the reference voltage (d-q component) which is then sampled and synthesized in the space vector modulator. In the modulator, the reference voltage is synthesized based on the particular voltage vector with stipulated switching time. In the two-level inverter, the reference voltage is placed in one of the sectors, as shown in Fig. 6(left). Thus, it is located between two adjacent vectors of $\bar{v}_{L2}$ and $\bar{v}_{L3}$ as well as the zero vector of $\bar{v}_{z0}$.

Meanwhile, in MLI, it is observed that the reference voltage is placed in one of the four small triangular regions enclosed by one triangular sector, as shown in Fig. 6(right) [36]. It is known that two-level inverter generates only one amplitude but the different angle of six active vectors. Oppose to MLI, and it generates various amplitudes and angle of several active vectors. Therefore, the coordination of adjacent and zero vector is more emphasized regardless of the level of vector amplitude in MLI. By transferring the reference voltage from the two-level inverter into MLI, the new vectors performed such two adjacent vectors are $\bar{v}_{L3}$ and $\bar{v}_{M2}$ while zero vector is $\bar{v}_{S3}$. It is proved that the position of the reference voltage vector in MLI is more optimized than a two-level inverter. Subsequently, the duty cycle is computed to generate the symmetrical switching of SVPWM with their respective interval of switching time. Hence, the lower switching stress and high reduction of torque ripple and switching frequency are achieved in MLI.

Thus, the position of reference voltage vector for both inverters are kept similar to analyze the torque ripple by using SVM between two-level and three-level inverter. Furthermore, the switching status produced by the realization of duty ratios and the triangular waveform is the same to generate the on-duration switching for each voltage vector. As illustrated in Fig. 7, in one sampling period, the sequence of voltage vector produced by the two-level inverter is $\bar{v}_{z0} \rightarrow \bar{v}_{L2} \rightarrow \bar{v}_{L3} \rightarrow \bar{v}_{z0} \rightarrow \bar{v}_{L3} \rightarrow \bar{v}_{L2} \rightarrow \bar{v}_{z0}$ while the sequence by the three-level inverter is $\bar{v}_{S3} \rightarrow \bar{v}_{M2} \rightarrow \bar{v}_{L3} \rightarrow \bar{v}_{S3} \rightarrow \bar{v}_{L3} \rightarrow \bar{v}_{M2} \rightarrow \bar{v}_{S3}$. For example, the phase 'a' voltage interprets the switching vectors sequence for both inverters. From the result of phase voltage, the three-level inverter reveals the lower dv/dt than two-level inverter despite

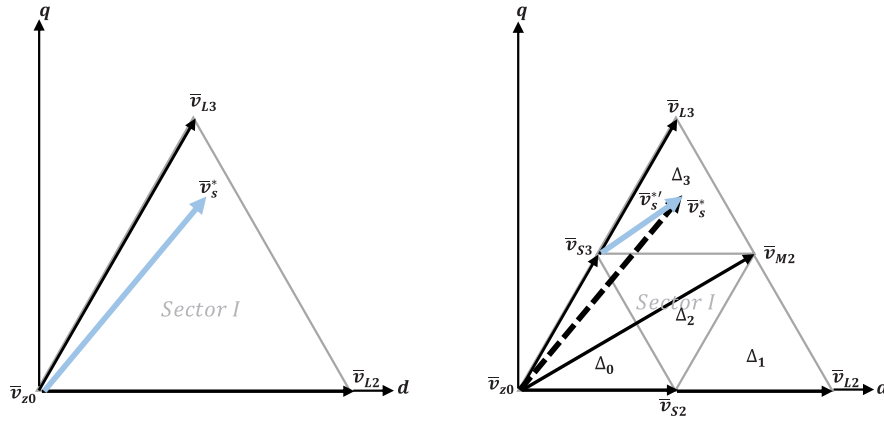


Fig. 6. The comparison location of reference voltage in SVPWM between two-level (left) and three-level inverter (right) [36].

the abundant voltage vector. Moreover, it supports the reduction of torque ripple by decreasing the rate of torque change by using a three-level inverter. Nevertheless, each voltage vector plays an essential part to complete the switching cycle that leads to the utilization of high switching frequency in DTC-SVM.

3.2. Torque ripple in hysteresis based multilevel inverter

The DTC drive system gains a lot of attention due to its high capability to control the instantaneous of torque and flux regardless of selecting an optimized voltage vector. The high demand for torque results in the higher torque error in the hysteresis torque comparator. Thus, a single torque error status produced by the hysteresis comparator generates an increase in torque. Meanwhile, the stator flux regulated by flux hysteresis must flow in a circular path performed by two active voltage vectors. Since the two-level inverter applies a single option controller, the torque or/and flux is produced at the same rate of increase using a single magnitude of active vectors. However, high switching frequencies and torque ripple can occur, particularly at extreme operating conditions (low-speed) due to the inappropriate selection of voltage vector in the DTC system.

In contrast to MLI, the various selection can be implemented from the great voltage vector to optimize the DTC performance. In the DTC hysteresis-based, the voltage vector is selected based on the tangential vector to the flux component [8]. Simultaneously, different from the DTC-SVM strategy, it has to implement the principle of the nearest voltage vector concept [34] to optimize the performance. Fortunately, the switching frequencies and torque ripple in hysteresis-based can be minimized using the optimal voltage vector at the various speed operations. In DTC hysteresis-based drives, the effect of voltage vectors on torque is studied by the torque equation as expressed in stator and rotor flux magnitude as given,

$$T_e = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} (\varphi_s) (\varphi_r) \sin \delta_{sr} \quad (6)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (7)$$

where the instantaneous torque related to the stator flux, φ_s and rotor flux, φ_r vector. Meanwhile, the parameter δ_{sr} is the load angle between the stator and rotor flux vector that affects the dynamic torque performance. The stator flux, φ_s and rotor flux vector, φ_r connection is represented in s-domain, as stated in (8).

$$\bar{\varphi}_r^r(s) = \frac{L_m/L_s}{1 + s\tau_r\sigma} \cdot \bar{\varphi}_s^r(s) \quad (8)$$

where the rotor constant $\tau_r = L_r/R_r$. At the time constant τ_r , the movement of the rotor flux vector, φ_r delays from the stator flux, φ_s as indicated in (8). Also, the first order at (8) creates the low pass filter action, which causes the irregular movement of the stator flux vector at the continuous rotation of the rotor flux vector. From (1), the stator resistance is assumed too small and $\omega_s = 0$, thus, the expression can be simplified as stated in (9).

$$\Delta\varphi_s \approx v_s \Delta t \quad (9)$$

However, in (9), the instantaneous angular velocity of stator flux becomes inconsistent because of the time switching rate of voltage vectors. On the other hand, the analysis of torque control behavior $T_{e,n}$, realized using the applied voltage vector on different speed operations represents (10).

$$\frac{dT_{e,n}}{dt} = C \bar{\varphi}_{r,n} [V_{s,n} \sin(\alpha_{sk,n} - \theta_{r,n-1}) - \omega_s \bar{\varphi}_{s,n-1} \cos(\theta_{s,n-1} - \theta_{r,n-1})] \quad (10)$$

where $V_{s,n}$ and $\alpha_{sk,n}$ are the magnitude and angle of applied voltage respectively, $\bar{\varphi}_{s,n-1}$ is the stator flux vector at sample time $(n-1)$, $\bar{\varphi}_{r,n}$ is the rotor flux vector at sample time n , C is constant, $\theta_{r,n-1}$ and $\theta_{s,n-1}$ are the angle of rotor flux and stator flux respectively at sample time $(n-1)$. Fig. 8 illustrates the suitable voltage vector that employs in the stator flux vector control for tracking its reference. From the figure, the voltage vector employment produces the desired load angle performed by the different angle between the stator and rotor flux vector, where the stator flux vector leads to the rotor flux vector. In simplified, the torque performance can be controlled by controlling the stator flux vector movement and the rate of change of load angle.

Fig. 9 interprets the variation of voltage vector provided by MLI that can reduce the torque ripple and maintain the torque regulation at certain operation speed. The voltage vector with the flux decrease is represented by $\bar{v}_{L2}$ (long vector), $\bar{v}_{M2}$ (medium vector) and $\bar{v}_{S2}$ (short vector). In contrast, the voltage vector with the flux increase is represented by $\bar{v}_{L3}$ (long vector), $\bar{v}_{M3}$ (medium vector) and $\bar{v}_{S3}$ (short vector). It is noticed that the voltage vector $\bar{v}_{L2}$ and $\bar{v}_{S2}$ have the same direction, but both have a different direction to $\bar{v}_{M2}$. At the same time, the zero vector $\bar{v}_{20}$ is positioned at the reference of the circular path. It is noted that the selection of voltage vector can be analyzed and compared according to Fig. 10. The torque ripple is high from the figure when it applies the long and zero voltage vector to increase and decrease the torque. Thus, the medium and short voltage vectors are proposed to increase and decrease torque respectively to minimize the torque ripple and switching frequency of DTC. It is observed that the torque ripple performance is reflected by the

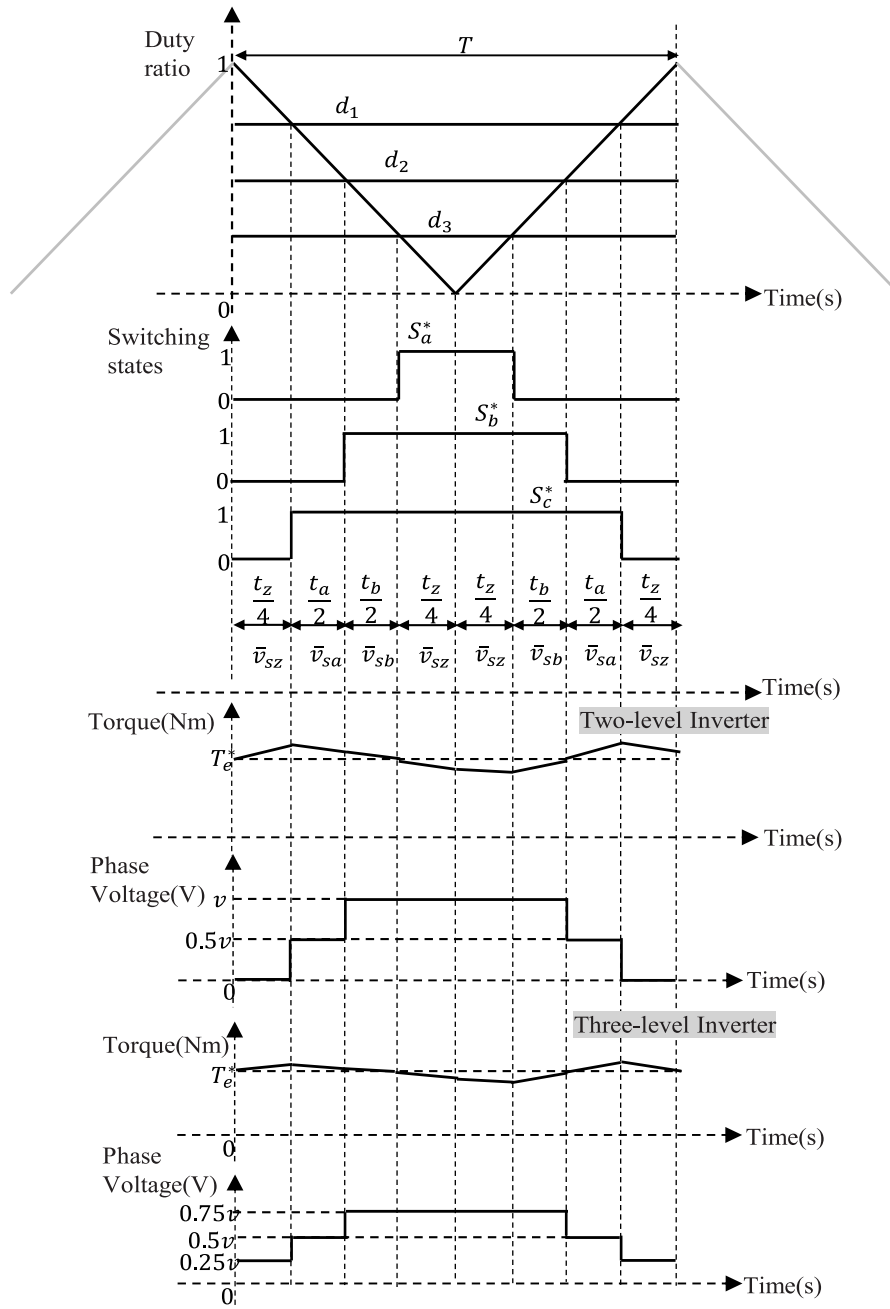


Fig. 7. The comparison of torque variation influenced by the generation and effect of switching vectors between two-level and three-level inverter.

different status and duty ratio of torque error status in Fig. 10. Hence, only two vectors will be chosen in one sampling time which remains the simple characteristic of DTC hysteresis-based rather than DTC-SVM. Therefore, the selection of voltage vector in MLI can be diverse as long as the estimated torque is still well regulated on its reference.

4. The proposed method of optimization torque ripple

Reduced torque ripple becomes the aim of developing the DTC performance. The event will be focused during a steady-state or constant torque region where the variety of speeds is utilized to realize the most optimal voltage vector to be employed. The selection of voltage vector must consider the prevention of extreme conditions of torque change and the sustainable control of torque. The abundant voltage vector preserved by the five-level

CHB allows the DTC to be employed at various speeds. Due to the variety of voltage vector amplitudes, it offers the several options to reduce the switching frequency and frequent change of torque error. The look-up of DTC fed by five-level inverter tabulated in Table 2 is referred to as where the classifications of voltage vectors are defined according to the amplitude of voltage vector and torque error status, σ_{Tstat} as follows.

- Shortest voltage vector (σ_{Tstat} is +1 or -1) = $\bar{v}_1, \bar{v}_2, \bar{v}_3, \bar{v}_4, \bar{v}_5, \bar{v}_6$
- Short voltage vector (σ_{Tstat} is +2 or -2) = $\bar{v}_8, \bar{v}_{10}, \bar{v}_{12}, \bar{v}_{14}, \bar{v}_{16}, \bar{v}_{18}$
- Medium-short voltage vector (σ_{Tstat} is +3 or -3) = $\bar{v}_7, \bar{v}_9, \bar{v}_{11}, \bar{v}_{13}, \bar{v}_{15}, \bar{v}_{17}$
- Medium-long voltage vector (σ_{Tstat} is +4 or -4) = $\bar{v}_{19}, \bar{v}_{22}, \bar{v}_{25}, \bar{v}_{28}, \bar{v}_{31}, \bar{v}_{34}$

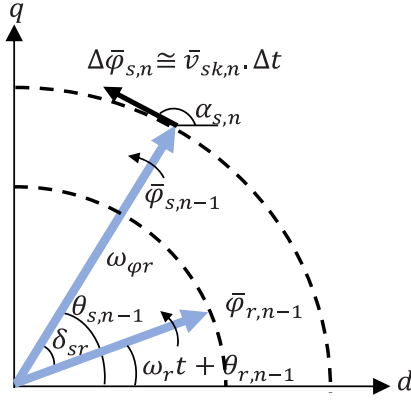


Fig. 8. Stator flux vector control for tracking its reference with a suitable voltage vector application.

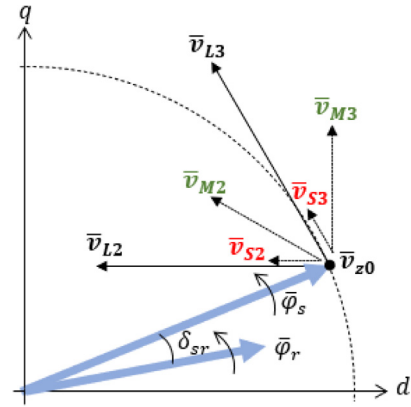


Fig. 9. The applications of voltage vector in MLI to control the reference of circular path in DTC.

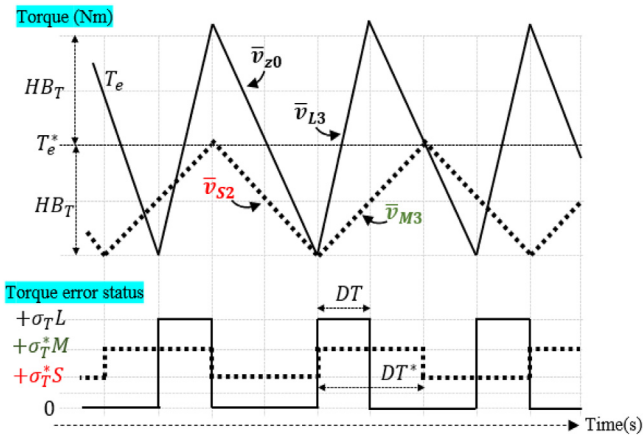


Fig. 10. The comparison of torque and torque error status performance by the selection of particular vector in DTC hysteresis-based MLI.

- e. Long voltage vector (σ_{Tstat} is +5 or -5) = $\bar{v}_{39}, \bar{v}_{43}, \bar{v}_{47}, \bar{v}_{51}, \bar{v}_{55}, \bar{v}_{59}$
- f. Longest voltage vector (σ_{Tstat} is +6 or -6) = $\bar{v}_{37}, \bar{v}_{41}, \bar{v}_{45}, \bar{v}_{49}, \bar{v}_{53}, \bar{v}_{57}$

However, only the most optimal voltage vector will be selected at a particular speed in the proposed method. The speed is adjusted by controlling the motor load that ignores the additional

control speed loop. The operating speed is classified into six levels; (1) speed_1, (2) speed_2, (3) speed_3, (4) speed_4, (5) speed_5, and (6) speed_6. During analysis, the conventional DTC that applies two-level inverter will be represented by the longest amplitude voltage vector with the torque error status, $\sigma_{Tstat} = +6$ and zero voltage vector with the torque error status, $\sigma_{Tstat} = 0$ for the increase and decrease torque respectively. Hence, the comparison between conventional method or DTC using a two-level inverter (non-optimal switching) and a proposed method using a five-level CHB inverter (optimal switching) for various speeds is discussed in the following section. The operating speed is attached with their particular figure to represent the comparison between conventional method (solid line) and proposed method (dotted line).

4.1. Operating speed_1

Fig. 11(a) shows the control operation of torque and flux at operating speed_1. In the conventional DTC, the active vector is solely based on a single option where the drastic torque increase ($T_e \uparrow \uparrow \uparrow$) is presented using the longest amplitude voltage vector. It is due to the increment of load angle δ_{sr} , which is greater and tends to apply the reverse or inappropriate vector that can cause to the sharp decrease of torque. The greater load angle is also caused by the increased rate of stator flux ($\varphi_s \uparrow \uparrow \uparrow \uparrow \uparrow$). Thus, to improve the performance, the proposed method has suggested the shortest amplitude of the active vector ($\sigma_{Tstat} = +1$) to decelerate the increment of load angle, δ_{sr} directly reduce the torque ($T_e \uparrow$).

For decreasing the torque, the proposed method has applied a similar vector like the conventional DTC, a zero-voltage vector ($\sigma_{Tstat} = 0$). As for a reason, the smaller decrease of load angle may cause the lower decrease rate of torque ($T_e \downarrow$), as proven by the reduction absolute value term in (10). The term is irrelevant when the speed decreases. By observing Fig. 11(a), the proposed voltage vector allows the movement of the stator flux vector to increase slowly ($\varphi_s \uparrow$), decrease slowly ($\varphi_s \downarrow$) or halt ($\varphi_s \downarrow \uparrow$).

4.2. Operating speed_2

In this case, shown in Fig. 11(b), the rapid increase torque remains occurred by the conventional DTC. However, there are two voltage vector options in the proposed method, either the shortest or short amplitude voltage vector. Thus, the short voltage vector ($\sigma_{Tstat} = +2$) is suggested to prevent the extreme condition of increased torque that can extend the stator flux angular frequency and sustain torque control ($T_e \uparrow$). Thus, the ability of stator flux from the longest amplitude voltage vector reduces ($\varphi_s \uparrow \uparrow \uparrow \uparrow \uparrow$). Meanwhile, it is difficult for the shortest amplitude voltage vector to accomplish the torque demand due to the restricted increased stator flux angular frequency to retain the desired load angle, δ_{sr} . It is noticed that the longest and shortest amplitude has the same angle vector, but both have different angle vector with a short amplitude of voltage vector.

At decrease torque, two options are also suggested either zero or shortest amplitude voltage vector. The zero-voltage vector brings the torque performance worst due to the rate of load angle decreasing drastically where the halt of the stator flux vector (by assumption) is approached continuously by the rotor flux vector. As a result, the shortest amplitude voltage vector ($\sigma_{Tstat} = +1$) is suggested to minimize the rate load angle and torque ($T_e \downarrow$) in the proposed method. It is followed by controlling the stator flux whether to increase (slowly $\varphi_s \uparrow$ or rapidly $\varphi_s \uparrow \uparrow \uparrow$) or to decrease (slowly $\varphi_s \downarrow$ or rapidly $\varphi_s \downarrow \downarrow$) as long as it is enclosed in the circular reference trajectory.

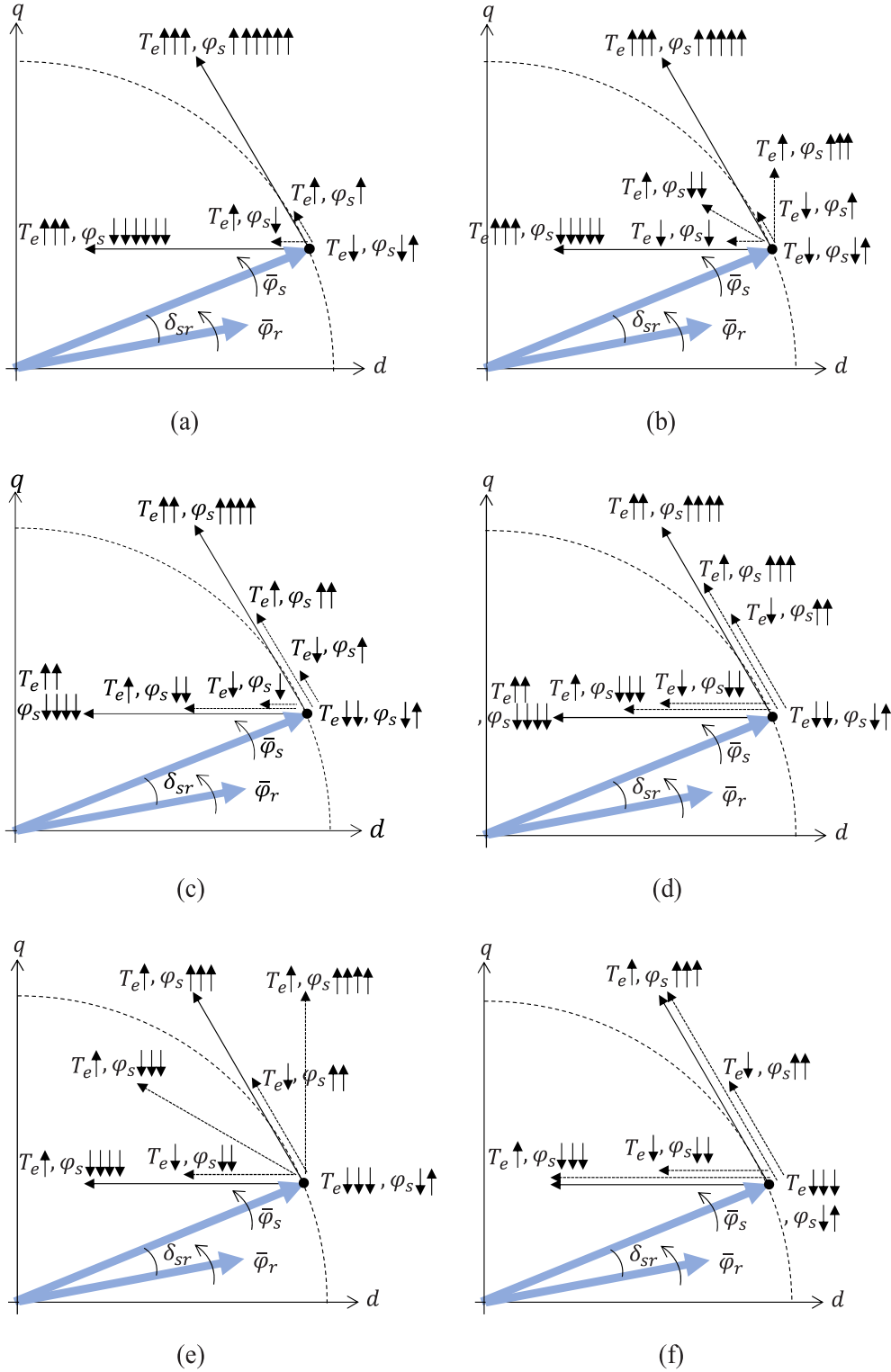


Fig. 11. The selection of voltage to control the operation of torque and flux in the conventional (solid line) and proposed (dotted line) DTC method at operating: (a) speed_1, (b) speed_2, (c) speed_3, (d) speed_4, (e) speed_5 and (f) speed_6.

4.3. Operating speed_3

In the conventional DTC, the torque increases moderately ($T_e \uparrow \uparrow$) due to the reduction term (10) becomes slightly greater on this operating speed shown in Fig. 11(c). Plus, the response of stator flux is slightly dropped ($\varphi_s \uparrow \uparrow \uparrow$). However, the switching

frequency is still high in the conventional DTC. The medium-short amplitude voltage vector ($\sigma_{T_{stat}} = +3$) is employed in the proposed method by ignoring the rest due to they cannot fulfill the torque and speed demand ($T_e \uparrow$). Thus, it allows the increment of rotor flux angular frequency to make the stator flux vector to have a moderate speed. It is necessary for maintaining the desired load angle, δ_{sr} .

On the other hand, the rapid torque reduction ($T_e \downarrow\downarrow$) occurs in the conventional DTC. Thus, the proposed method has employed the shortest amplitude voltage vector ($\sigma_{T_{stat}} = +1$) similar to the former operating speed for decreasing the torque ($T_e \downarrow$). The zero-voltage vector is terminated as explained previously. While the short voltage vector is also not suggested because of the extremely increasing rate of load angle that could not promise to reduce the torque. The variation of stator flux is slightly changed from the previous case when the stator flux increases (slowly $\varphi_s \uparrow$ or rapidly $\varphi_s \uparrow\uparrow$) and decreases (slowly $\varphi_s \downarrow$ or rapidly $\varphi_s \downarrow\downarrow$).

4.4. Operating speed₄

There is no much difference in the control operation of torque and flux between the previous case (Fig. 11(c)) and the current case (Fig. 11(d)). Both cases operate at medium speed, but the previous case bias to the slow speed while the current case bias to the high speed. Similar to the former operating speed, the torque increases moderately, and the stator flux response maintains in the conventional DTC. Therefore, the proposed method has employed the medium-long amplitude voltage vector ($\sigma_{T_{stat}} = +4$) which has increased the desired load angle, δ_{sr} and angular frequency by raising the speed rotation of the stator flux vector due to another medium speed level.

In contrast to the decreased torque, the medium-short amplitude voltage vector ($\sigma_{T_{stat}} = +3$) is the best potential to minimize the rate of load angle compared with the short and shortest amplitude voltage vector in the proposed method. Therefore, the stator flux at the current speed has shown the moderate rate variation of increase (slowly $\varphi_s \uparrow\uparrow$ or highly $\varphi_s \uparrow\uparrow\uparrow$) and decrease (slowly $\varphi_s \downarrow\downarrow$ or highly $\varphi_s \downarrow\downarrow\downarrow$).

4.5. Operating speed₅

At speed₅ operation speed, specifically to the increased torque, as illustrated in Fig. 11(e), the torque in the conventional DTC is not extremely increased ($T_e \uparrow$), as expressed in (10). However, to reduce the torque ripple and switching frequency, the long amplitude voltage vector ($\sigma_{T_{stat}} = +5$) is employed in the proposed method. At this moment, the rotation of the stator flux vector has to increase ($\varphi_s \uparrow\uparrow\uparrow\uparrow$) and retain the desired load angle, δ_{sr} . The mentioned event occurs because the long voltage vector has a different angle to the longest voltage vector.

Alternatively, to the decreased torque, it is noticed that the rapid torque reduction ($T_e \downarrow\downarrow\downarrow$) occurred by conventional DTC, as shown in Fig. 11(e). Similar to the former case, the medium-short amplitude of voltage vector is applied in the proposed method. The medium-long vector is not suggested because it brings the uncertainty to reduce the torque and may produce the greatest rate of increase load angle. There is a slight increase (slowly $\varphi_s \uparrow\uparrow$ or highly $\varphi_s \uparrow\uparrow\uparrow\uparrow$) and a decrease (slowly $\varphi_s \downarrow\downarrow$ or highly $\varphi_s \downarrow\downarrow\downarrow$) of stator flux variation.

4.6. Operating speed₆

As shown in Fig. 11(f) for increasing the torque, both methods (proposed and conventional) have applied the longest amplitude voltage vector $\sigma_{T_{stat}} = +6$ at operating speed₆. Therefore, the increased torque is not harshly occurred as the greatest reduction term is produced by (10). Furthermore, the torque control capability can be maintained by the sustained desired load angle, δ_{sr} and the stator flux vector ($\varphi_s \uparrow\uparrow\uparrow$).

In contrast, for decreasing the torque, the proposed method has employed the medium-short amplitude of voltage vector ($\sigma_{T_{stat}} = +3$) where it can produce the smallest desired load

angle, δ_{sr} rather than the rest. It is more preferred than the rest because it is the best optimal to decrease the torque, and its rate to increase the load angle is the lowest. Meanwhile, the stator flux at the speed₆ operating speed has shown the higher rate variation of increase (slowly $\varphi_s \uparrow\uparrow$ or highly $\varphi_s \uparrow\uparrow\uparrow$) and decrease (slowly $\varphi_s \downarrow\downarrow$ or highly $\varphi_s \downarrow\downarrow\downarrow$).

4.7. The summary of optimal voltage vector

For further analysis, the configuration of conventional DTC is modified into the proposed method, as shown in Fig. 12. It introduces a new modification torque status block together with the employment of five-level CHB into inverter and look-up table of DTC. It keeps maintained the three-level hysteresis torque and two-level hysteresis flux comparator as a coupled comparator. The modified block will modify the torque error status, $\sigma_{T_{stat}}$ into the new error torque status, $\sigma_{T_{stat}}^*$ based on the adjustment of speed, ω through the definition status as described earlier. The motor load will control the induction motor speed, ω that can accomplish the requirement of new error torque status, $\sigma_{T_{stat}}^*$ to select the optimal voltage vector provided by the five-level look-up table. Hence, the look-up table will generate the switching states to run the five-level inverter. Therefore, the summary of the optimal voltage vector to optimize the torque ripple reduction in the proposed method for each operating speed is described as follows.

Operating Speed₁

- Increase torque – shortest voltage vector ($\sigma_{T_{stat}}^* = +1$ or -1)
- Decrease torque – zero voltage vector ($\sigma_{T_{stat}}^* = 0$)

Operating Speed₂

- Increase torque – short voltage vector ($\sigma_{T_{stat}}^* = +2$ or -2)
- Decrease torque – shortest voltage vector ($\sigma_{T_{stat}}^* = +1$ or -1)

Operating Speed₃

- Increase torque – medium-short voltage vector ($\sigma_{T_{stat}}^* = +3$ or -3)
- Decrease torque – shortest voltage vector ($\sigma_{T_{stat}}^* = +1$ or -1)

Operating Speed₄

- Increase torque – medium-long voltage vector ($\sigma_{T_{stat}}^* = +4$ or -4)
- Decrease torque – medium-short voltage vector ($\sigma_{T_{stat}}^* = +3$ or -3)

Operating Speed₅

- Increase torque – long voltage vector ($\sigma_{T_{stat}}^* = +5$ or -5)
- Decrease torque – medium-short voltage vector ($\sigma_{T_{stat}}^* = +3$ or -3)

Operating Speed₆

- Increase torque – longest voltage vector ($\sigma_{T_{stat}}^* = +6$ or -6)
- Decrease torque – medium-short voltage vector ($\sigma_{T_{stat}}^* = +3$ or -3)

5. Experimental result and discussion

To analyze the performance of the DTC scheme between the non-optimal switching applied by using two-level inverter (conventional method) and optimal switching applied by five-level CHB inverter (proposed method), the experimental test has been

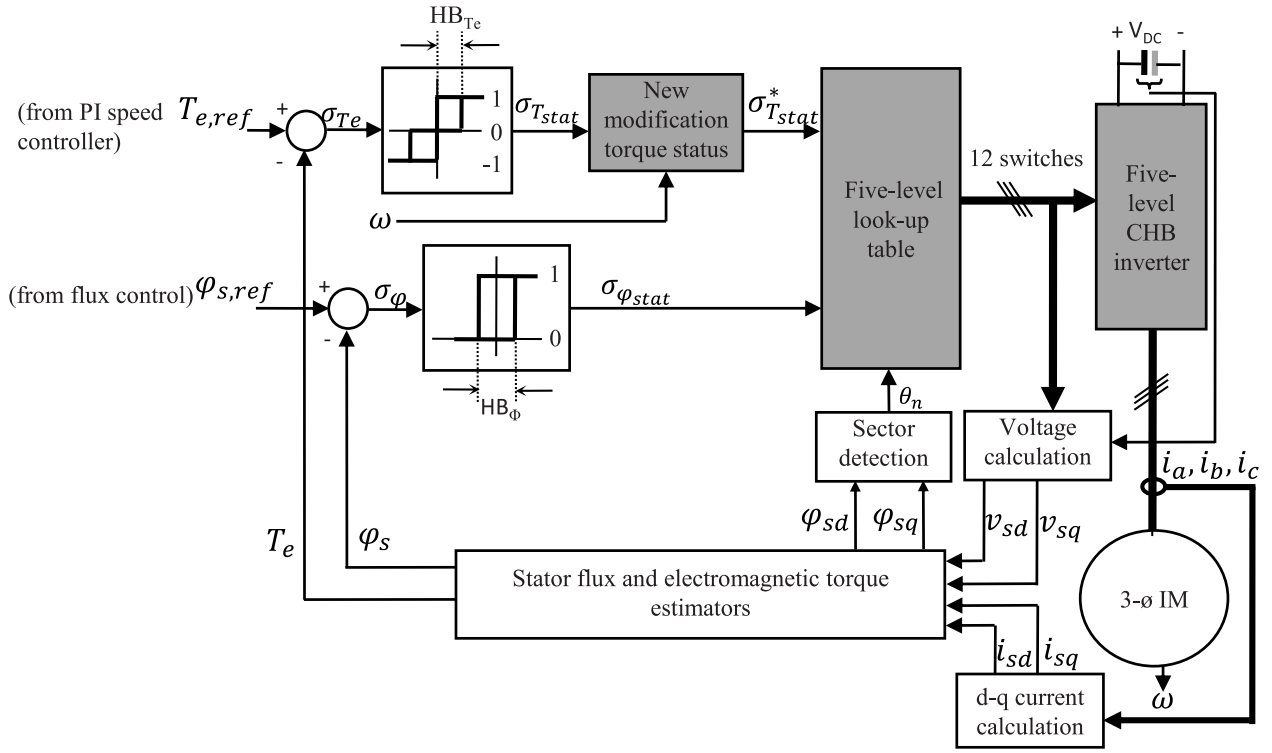


Fig. 12. The new configuration of DTC in the proposed method.

Table 3

The list parameter of induction machine.

Induction machine	
Rated power, P	1.1 kW
Rated speed, $\omega_m(rated)$	2800 rpm
Rated torque, $T_e(rated)$	4 Nm
Rated flux, $\varphi_s(rated)$	0.8452 Wb
Frequency, f	50 Hz
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
Combined Inertia, J	0.0565 kg m ²
Numbers of pole pairs	1

conducted by using the three-phase induction motor as listed in Table 3. The experimental test for realizing the simulation result is set up, as shown in Fig. 13. A 1.1kW one pole-pair squirrel-cage induction motor as well as the CHB inverter employed by 24 insulated-gate bipolar transistors are applied in this experiment. Each module in the CHB inverter uses 55 V DC supply which the total of DC supply of six modules is 220 V. For standardize the performance, the single DC supply of conventional inverter is also set at 220 V. The DTC scheme is performed by using dSPACE 1104 controller board with the sampling time of 50 μ s.

The test has been conducted at constant torque region on the six operating speeds. The experimental result is presented and discussed in this paper. All results show the three performances such as torque, T_e (upper), phase current, I_s (middle) and phase voltage, V_s (lower). For detail observation, all results are magnified to identify the precise comparison of both methods. In DTC scheme, the reference torque is set at 1.55 Nm. As results, the estimated torque is regulated well on the reference torque while the stator current has achieved peak-to-peak 2 A on every operating speed. In contrast, the phase voltage is different in terms of

amplitude and pattern due to the selection of appropriate voltage vector by optimal switching on each operating speed. Meanwhile, the phase voltage remains the same in non-optimal switching.

As shown the magnified result at operating speed₁ in Fig. 14(a), the extreme sharp increase of torque is produced by the non-optimal switching. It occurs due to the application of the longest amplitude of voltage vector that causes the high torque ripple and switching frequency in non-optimal switching. Therefore, the optimal switching has applied the shortest voltage vector to reduce the extreme torque. Conversely, to the decreased torque, both methods have used the zero-voltage vector as it is suitable in the smaller rate decrease of torque at operating speed₁. Thus, the extreme reduction of phase voltage amplitude is shown in the optimal switching that produces a low switching frequency rather than high switching frequency in the non-optimal switching. From the adjustment, the estimated operating speed achieves around 100 rpm (3.6%) while the torque ripple decreases at around 50%.

At operating speed₂, the extreme increase torque pattern keeps retained by the non-optimal switching through the magnified result, as shown in Fig. 14(b). Thus, to reduce the extreme increase torque, the amplitude of short voltage vectors is employed in the optimal switching with the minimized approximate ripple of 30%. Meanwhile, to the decreased torque, non-optimal switching that applies zero voltage vector has caused the severe reduction of torque which it must be prevented from producing the large torque ripple. So, the optimal switching selects the amplitude of the shortest voltage vector to minimize the drastic effect of torque decrease. The amplitude of phase voltage as well as less torque regulation decreases in the optimal switching. The estimated speed attained at this operating speed₂ is 300 rpm (10.7%).

Fig. 14(c) shows the results at operating speed₃ with the approximate speed of 350 rpm (12.5%). The longest amplitude and zero voltage vector in the non-optimal switching maintain the high switching frequency, but lesser steep on the increase and

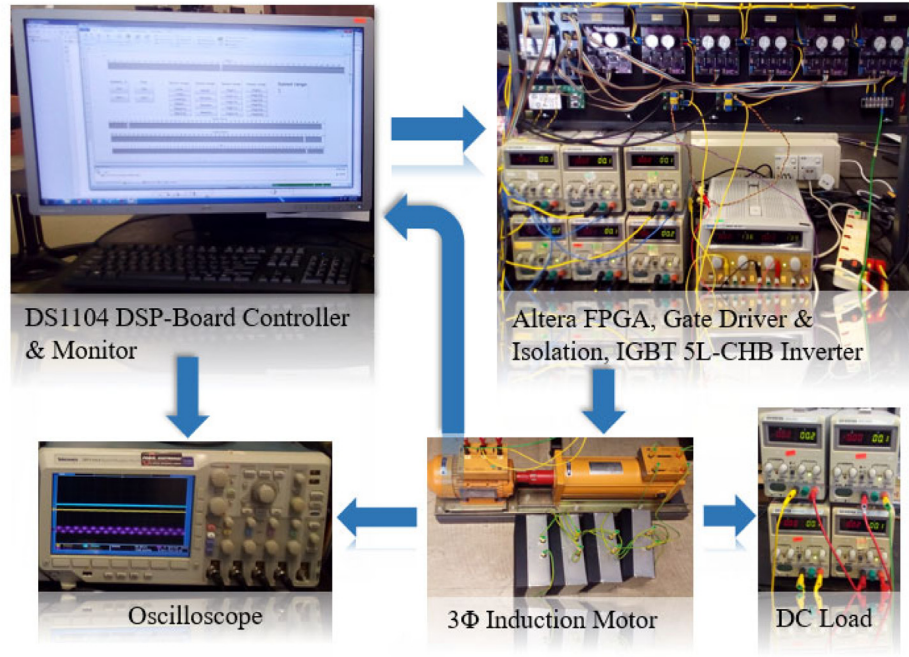


Fig. 13. The practical experimental setup of DTC drive system.

decrease torque which is different from the earlier two operating speed cases. However, the amplitude of the torque pattern in the non-optimal switching is still higher than optimal switching. For solving the previous problem, the optimal switching suggests the medium-short voltage vector for the increased torque whereas the short voltage vector for the decreased torque. Thus, the reduction of ripple is attained at about 30%, which is very suitable at the operating speed₃.

On the other hand, the operating speed₄ at around 800 rpm (28.6%) yields the result, as shown in Fig. 14(d). The torque ripple in non-optimal switching, in this case, keeps a similar pattern like the former case (speed₃). For being applicable in this operating speed, the medium-long amplitude of voltage vector is employed for the increased torque while the medium-short amplitude voltage vector used for the decreased torque in the optimal switching. Medium-short voltage vector is selected because the reduction change rate of decrease torque is more significant rather than other vectors. This option has led to minimizing the torque ripple about 20%. It is seen that the amplitude of phase voltage in the optimal switching slightly increases rather than the previous operating speed.

Meanwhile, at operating speed₅, the comparison result between both switching can be observed in Fig. 14(e). The torque amplitude in the non-optimal switching is still high, as shown in Fig. 14(e)(left). As observed in the magnified result (shown in Fig. 14(e)(right)), it is noticed that the non-optimal switching has shown the less steep on the increased torque but drastically reduced on the decreased torque. Thus, to improve the increased torque of non-optimal switching, the optimal switching has suggested the long amplitude of voltage vector to reduce the torque. Similar to the previous operating speed (speed₄), the medium-short amplitude of voltage vector is the best option in the optimal switching to lower the drastic reduction effect of the decreased torque. As a result, the torque ripple has reduced around 20% in the estimated operating speed of 900 rpm (32.1%). The change of amplitude and pattern of phase voltage also occurs in the optimal switching due to the selection of appropriate voltage vector.

Table 4

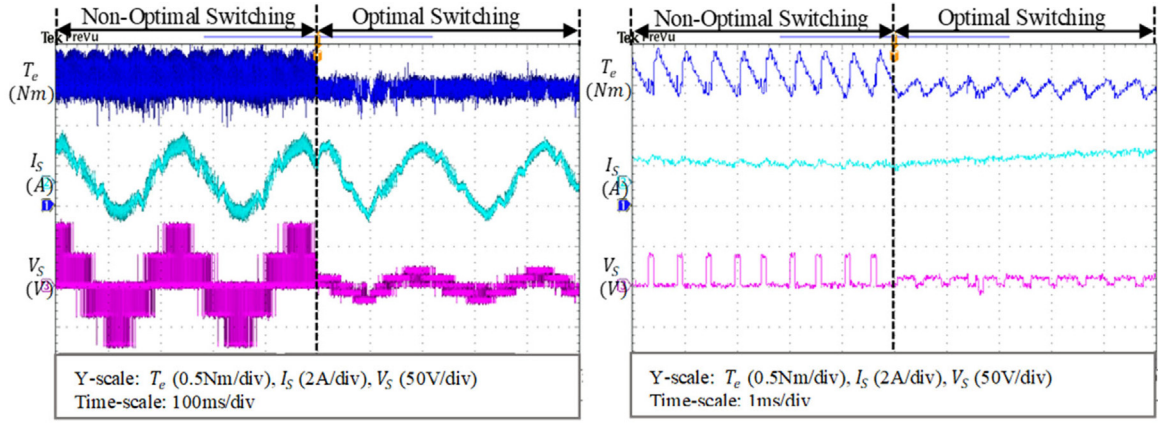
The evaluation of DTC performance for each classification of operating speed.

Classification of Operating Speed	Achievement of estimated speed (%)	Estimated torque ripple reduction (%)
Speed ₁	3.6	50
Speed ₂	10.7	30
Speed ₃	12.5	30
Speed ₄	28.6	20
Speed ₅	32.1	20
Speed ₆	35.7	10

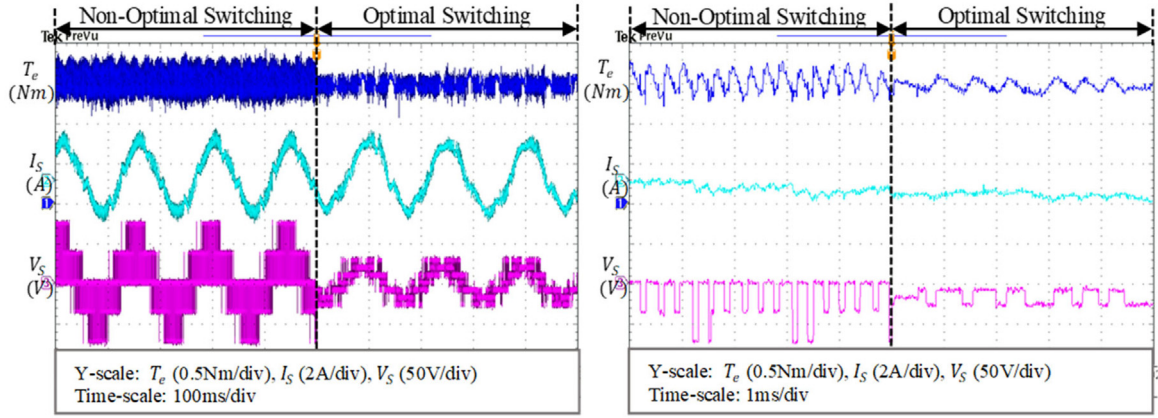
At operating speed₆ as shown in Fig. 14(f), both switching has employed the longest voltage vector at increase torque which is seen through the magnified result in Fig. 14(f)(right). Therefore, both have the same rate change of torque. Nevertheless, the torque pattern produced in the non-optimal switching is still higher due to the application of a zero-voltage vector that shows the extreme reduction on decrease torque. So, to enhance the performance, the optimal switching has employed the medium-short amplitude of voltage vector to minimize the change rate of torque when the torque decrease. Therefore, the minimization of torque ripple is able to reduce the approximate changed by 10% between both switching. The similar amplitude voltage vector, but with a different pattern has appeared, as shown in Fig. 14(f)(left). The speed adjusted at this operating speed is about 1000 rpm (35.7%). Thus, the achievement of DTC performance for each classification of operating speed is summarized into Table 4 which it contains the result of the estimated torque ripple reduction as well as the estimated speed based on the employment of the selected optimal voltage vector.

6. Conclusion

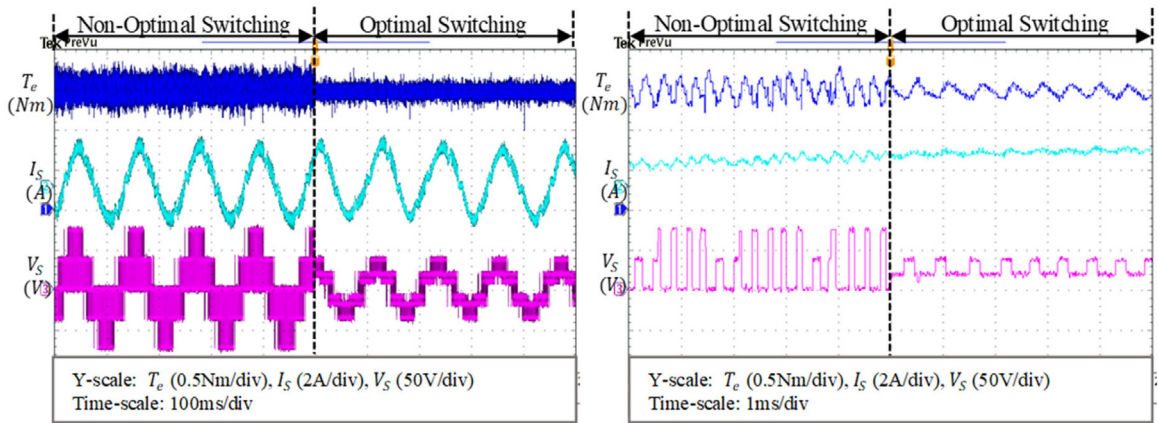
MLI contributes to the benefit of large torque ripple reduction in DTC hysteresis-based. It is due to the utilization of various voltages vector that consists of different amplitude and angle. In this paper, the selected optimal voltage vectors are proposed to



(a)



(b)

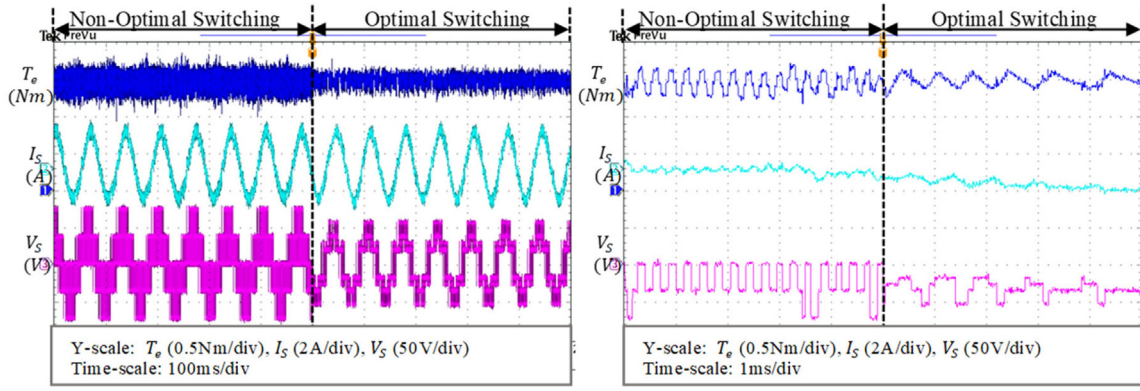


(c)

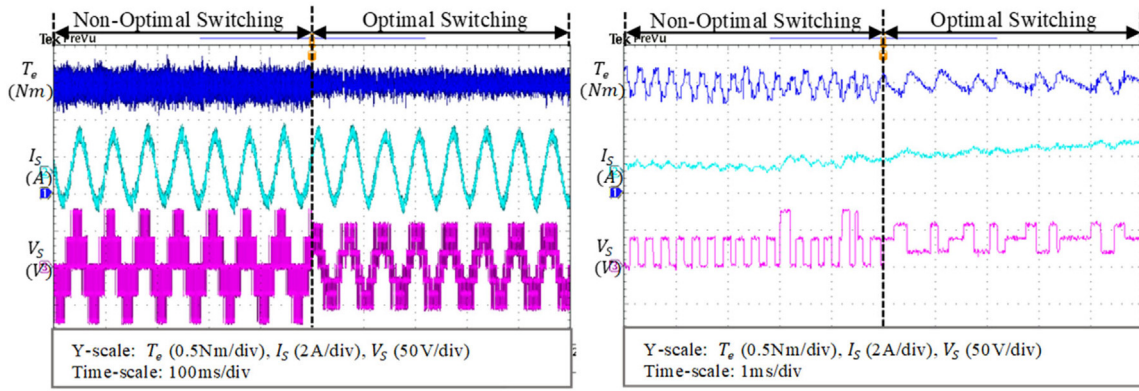
Fig. 14. The experimental result (left) and magnified result (right) between non-optimal switching and optimal switching at operating: (a) speed_1, (b) speed_2, (c) speed_3, (d) speed_4, (e) speed_5 and (f) speed_6.

optimize the DTC performance. The justification of the selected optimal voltage vector aims to minimize the torque ripple and

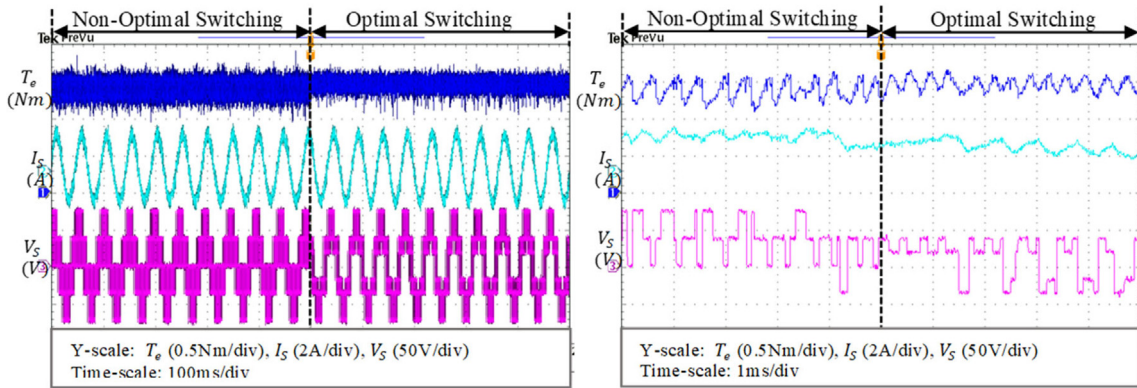
maintain the torque capability of the drive system. By using five-level CHB feeding in DTC drive scheme, the selection of optimal voltage vector in the proposed method is achieved through the



(d)



(e)



(f)

Fig. 14. (continued).

analysis and justification on the six operating speeds including the low operating speed at constant torque region. All of the achievements are summarized in Table 4.

In this paper, the experimental results accomplish the optimization performance on every operating speed by using the selected optimal voltage vector. It is concluded that the implementation of five-level CHB in DTC able to eliminate the drawback of two-level inverter that has a limited voltage vector and degraded performance at low operating speed. Although MLI

produces large algorithm due to the abundant of voltage vector, however, DTC hysteresis-based achieves a similar optimization performance but with the uncomplicated method compared to the DTC-SVM.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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