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# Enhanced Torque Control and Reduced Switching Frequency in Direct Torque Control Utilizing Optimal Switching Strategy for Dual-Inverter Supplied Drive

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**ABSTRACT**

Direct Torque Control (DTC) of induction machine has received wide acceptance in many adjustable speed drive applications due to its simplicity and high performance torque control. However, the DTC using a common two-level inverter poses two major problems such as higher switching frequency (or power loss) and larger torque ripple. These problems are due to inappropriate voltage vectors which are selected among a limited number of voltage vectors available in two-level inverter. The proposed research aims to formulate an optimal switching strategy using Dual-Inverter Supplied Drive for high performances of DTC. By using dual-inverter supplied, it provides greater number of voltage vectors which can offer more options to select the most appropriate voltage vectors. The most appropriate voltage vectors should able to produce minimum torque slope but sufficient to satisfy torque demands. The identification is accomplished by using an equation of rate of change of torque which is derived from the induction machine equations. The proposed strategy also introduces a block of modification of torque error status which is responsible to modify the status such that it can determine the most optimal voltage vectors from a look-up table, according to motor operating conditions. The improvements obtained are as follows; 1) minimization of switching frequency (reduce power loss), and 2) reduction of torque ripple. Some improvements obtained in the proposed strategy were verified via experimentations.



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## 1. INTRODUCTION

Nowadays, the type of AC motor which is known to offer low maintenance, rugged and high-efficiency, is preferable for many industrial applications. Since 1970's, several vector control techniques were proposed which mainly aim to provide excellent dynamic control performance, comparable to that obtained in DC motor drives. At early stage, the vector control known as field oriented control (FOC) was introduced by [1] which enables the control of torque and flux using their respective current producing components, i.e. $i_{sq}^{e*}$ and $i_{sd}^{e*}$ in synchronous reference frame. However, the FOC method requires a frame transformer, speed information, knowledge of machine parameters and current controllers to establish the control of torque and flux. Later, the direct torque control (DTC) method was introduced in the mid of 1980's by [2]. Compared to FOC, DTC has lesser sensitivity on parameter variations due to temperature changes, since it does not totally depend on machine parameters to estimate the control parameters. Due to its simplicity and fast instantaneous control performance, the DTC scheme gradually replaces the FOC for many industrial applications.

However, the DTC has major drawbacks such as larger torque ripple and variable switching frequency because of hysteresis operation in controlling the stator flux and torque. Several technical papers were proposed to minimize the problems and improve further the DTC performances. These includes the improvement of flux estimation [3], sensorless drive[4], torque capability for wide speed ranges [5-6], torque dynamic control in flux weakening region [7], reduction of torque ripple [8-9] and a constant switching frequency [10-12].

Among various modifications of DTC, the adaptation of space vector modulation (SVM) in DTC structure has received widely acceptance due to its features can offer great reduction of torque ripple and a constant switching frequency [13] [11]. However, the adaptation of SVM increases the complexity which somehow degrades the accuracy of control performance and dynamic torque control performance.

Lately, the application of multilevel inverter has gained popularity in improving DTC performances due to its attractive features, which are as follows, 1) low voltage stress on switching devices which allows to operate at high-voltage and current operations, 2) low harmonic current or voltage distortion (i.e. due to low $dv/dt$ or $di/dt$ ) which eliminates the use of filter and 3) improved efficiency and torque dynamic performance with optimal selection of voltage vectors. The third feature can be offered as the multilevel inverter uniquely provides greater number of voltage vectors, as compared to that available in the conventional inverter. This provides more degrees of freedom to select the most optimal vectors among vectors available to achieve excellent DTC performances. There are three types of multilevel inverter normally used in AC drives, namely cascaded H-bridge [14], neutral point clamped [15] and flying capacitor [16].

This paper proposes a simple, yet significant, method of optimal switching strategy in the DTC-hysteresis based induction machine to produce fast torque dynamic control and to reduce switching frequency as well as torque ripple. All improvements obtained in the proposed method are verified via experimental results.

## 2. BASIC CONCEPT OF DTC

Over the past three decades, DTC method was introduced by Takahashi and Noguchi [2] is depicted in Figure 1. In the conventional DTC structure, it employs a pair of hysteresis comparator; one utilizes a two-level hysteresis comparator for controlling the stator flux and the other one uses a three-level hysteresis comparator for controlling the torque. The output status of hysteresis comparators ($T_{stat}$ and $\varphi_{stat}$) and stator flux position (sector) are used to tabulated a look-up table with most optimal voltage vectors as suggested by [2], so the appropriate voltage vectors able to control both torque and stator flux, respectively.

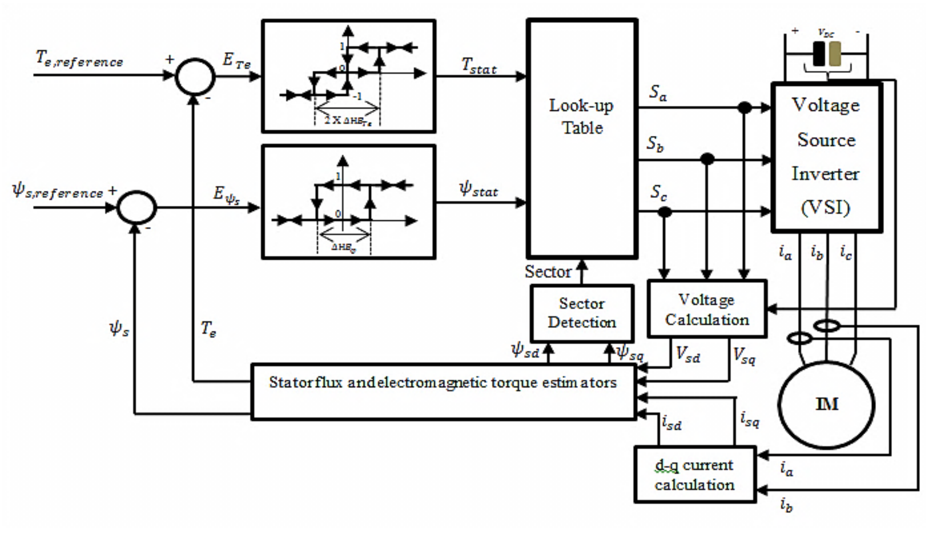



Figure 1. Structure of Basic DTC-hysteresis based Induction Machine [2]

In DTC, the trajectory of stator flux is controlled to form a circular locus by controlling the radial component of stator such that its ripple (or error) is restricted within the predefined band (or upper and lower bands) of the two-level hysteresis comparator as depicted in Figure 2. Every sector, there are two possible voltage vectors used to control the stator flux. For example, the vectors $\bar{v}_3$ and $\bar{v}_4$ are tangential to the flux at the boundaries between Sector I and II, and boundaries between Sector II and III, respectively. Thus, these vectors are used to control the stator flux, when the stator flux vector lies in Sector II. In this sector, the vector $\bar{v}_3$ is used to increase the stator flux; on the other hand, the vector $\bar{v}_4$is switched to decrease the stator flux. Meanwhile, in the case of torque control, the same voltage vector used to control stator flux (either $\bar{v}_3$ or $\bar{v}_4$) is selected to increase the torque to its demand. When the torque demand is satisfied, the application of zero voltage vector (either $\bar{v}_0$ or $\bar{v}_7$) is switched to decrease the torque. Note that the stator flux movement is ideally halted each time the zero voltage vector is selected. By ensuring the torque and flux errors within their respective hysteresis bands, then a decoupled control of torque and stator flux able to be accomplished in DTC.

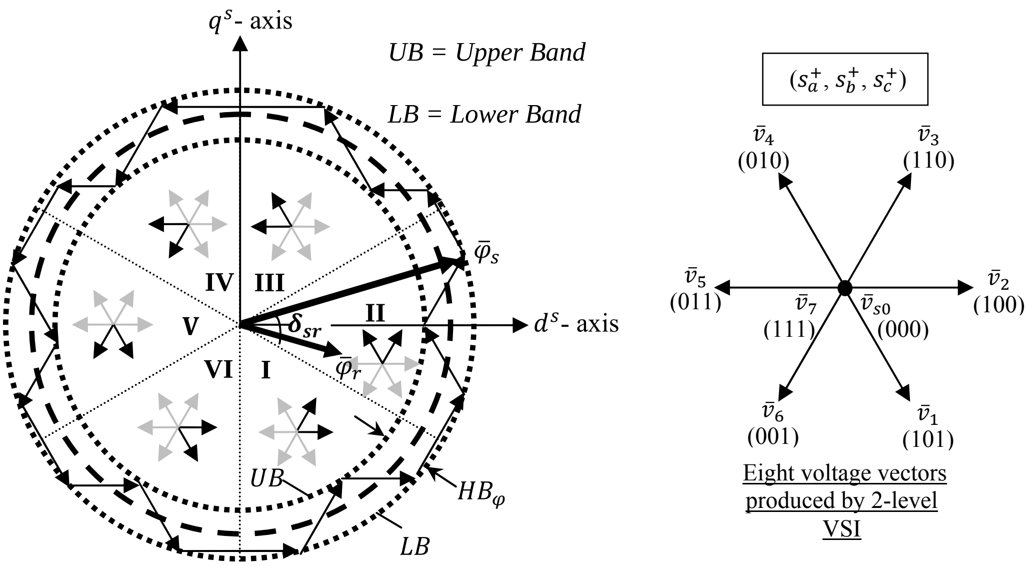



Figure 2. Trajectory of Stator Flux with optimal voltage vectors selection

## 3. DUAL-INVERTER SUPPLIED DRIVE TOPOLOGY

In the dual-inverter supplied drive topology, the power from voltage source inverter (VSI) are fed to both side of stator winding of induction machine (either by two-level or multilevel inverter). Figure 3 shows a dual-inverter supplied configuration for induction machine. Noted that the DC sources used to power-up the VSIs are electrical isolated for preventing the damage to the power switching device or machine which causes by the flow of zero-sequence current. In addition, each inverter DC supply voltage is set to half compared to the conventional two-level single-sided supplied (conventional DTC). Although that, the generation amplitude of output voltage at stator winding is equivalent to two-level inverter. Due to the power is fed from both sided of stator winding, therefore the output voltage generated across stator winding is similar as available in conventional three-level inverter (conventional multilevel).

As shown in Figure 3, each of this two-level inverter able to produce $2^3$ or 8 switching state combinations. However, since these dual two-level inverters are connected in open-end winding configuration, the numbers of switching state combinations are increased to $2^3 \times 2^3$ or 64. In practice, only 19 switching state combinations are fully utilized, this due to the remained switching state combinations just overlaps to others. Therefore, these 18 active voltage vectors and one zero voltage vector can be gathered into four groups according to their amplitude vectors such as zero voltage vector ($\bar{v}_{z0}$), small voltage vectors ($\bar{v}_{sx}$), medium voltage vectors ($\bar{v}_{Mx}$) and large voltage vector ($\bar{v}_{Lx}$) as illustrated in Figure 4 (x = 1, 2..., 6). The binary number is used to indicate switching state conditions and can be expressed as follows: -

$$S_x^{Y+} = \begin{cases} 1 \text{ Indicate the upper switch is turn ON} \\ 0 \text{ Indicate the upper switch is turn OFF} \end{cases} \quad (1)$$

‘x’ is the referring to the phase (x = a, b, c), ‘y’ is either 1 or 2 which referred to inverter 1 or 2 while ‘+’ referred to the upper switch. It should be noted that the lower switch for each phase of inverter is always complimentary to the upper switch.

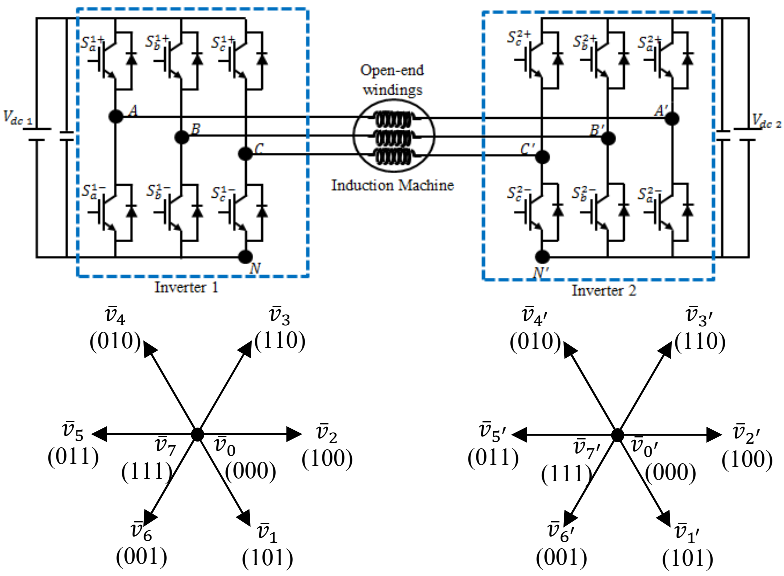



Figure 3. Configuration and voltage vectors produced by each inverter of two-level in dual-inverter supplied drive

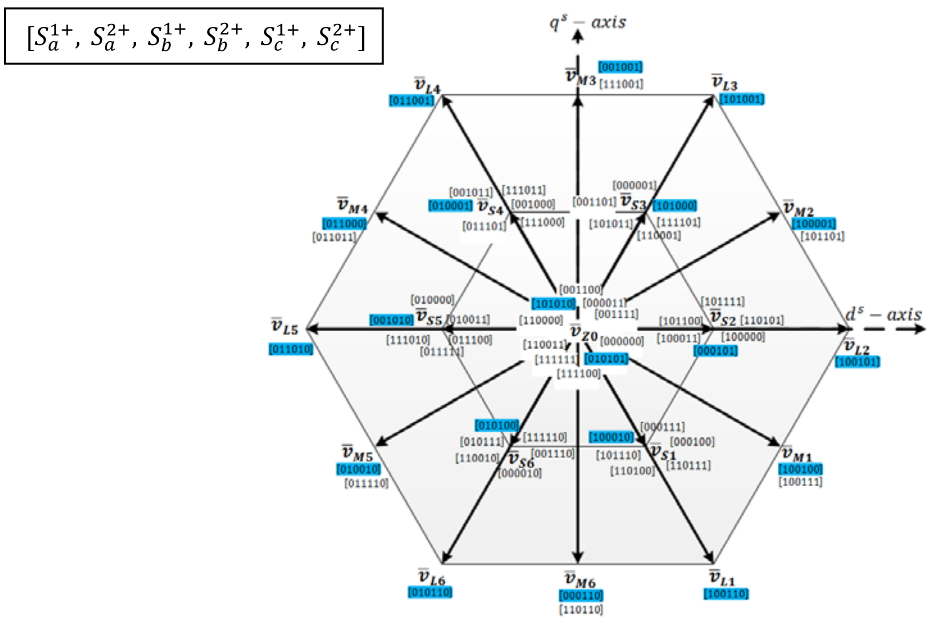



Figure 4. Voltage vectors produced by dual two-level inverters

## 4. PROPOSED OPTIMAL SWITCHING STRATEGY

This section will present briefly on how the proposed optimal switching strategy in DTC with the dual-inverter supplied drive able to improve DTC performances which as follows; 1) reduction of torque ripple, 2) minimization of switching frequency that can improve power efficiencies. The optimal switching strategy is executed through the modification of torque error status based on evaluation of torque control capability for every application of amplitude of vectors and operating speeds. Based on the previous statement, it is possible to evaluate the capability of torque control for every speed region by comparing the switching frequencies obtained from the torque and stator flux hysteresis comparator as shown in Figure 5 (highlighted by blue block). Therefore, the proposed method modifies the torque error status ($T_{stat}$) to a new torque error status ($T_{stat}^{new}$) without require speed information and the use of a speed sensor. In such a way, the simplicity and reliability of control, as featured in the conventional DTC can be retained. Taking into account that, the switching of appropriate amplitude of vectors determined by the modified torque error status (Optimum Status Detection) for every speed region, which as suggested above, able to reducing the rate of change of torque (to improve DTC performances) at the same time retains the control of torque. Another thing considered by the Optimal Status Detection block is the necessary to switch the longest amplitude (i.e. $T_{stat}^{new}$ = +3 or -3) of vectors for achieving the fastest torque dynamic response when a sudden large torque demand occurs. This dynamic condition or this sudden large torque demand can be easily detected by measuring the torque error ($ET_e$) using three-level hysteresis comparator. The following subsections will describe the effect of different amplitude of voltage vectors toward torque dynamic behaviors (DTC performances) and others crucial parts in the proposed scheme.

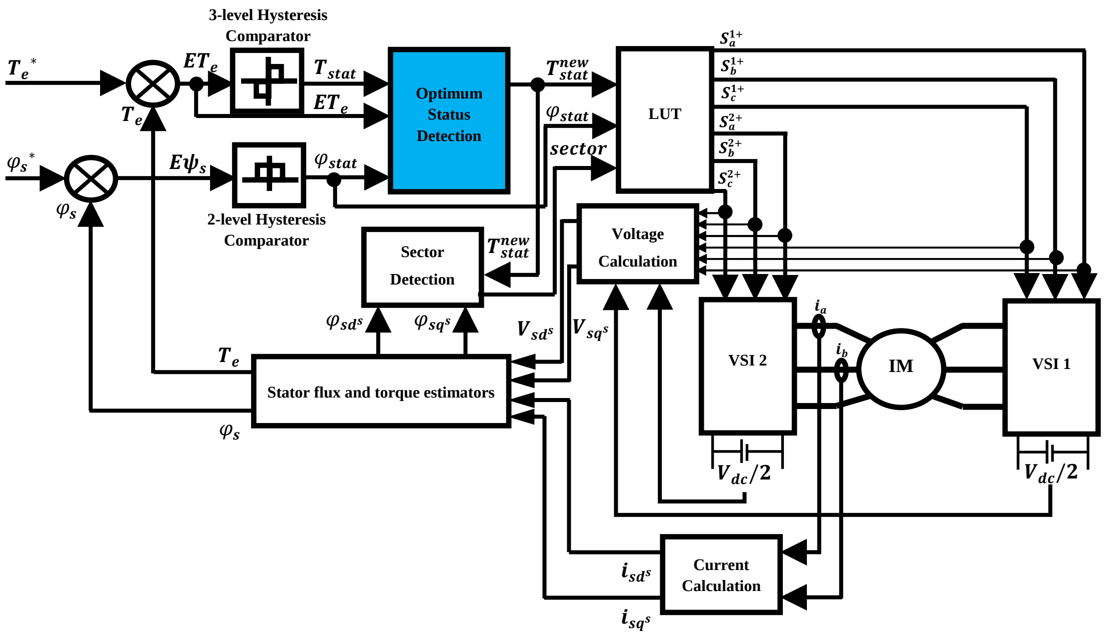



Figure 5. The structure of proposed DTC utilizing dual inverter supply drive with an optimal status detection block

### 4.1. Effect of Different Amplitude of Voltage Vectors on Torque Dynamic Behaviors

In this subsection, the rate of torque change equation (2) is derived based on a vector diagram as shown in figure 6. This equation is necessary to analysis the behavior of torque dynamic for different amplitude vectors applications at different speed operations. Then, the following cases below describe the reduction of torque ripple and switching frequency obtained with the proposed switching vectors for every level of speed operation as well as comparison with that obtained in the conventional DTC.

(I) Case 1: Proposed selection of vectors at Low-Speed

Firstly, let assume that the rotor flux angle ($\theta_{r,n-1}$) is equivalent to the stator flux angle ($\theta_{s,n-1}$), since the slip very small in practice. Therefore, only the speed or angular frequencies need to be considered for the second term in equation (2). At low speed operations, the torque tends to increase rapidly as the stator flux angle increases at a higher rate than that of the rotor flux angle, particularly employing the largest tangential voltage vector (i.e. $\alpha_{sk,n} - \theta_{r,n-1} = 90^0$) that has the longest amplitude. As it can be noticed that the second term in (2) becomes smaller, i.e. insignificant reduction term (at low speed operations), which proves that the rate of increment of torque strongly influenced by the applied voltage vectors. These conditions normally occur in the conventional DTC with the only single option of amplitude (i.e. the longest amplitude of vector) in selecting active voltage vectors. As the result, it contributes to larger torque ripple and high switching frequency which very significant due to the following factors; 1) extreme increase of torque since that the reduction term in (2) becomes smaller as the speed decreases, and 2) extreme decrease of torque because of selection of reverse voltage vectors which is happened whenever the torque error touches the lower band of the three-level hysteresis comparator. Fortunately, the proposed strategy has another option to employ shorter amplitude of active vectors that can slow down the increment of load angle $\delta_{sr}$ and torque, as well. According to (2), the application of the shorter amplitude of active vectors results in a smaller motion or increase of the load angle$\Delta\delta_{sr}$, thus the vector that has the shortest amplitude (based on the categorization of vectors in Figure 4 is chosen in the proposed method to reduce the rate of increase of torque. In addition, the reduction of the positive torque slopes in the proposed method consequently prevent the incidence of undershoot of torque error to touch the lower band of hysteresis comparator. By employing the proposed vectors, particularly in increasing the torque, torque ripple and switching frequency can be reduced.

In decreasing the torque, zero voltage vectors are chosen in the proposed method similar to that employed in the conventional DTC. By selecting the zero vectors at low-speed, the rate of decrease of torque turns out to be smaller. This can be proven by (2), as the rate is only determined by the second or reduction term in (2), which becomes a insignificant term as the speed decreases. It should be also noted that the selection of the proposed voltage vectors are also employed to increase or decrease slowly or to halt the stator flux.

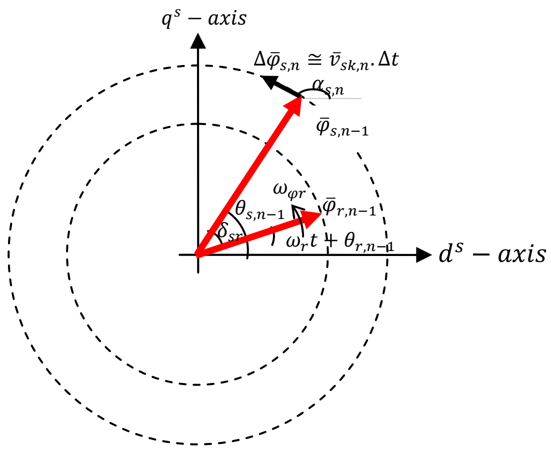



Figure 6. Control of stator flux vector to track its reference (into a counter clockwise) with a suitable voltage vector application

$$\frac{dT_{e,n}}{dt} = C\bar{\varphi}_{r,n}\left[V_{s,n}sin\left(\alpha_{sk,n} - \theta_{r,n-1}\right) - \omega_s\bar{\varphi}_{s,n-1}cos\left(\theta_{s,n-1} - \theta_{r,n-1}\right)\right] \quad (2)$$

(II) Case 2: Proposed selection of vectors at Medium-Speed

At medium-speed, it is necessary to employ voltage vectors that can avoid extreme torque changes and at the same time, the selection of voltage vectors able to retain the capability control of torque.

In the case of increasing of torque, if the longest amplitude of voltage vectors is employed (i.e. the same voltage vectors employed in the conventional DTC), the torque may increase rapidly, which causes a large torque ripple and high switching frequency. On the other hand, if the shortest amplitude of voltage vectors is employed, the increase of torque might not be able to satisfy its demand because the angular frequency of the stator flux vector cannot be increased further to maintain at a desired load angle ($\delta_{sr}$). Therefore, the proposed method employs medium amplitude of vectors, which can extend the limit of the stator flux angular frequency for retaining the control capability of torque as well as avoiding the extreme torque increases.

In the case of decreasing the torque, if zero voltage vectors are employed as in the conventional DTC, the torque may decrease rapidly since the reduction of the load angle ($\delta_{sr}$) occurs at higher rate, as the stator flux vector is assumed to be halt, while the rotor flux vector continuously approaches to the stator flux vector. Thus, to slow down the rate of load angle reduction, the smallest amplitude of active vectors ($T_{stat}^{new} = +1\ or\ -1$) is employed in the proposed method. By selecting the proposed voltage vectors, the positive and negative torque slopes can be reduced and consequently minimizes the torque ripple at the same time reduce the switching frequency.

(III) Case 3: Proposed selection of vectors at High-Speed

At high-speed, it is required to employ voltage vectors that can fulfill the capability control of torque demand. As the speed increases, the rotor flux angular velocity also increases; it is therefore the stator flux vector has to rotate faster, i.e. at higher angular frequencies to maintain the desired load angle.

In the case of increasing the torque, the proposed method has to employ the longest amplitude of vector to move quickly the stator flux vector to retain the desired load angle and hence retains the control of torque. The selection of the longest amplitude of vector is the same as selected in the conventional DTC. Referring to (2), the longest amplitude of vector at high speeds will not drastically increase the torque, as the reduction term becomes greater.

On the other hand, for reducing the torque, the proposed method employs the shortest amplitude of vectors, similar to that employed in the case of medium speeds. As justified in the case of medium speeds, the selection of the shortest amplitude of vectors may slow down the rate of load angle reduction and torque slope, as well. Note that, the selection of zero vectors as employed in the conventional DTC results in a higher rate of load angle reduction and larger negative torque slope. On the other hand, the selection of medium amplitude of voltage vectors is not recommended because it may produce a higher rate of increase the load angle, which does not guarantee to decrease the torque. As discussed above, the negative torque slope obtained in the proposed method is lower, as compared to that obtained in the conventional DTC. Hence, this will reduce the torque ripple as well as switching frequencies at the inverter.

### 4.2. Definition of Flux Sectors for Selecting Optimal Vectors

This section introduces two definitions of flux sector for selecting optimal vectors, it is necessary in the proposed DTC for ensuring the selection of the optimal vectors with larger tangential flux component are the most efficient to improve the DTC performances. Since the proposed DTC utilizing the dual-inverter supplied has eighteen active vectors, which can be categorized into three different amplitudes and among them, there are six medium amplitude of vectors which are shifted by 30 degrees with respect to the other particular vectors. Note that, there are two active vectors that have the larger tangential to the flux component for every flux sector is selected as shown in Figure 7. These vectors are employed to increase the torque, also employed to either increase or decrease the stator flux. Due to these shifted medium vectors, it is therefore, the proposed DTC has to introduce two definitions of flux sector, as given in Figure 7. As shown by Figure 7 (a), the short and the long amplitudes of vectors have a same definition of flux sector, similar to that defined in the conventional DTC. However, the medium amplitude of vectors using a different definition of sector, in which shifted by 30 degrees to that defined in the conventional DTC (or in Figure 7 (a)). By introducing the new definition of the flux sector, the tangential component of respective two medium amplitude vectors will be significant for every flux sector.

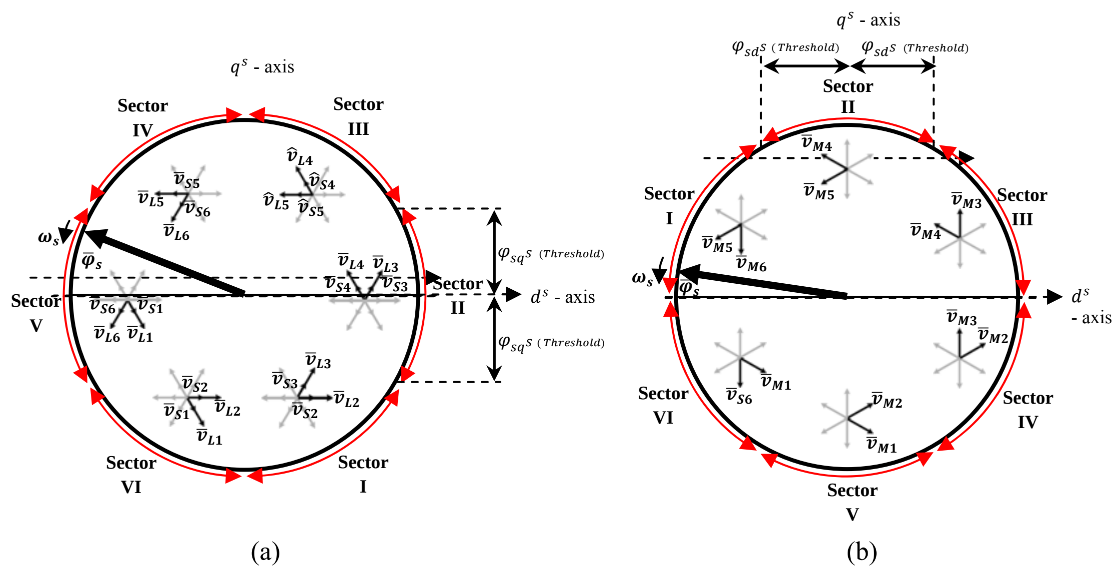



Figure 7. Proposed Two Flux Sector Definitions for (a) Optimal Switching of Short and Long Amplitude of Vectors and (b) Optimal Switching of Medium Amplitude of Vectors

### 4.3. Look-up Table for Selecting Optimal Voltage Vectors

Entire identified optimal vectors for every error status and flux sector to improve DTC performances are then tabulated into a look-up table, as given in Table 1. Clearly, the look-up table requires three information to select the optimal vectors, which are the flux error status $\varphi_{stat}$, the modified flux error status $T_{stat}^{new}$ and flux sectors. It should be noted that, the look-up table is valid for four-quadrant of operation.

Table 1. Selection of the Most Optimal of Voltage Vectors in Proposed Method

| Stator flux error status, $\varphi_{stat}$ | Torque error status, $T_{stat}^{new}$ | Sector I | Sector II | Sector III | Sector IV | Sector V | Sector VI |
|---|---|---|---|---|---|---|---|
| | 3 | $\bar{v}_{L2}$ | $\bar{v}_{L3}$ | $\bar{v}_{L4}$ | $\bar{v}_{L5}$ | $\bar{v}_{L6}$ | $\bar{v}_{L1}$ |
| | 2 | $\bar{v}_{M5}$ | $\bar{v}_{M4}$ | $\bar{v}_{M3}$ | $\bar{v}_{M2}$ | $\bar{v}_{M1}$ | $\bar{v}_{M6}$ |
| | 1 | $\bar{v}_{S2}$ | $\bar{v}_{S3}$ | $\bar{v}_{S4}$ | $\bar{v}_{S5}$ | $\bar{v}_{S6}$ | $\bar{v}_{S1}$ |
| 1 | 0 | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ |
| | -1 | $\bar{v}_{S6}$ | $\bar{v}_{S1}$ | $\bar{v}_{S2}$ | $\bar{v}_{S3}$ | $\bar{v}_{S4}$ | $\bar{v}_{S5}$ |
| | -2 | $\bar{v}_{M3}$ | $\bar{v}_{M2}$ | $\bar{v}_{M1}$ | $\bar{v}_{M6}$ | $\bar{v}_{M5}$ | $\bar{v}_{M4}$ |
| | -3 | $\bar{v}_{L6}$ | $\bar{v}_{L1}$ | $\bar{v}_{L2}$ | $\bar{v}_{L3}$ | $\bar{v}_{L4}$ | $\bar{v}_{L5}$ |
| | 3 | $\bar{v}_{L3}$ | $\bar{v}_{L4}$ | $\bar{v}_{L5}$ | $\bar{v}_{L6}$ | $\bar{v}_{L1}$ | $\bar{v}_{L2}$ |
| | 2 | $\bar{v}_{M6}$ | $\bar{v}_{M5}$ | $\bar{v}_{M4}$ | $\bar{v}_{M3}$ | $\bar{v}_{M2}$ | $\bar{v}_{M1}$ |
| | 1 | $\bar{v}_{S3}$ | $\bar{v}_{S4}$ | $\bar{v}_{S5}$ | $\bar{v}_{S6}$ | $\bar{v}_{S1}$ | $\bar{v}_{S2}$ |
| 0 | 0 | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ | $\bar{v}_{Z0}$ |
| | -1 | $\bar{v}_{S3}$ | $\bar{v}_{S4}$ | $\bar{v}_{S5}$ | $\bar{v}_{S6}$ | $\bar{v}_{S1}$ | $\bar{v}_{S2}$ |
| | -2 | $\bar{v}_{M2}$ | $\bar{v}_{M1}$ | $\bar{v}_{M6}$ | $\bar{v}_{M5}$ | $\bar{v}_{M4}$ | $\bar{v}_{M3}$ |
| | -3 | $\bar{v}_{L5}$ | $\bar{v}_{L6}$ | $\bar{v}_{L1}$ | $\bar{v}_{L2}$ | $\bar{v}_{L3}$ | $\bar{v}_{L4}$ |

## 5. IMPLEMENTATION AND EXPERIMENTAL RESULT

These sections presents the comparative analysis of performances, in terms of switching frequency, torque ripple and torque dynamic control between the conventional DTC and the proposed DTC. The complete experimental set-up has been realized as shown in Figure 8. Furthermore, the control algorithms are executed on a dSPACE 1104 with sampling period of 50µs.

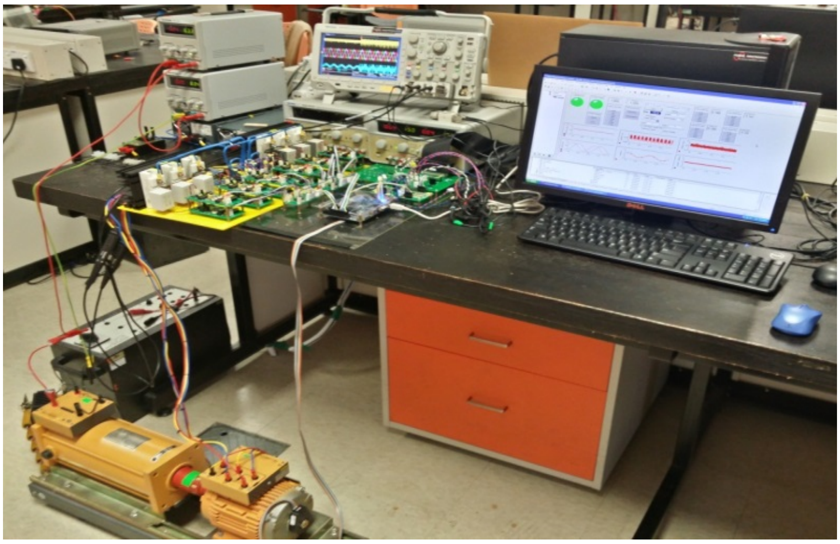


Figure 8. Complete drive system of the experiment set-up

The parameters of the induction motor and DTC drive used in this experiment are tabulated in Table 2. It should be noted that the isolated DC-Link voltage source is set at 120V, to conduct dual-inverter supplied drive. The entire performances analysis for the proposed and the conventional DTC were performed under same operating conditions in order to have fair comparison.

Table 2. 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 |
| **The Conventional and Proposed DTC** | |
| Torque Rated | 4Nm |
| Flux Rated | 0.8452Wb |
| Torque hysteresis band, $HB_T$ | 0.36Nm |
| Flux hysteresis band, $HB_\varphi$ | 0.02Wb |

Some test has been carried out to evaluate the performances improvements obtained using the proposed DTC scheme via experimental results, as well as comparison with the conventional 2-level DTC scheme. In this first case, a step change of reference torque from 0.9 Nm to 2.5 Nm is applied for proposed DTC scheme. From Figure 9, the selection of appropriate amplitude of voltage vectors, as suggested in proposed scheme, can be observed from the pattern of waveform of phase stator voltage $\boldsymbol{v_{an}}$ which exhibits the increment of the fundamental component for satisfying the higher torque demand, as the motor speed increases. As shown by experimental results obtained in the proposed DTC (in Figure 9), the selection of appropriate amplitude of vectors is based on the region of speed operations, which is as follows 1) at low-speed the proposed DTC switches between zero ($T_{stat}^{new} = 0$) and short ($T_{stat}^{new} = 1$) amplitudes of voltage vectors, 2) at medium-speed the proposed DTC employes the short ($T_{stat}^{new} = 1$) and the medium ($T_{stat}^{new} = 2$) amplitudes of voltage vectors, and 3) at high-speed the proposed DTC applies the long ($T_{stat}^{new} = 3$) and the short ($T_{stat}^{new} = 1$) amplitudes of voltage vectors. The proposed DTC also retains the important feature of the conventional DTC that is to provide a quick torque dynamic control. The magnified results as depicted in Figures 9 shown the longest amplitude of voltage vector is suddenly applied during torque dynamic condition, i.e. a sudden large torque demand (highlighted by red dotted line). The longest amplitude of voltage vector is applied to increase the rate of change of load angle which can provide a fast torque dynamic control, as mentioned in section 4.

In the second case, some verification tests were carried out with the proposed optimal switching and non-optimal switching using the same experimental platform and a constant of reference torque, i.e. at 1.9 Nm, for every speed operation, i.e. low-speed, medium-speed and high-speed. The experimental platform comprises dual inverters for open-end windings of induction machine, where the optimal and non-optimal switching modes can be switched via program or software. From the results obtained in Figure 10, initially, the DTC activates the proposed optimal switching mode, and then it activates the non-optimal switching mode which can be referred as the conventional DTC switching. Figure 10 (a) shows the waveforms of torque, currents and phase voltage obtained from experimental results for the case of low speed operations. As noticed in Figure 10 (a), by employing optimal vectors, the torque ripple is greatly reduced as the rate of increase of torque is slower. The effect of torque increase due to appropriate vector selection, i.e. with short amplitude, can be clearly seen by magnifying the results as depicted in Figure 10 (a). From the magnified results, it can also be seen that the switching indicated by regulation of torque is less often with the optimal switching. Meaning that, the selection of short vector which reduces slope of torque increase mainly contributes the reduction of switching frequency. Figure 10 (b) shows the waveforms of torque, currents and phase voltage obtained from experimental results for the case of medium speed operations. As shown by Figure 10 (b), similar improvements are obtained with the optimal switching, as clearly be seen that the torque ripple and switching frequency are greatly reduced. Same reason is used to justify the improvements, in which the reductions are obtained by slowing down the change of torque rates, provided that in the case of medium-speed the slowing down of torque rate is contributed by two changes; either to increase or decrease the torque with appropriate vectors, i.e. medium and short vectors. The improvements have also been verified at high-speed operation as shown in Figure 10 (c). As can be observed from magnified result in Figure 10 (c), the rate of torque decrease is slower than that obtained in the non-optimal switching. The slower rate is resulted due to selection of short vector (instead of using zero vector in the non-optimal switching) which reduces the rate of decrease of load angle, as mentioned in section 4.1.

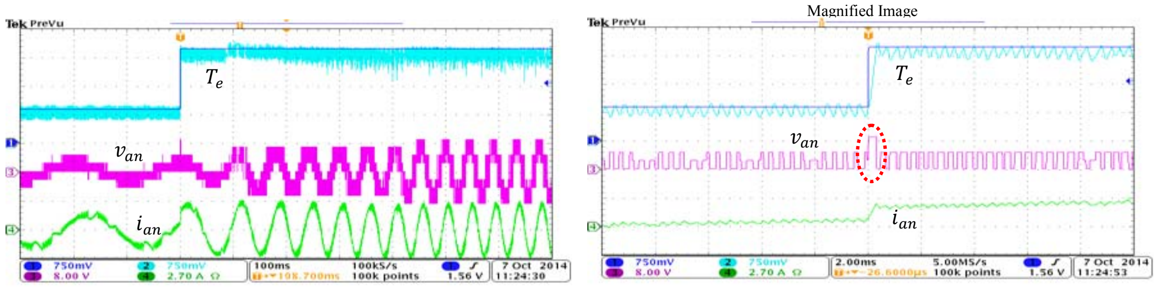
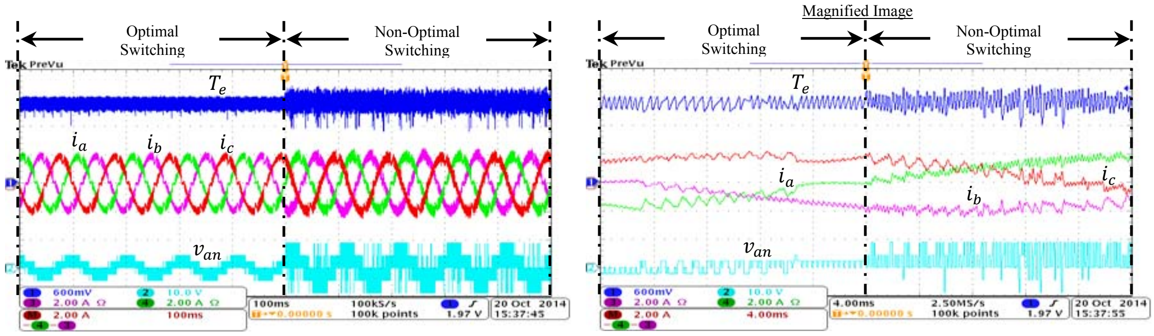
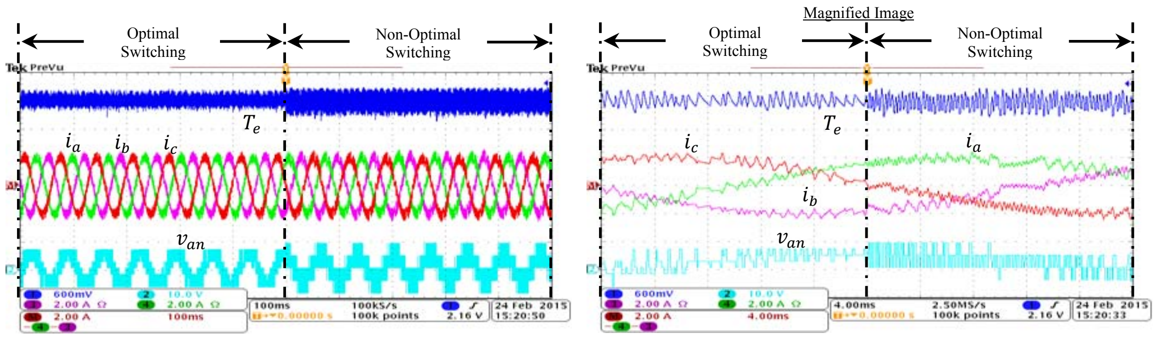


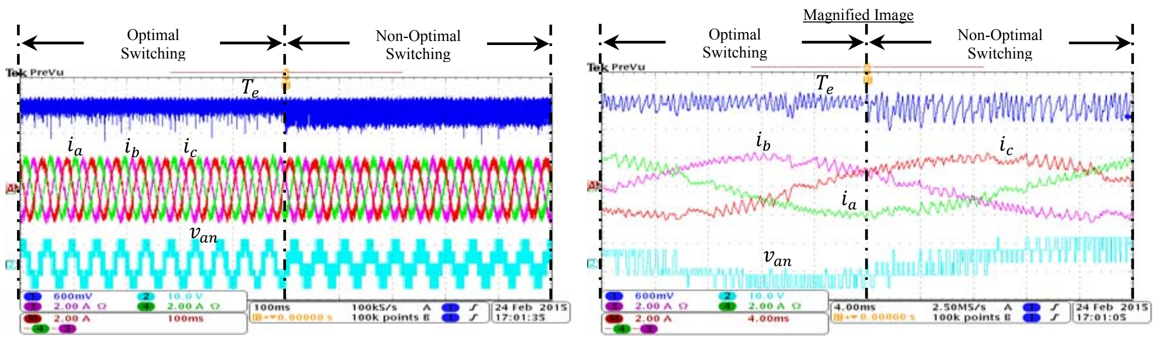

Figure 9. The experimental waveforms result of Torque ($T_e$), phase voltage ($v_{an}$) and stator current ($i_a$) for step change of reference torque from 0.9 Nm to 2.5 Nm




(a)




(b)




(c)

Figure 10. Comparison waveforms of Torque ($T_e$), stator current ($i_a, i_b, i_c$), and phase voltage ($v_{an}$) at constant torque for proposed switching and non-optimal switching strategies for three speed condition (a) Low speed condition, (b) Medium speed condition and (c) High speed condition

## 6. CONCLUSION

This paper has presented improvements of DTC performances of induction machines, in terms of reductions of torque ripple and switching frequency with the proposed optimal switching strategy using Dual-Inverter Supplied. Most of previous works can not achieve these two reductions at the same time. Several works attempt to reduce the torque ripple; however, they have to sacrifice efficiency performance by enlarging the switching frequency as well as switching losses. It has also shown that the effectiveness of the modification of torque error status to select appropriate amplitude of voltage vectors, according to motor operating conditions. Finally, the main benefits of the proposed method are the two improvements can be obtained, simultaneously, without the use of complex SVM and knowledge of machine parameters. This means that the proposed method retains the simple structure of DTC which may lead to robust and reliable controls. It also can offer important requirements, i.e. improved efficiency due to lower switching frequency/losses and dynamic torque control, which are mainly required for many high power applications.

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