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Simple Switching Strategy for High-Torque Control Performance utilizing Neutral Point Clamped Multilevel Inverter

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Article Info	ABSTRACT
	Three-level Neutral Point Clamped (NPC) inverter allows the configuration of switching devices to operate at high voltage and produce lower current/voltage harmonics. It is known that, DTC of induction machine which employs hysteresis controller has major drawbacks namely larger torque ripple and variable switching frequency. This paper aims to propose a suitable voltage vector selection to provide better torque regulation and lower switching frequency by employing DTC with 3-level NPC multilevel inverter. A simple switching strategy was formulated using 7-level torque hysteresis and 2-level flux hysteresis controllers to give more options in selecting an appropriate voltage vector, inherently, according the motor operation conditions. The improvements offered were verified through simulations.

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1. INTRODUCTION

The requirement of independent control of magnetic flux and torque in electrical machines leads to the introduction of Field Oriented Control (FOC). By applying FOC, the robust induction machine can be controlled with high performances. Direct torque control (DTC) that is introduce to replace FOC [1] has brought a huge improvements where it introduces a more simpler implementation and fsst dynamic response. The DTC which is operated with hysteresis controllers, however, causes two major drawbacks, namely variable switching frequency and larger torque ripple. Thus, several variation methods were proposed to solve/minimize the problems, these includes the use of dithering signals [2], modification of torque hysteresis controllers [3], application of space vector modulation (SVM) [4][5] and recently, the optimization of switching vector selection by means of multilevel inverter [6][7].

Basically, the construction of the multilevel consists of an array of power semiconductors, capacitors and DC voltage sources; depending on the type of multilevel inverters. Obviously, the use of multilevel inverter can offer significant advantages to attract many researchers to improve DTC performances, especially for high-power and medium voltage applications. The uniqueness of the multilevel structure allows the configuration of switching devices to operate at high voltage and produce low harmonics (i.e. slope of voltage change, dV/dt). Its main feature is to decrease the harmonic distortion in the output

waveform without having to decrease the inverter power output. The number of voltage levels has to increase with appropriate switching vector sequences and minimum number of switching so that the harmonics of output voltage waveform decreases substantially and with improved power efficiency.

In fact, there are many DTC strategies proposed using multilevel inverter, especially based on NPC-type, for examples; [8][9] introduced virtual vectors selection and [10] applied SVM method to obtain minimization of torque ripple and potential capacitor balancing. Ultimately, all these methods require major modifications on the simple DTC structure.

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

2.   BASIC PRINCIPLE OF DIRECT TORQUE CONTROL

Direct torque control (DTC) offers fast torque response, simpler structure and low cost maintenance. DTC scheme used simple processing method and depends fully on the non-ideal nature of the power source; therefore it can only be applied to power electronic converter-fed machines only. Unlike FOC drives, the torque and flux of DTC scheme are controlled independently and the demands are satisfied by selecting the appropriate voltage vector.
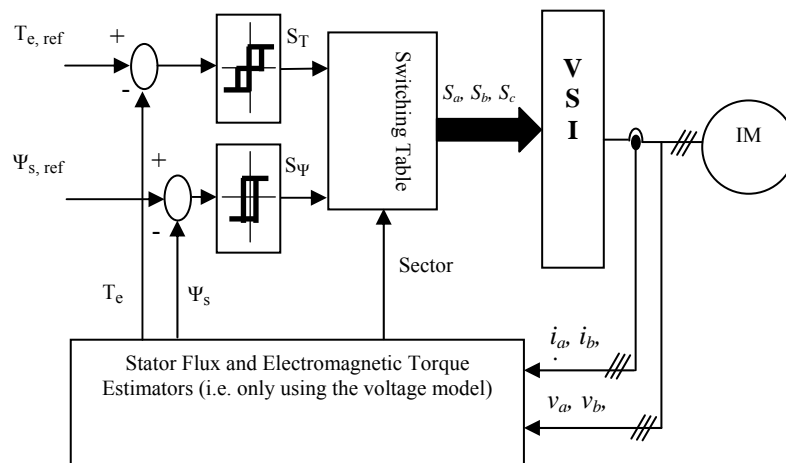

Figure 1. Structure of basic DTC of induction machine

The structure of DTC shown in Figure 1 contains a pair of hysteresis comparator, switching table, 3-phase voltage source inverter (VSI) and torque and flux estimators. In hysteresis-based DTC, 2-level hysteresis comparator and 3-level hysteresis comparator are used to control the flux and torque, respectively. The torque and flux demands are controlled independently which make possible for them to be controlled at a faster rate. The selection of appropriate voltage vector from the look-up table is made based on the flux error status (S_Ψ) and torque error status (S_T).

Figure 2 illustrates the selection of voltage vectors in controlling the stator flux vector ($\mathbf{\Psi_s}$) as it lies in Sector II. Using the same figure, the principle of torque control can be described by studying the effect of angle δ change due the selection of possible voltage vectors. Note that the angle δ plays a vital role in controlling the torque as noticed in (1).

$$T_e = \frac{3}{2} \frac{L_m}{\sigma L_s L_r} \Psi_s \Psi_r \sin\delta \qquad\qquad (1)$$

where σ is the total leakage factor, L_m, L_s and L_r are the motor inductances and δ is the angle difference between the stator flux vector (Ψ_s) and rotor flux vector (Ψ_r). Assuming that, the flux vector has to be controlled into counterclockwise direction. Thus, to increase the flux; the radial component of flux needs to be increased by selecting voltage vector v_2, on the other hand, to decrease the flux; the radial component should be decreased by choosing the voltage vector v_3. It can also be noticed that, these selection of voltage vectors result in increasing of angle δ which indicates the output torque increases. In the conventional DTC with 2-level inverter, the look-up table will produce zero voltage vectors (either v_0 or v_7) as the torque satisfies to its demand. With this selection of voltage vector, this ideally halts the stator flux vector and consequently decreases the angle δ as the rotor flux vector (Ψ_r) approaching continuously towards the stator flux vector (Ψ_s).

By applying a conventional or 2-level inverter, there are only 8 switching vectors available. This unfortunately limits the potential in providing more options to choose the most optimal vectors for enhancing the DTC improvements.
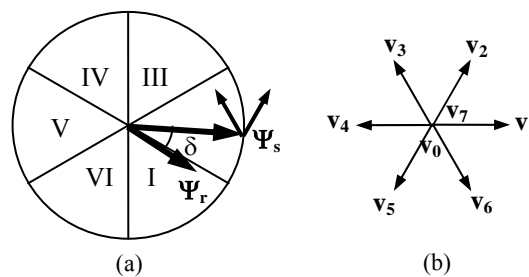

Fig.ure 2. Possible voltage vectors to be selected as the stator flux in Sector II. (a) Circular stator flux control (b) voltage vectors in voltage vector plane.

3.   NEUTRAL POINT CLAMPED MULTILEVEL INVERTER

There are several multilevel inverter topologies introduced to improve output voltage waveform and reduce voltage stress across power switching devices. The most popular topologies can be classified into three categories which are Neutral Point Clamped (NPC), Cascaded H-bridge and Flying Capacitor (FC) [11].

Figure 3 shows a 3-level Neutral Point Clamped (NPC) multilevel inverter which consists of 12-IGBT (with anti-parallel diode), 6-diode and 2-capacitor. By applying the NPC type of multilevel inverter, the two capacitors are connected across to a DC source voltage (or a series of DC batteries). The capacitors voltage may have potential imbalance to each other, because their voltage variations depend on the switching vectors of inverter, particularly at lower amplitude vector applications. Some analyses were done to achieve high performance as well as considering the neutral point potential balance [12][13]. Small DC-link capacitor based NPC three-level converter operation requires an average neutral point current to obtained zero in a switching period and a high performance neutral-point voltage controller. Therefore, several different modulation strategies and controllers for neutral-point voltage balance are presented as reported in [12][13]. When small disturbance occurs in neutral point current, it can drift in few switching periods because of the low energy stored in DC-link capacitors. As a result, PI controller can be used to control the neutral-point voltage [14][15].

For a 3-level NPC multilevel inverter, there are 27-voltage vector available as shown in Fig. 4. Note that the outer layer of hexagonal contains 12-vector where each vector has a single switching state, while the inner layer of hexagonal has 6-vector, in which each vector has two different states. In general, the switching condition for each vector that generates three-level output can be defined as given in Table 1. The rest of voltage vectors are defined as zero vectors (i.e. 0, 1 and 2) located at the origin of voltage vector plane. With greater number of vectors, it provides more options to choose the most appropriate voltage vector to achieve high-performance DTC drive systems.
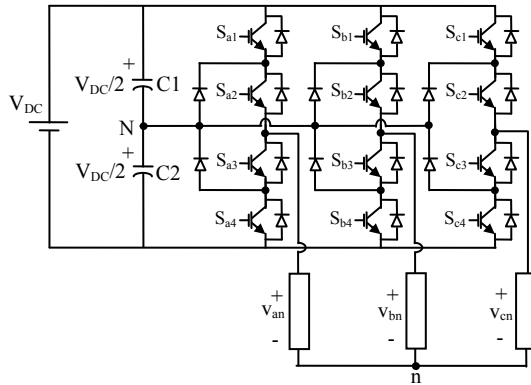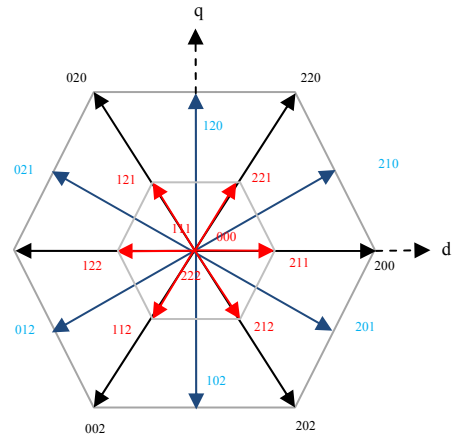
Figure 3. 3-level Neutral Point Clamped (NPC)

Figure 4. Greater number of switching vectors available in NPC inverter

Table 1. Switching combination for switches in each phase leg on NPC (X= {A, B, C})

S_{x1}	S_{x2}	S_{x3}	S_{x4}	V_x	Switching State
ON	ON	OFF	OFF	V_{DC}	2
OFF	ON	ON	OFF	0	1
OFF	OFF	ON	ON	$-V_{DC}$	0

4. PROPOSED SWITCHING STRATEGY

Figure 5 shows the proposed structure of DTC employed switching strategy using Neutral Point ClampedMultilevel Inverter. The different parts compared to conventional DTC structure are that; 1) the calculation of d-axis and q-axis voltage components, 2) sector definition, 3) torque hysteresis controller with 7-level of hysteresis bands and 4) modified look-up table with optimal voltage vectors.
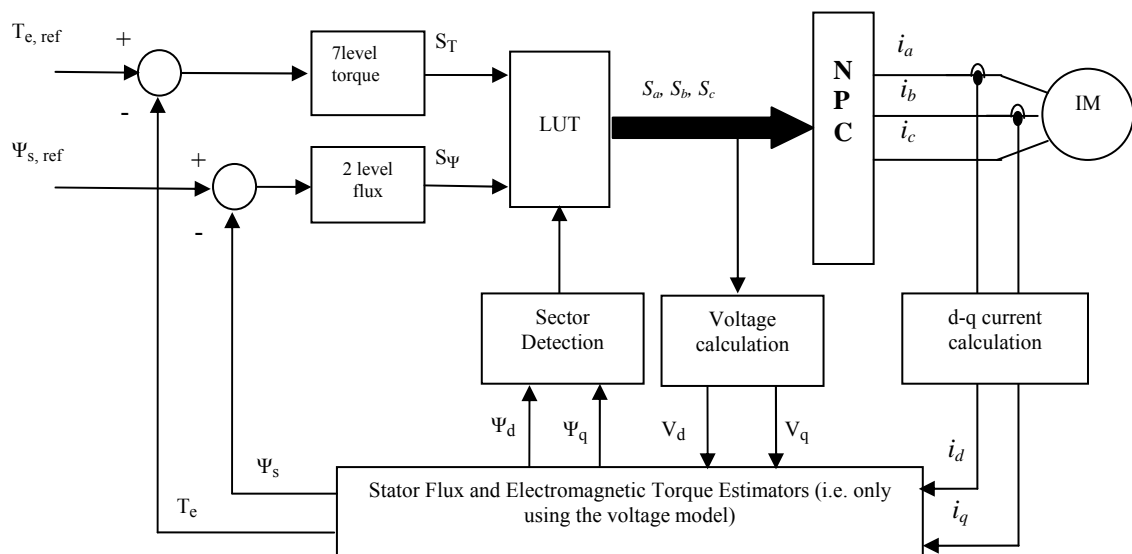

Figure 5. Propose structure of DTC of induction motor using simple multilevel inverter switching strategy
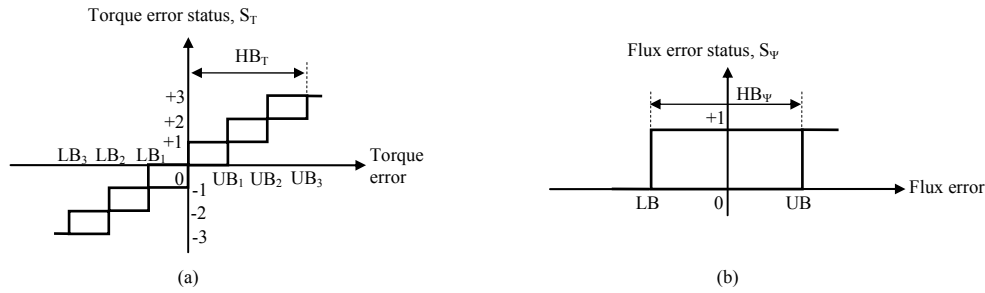
a. 7-level torque hysteresis controller

Figure 6. Hysteresis comparators for (a) torque controller with 7- Level hysteresis band (b) flux controller with 2-level hysteresis band

The selection of voltage vector is based on the operating conditions whether it is in low, medium or high speed (or torque). 7 level torque hysteresis and 2- level flux hysteresis comparator inherently produce the appropriate status according the motor operating conditions. By using this method, it will define more levels for torque error to be regulated. In this way, the largest amplitude of voltage vector is chosen due to large errors and hence provides quick torque dynamic response as well as better torque regulation at high speed (or torque) operations. In another case, lower amplitude of voltage vector is chosen when the small error resulted; this may reduce the torque ripple as well as switching frequency. As compared to the DTC with conventional inverter, the available voltage vectors to increase the torque are limited with same amplitude vectors and this cannot prevent the extreme torque increases which causes larger torque ripple resulted [16].

b. Calculation of d-axis and q-axis Voltage Components
The voltage in terms of d and q are:

$$V_d = \frac{1}{3}(2V_{aN} - V_{bN} - V_{cN})$$

$$V_d = \frac{V_{dc}}{12}\{[(2S_{a1} - 2\overline{S_{a1}}) + (2S_{a2} - 2\overline{S_{a2}})] - [(S_{b1} - \overline{S_{b1}}) + (S_{b2} - \overline{S_{b2}})] - [(S_{c1} - \overline{S_{c1}}) + (S_{c2} - \overline{S_{c2}})]\}$$

$$V_q = \frac{1}{\sqrt{3}}(V_{bN} - V_{cN})$$

$$V_q = \frac{V_{dc}}{6.93}\{[(S_{b1} - \overline{S_{b1}}) + (S_{b2} - \overline{S_{b2}})] - [(S_{c1} - \overline{S_{c1}}) + (S_{c2} - \overline{S_{c2}})]\} \qquad (2)$$

c. Sector Definition
The stator flux is divided into twelve sectors of 30 degrees, starting with the first sector situated between -30 and 0. By increasing the numbers of sectors to twelve, a more accurate selection of the inverter switching voltage vectors is obtained. This result in minimizing the error thus brings improvements of the responses of the flux and torque. By using this method, the change of flux error is restricted within the upper bands (UB) and the lower bands (LB) with the application of suitable active voltage vectors in order for the stator flux vector to keep track in its circular reference. In Figure 7, the angle δ_{sr} mainly affects the torque control behavior. If the rate of angle δ_{sr} increases at a particular operating condition (either higher or lower), the longest or the shortest amplitude of voltage vectors needs to be choosen. This method is applied if the rate of angle decreases.
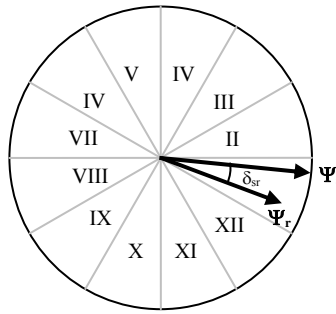
Figure 7. Control of torque is directly influenced by the variation of angle δ_{sr} due to the irregular motion of stator flux vector (e.g. in Sector I).

d.   Modified Look-Up Table
Table 2 shows a new lookup-table to index suitable voltage vectors based on flux sector information, the status generated from 7-level torque and 2-level flux hysteresis controllers.

Table 2. Proposed Look-Up Table

Status		Sector											
S_Ψ	ST	1	2	3	4	5	6	7	8	9	10	11	12
1	3	220	220	020	020	022	022	002	002	202	202	200	200
	2	210	120	120	021	021	012	012	102	102	201	201	210
	1	221	221	121	121	122	122	112	112	212	212	211	211
	0	222	000	222	000	222	000	222	000	222	000	222	000
	-1	212	212	211	211	221	221	121	121	122	122	112	112
	-2	102	201	201	210	210	120	120	021	021	012	012	102
	-3	202	202	200	200	220	220	020	020	022	022	002	002
0	3	020	020	022	022	002	002	202	202	200	200	220	220
	2	120	021	021	012	012	102	102	201	201	210	210	021
	1	121	121	122	122	112	112	212	212	211	211	221	221
	0	000	222	000	222	000	222	000	222	000	222	000	222
	-1	112	112	212	212	211	211	221	221	121	121	122	122
	-2	012	102	012	201	201	210	210	120	120	021	021	012
	-3	002	002	202	202	200	200	220	220	020	020	022	022

5.   SIMULATION RESULTS

Some simulations were carried out to verify the effectiveness of using the proposed switching strategy. The motor parameters and DTC system values used in the simulations are given in Table 3.

Table 3. Values of Induction Motor Parameters

Parameters	value
Stator resistance, R_s	1.405 Ω
Rotor resistance, R_r	1.395 Ω
Stator self inductance, L_{1s}	0.178 H
Rotor self inductance, L_{lr}	0.178 H
Mutual inductance, L_m	0.172 H
No of poles, p	4
Torque hysteresis band, HB_T	0.6 Nm
Flux hysteresis band, HB_Ψ	0.01 Wb
Torque rated	10 Nm
Flux rated	1.0 Wb
Sampling period	1 μs

The improvements of the proposed switching strategy were verified through simulation results as shown by Figure 8. A step change of reference torque (T_e^*) was applied from -10 Nm to +10 Nm at t=0.7 s. It can be seen from the Figure 8 that the output torque regulated at its reference.
Initially, the stator flux angular velocity as well as motor speed is slower. It is therefore, the torque error status switches alternately between 0 and 1 in order to select lower amplitude voltage vectors. When the

torque is suddenly changed to +10 Nm, it can be noticed that the torque error status, S_T=2 momentarily for very short period of time (i.e. during torque transient). This indicates that the largest amplitude voltage vector is applied to produce the quickest torque increases to reach its new demand. Then, it can also be noticed that the switching of torque error status S_T gradually changes from S_T=0↔1 to S_T=1↔2 and finally to S_T=2↔3 for increasing the output voltage in satisfying the torque demand as the stator flux angular velocity increases. The mapping of voltage vectors during the respective switching operation can be shown by simulation results given in Figure 9. The corresponding d- and q-axis flux components resulted in Figure 8 can be re-plotted in order to show a circular flux locus (in Figure 10) for control of stator flux at 0.9 Wb.
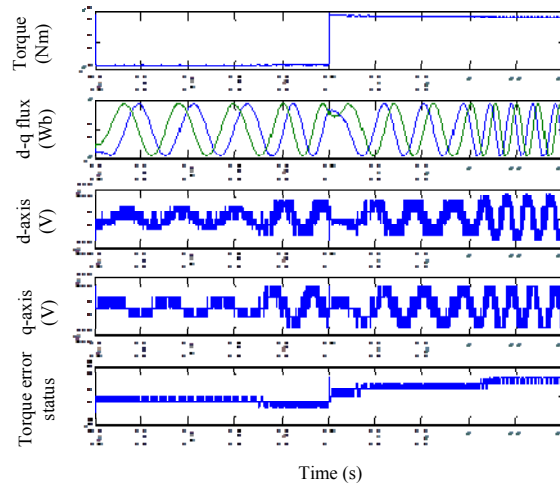

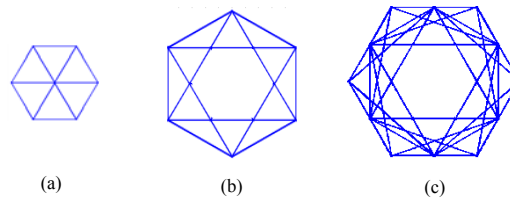Figure 8. Simulation results of torque control using the proposed

Figure 9. Simulation results of voltage vector selection when ST switches alternately between (a) S_T=0 and 1, (b) S_T =1 and 2 and (c) S_T=2 and 3.
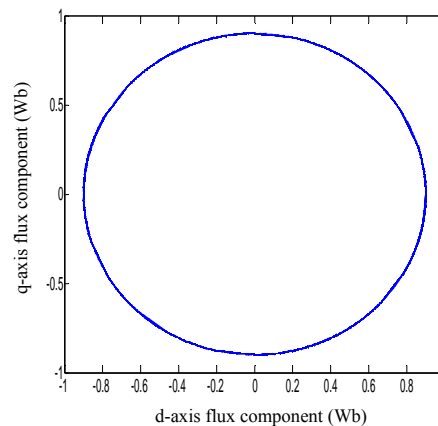

Figure 10. Stator flux locus

6. CONCLUSION

This paper presented a simple implementation to improved performance of Direct Torque Control of induction machine with 3-level Neutral Point Clamped multilevel inverter. It has shown that the selection of appropriate voltage vector based on the status generated from 7-level hysteresis controller which inherently influenced by the operating conditions. It can be proved that the appropriate selection of vectors can improve the DTC performances in terms of torque ripple, switching frequency and torque dynamic control. With application of lower amplitude vector, particularly at lower speed, this can prevent the extreme torque slope, larger torque ripple and switching frequency. On the other hands, the larger amplitude vector is chosen to improve torque dynamic and torque regulation particularly at high speed operations

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