Three-level Inverter Direct Torque Control of Induction Motor Based on Virtual Vectors

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Abstract- **Multilevel inverter has attracted great interest in high-voltage high-power field because of its less distorted output. In this paper, a direct torque control (DTC) technique based on a three-level neutral-point-clamped (NPC) inverter is presented. In order to solve the intrinsic neutral-point voltage-balancing problem and to obtain a high performance DTC, a special vector selection method is introduced and the concept of virtual vector is developed. By using the proposed PWM strategy, a MRAS speed sensor-less DTC drive can be achieved without sensing the neutral-point voltage. The strategy can be verified by simulation and experimental results.**

Keywords: **Three-level, NPC, DTC, Virtual Vectors**

I. INTRODUCTION

Direct torque control (DTC), with its fast response in torque, parameter insensibility and minimized inverter switching frequency, has attracted great interest [1]-[3] [8] [9] in the field of high dynamic ac drive since it was proposed [4]. Many of literatures, however, focus on two-level inverter-fed DTC, and there are only a few researches on the direct torque control of high voltage motor.

In high voltage and high power applications, the three-level neutral-point-clamped (NPC) inverter presents more advantages over the conventional two-level inverter, such as smoother waveform, less distortion, less switching frequency and lower costs, etc. Though this type of inverter has been already implemented in practical applications, the control strategies on this topology are still mostly based on space vector modulation method [5][6], and cannot achieve high performance. Actually, with NPC inverter, more flexible control, i.e. DTC, can be implemented, but the complexity of voltage selection becomes another problem. In the following paragraphs, a newly developed direct torque control technique based on NPC inverter will be presented, and details of its two techniques: voltage vector selection and dc link neutral-point voltage-balancing are described.

II. PRINCIPLES OF VOLTAGE VECTOR SELECTION FOR NPC INVERTER-FED DTC

A. Voltage vectors of the three-level NPC inverter

The basic principle of vector selection on an NPC inverter is similar to a conventional two-level one in a DTC system. However, as the NPC inverter gives more vectors than a two-level one, there may exist multiple modulation schemes. Fig. 1 shows the voltage vectors of a three-level NPC inverter in the α - β reference axes.

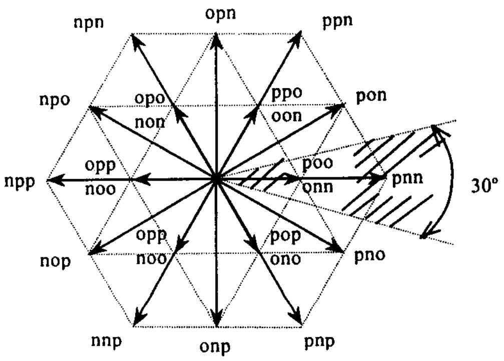


Fig. 1 Voltage vectors of a three-level NPC inverter

And these voltage vectors can be divided into four groups, as shown in Table 1.

TABLE 1

CATALOG OF VOLTAGE VECTORS

Vector groups	Voltage vectors
Large vectors	pnn, ppn, npn, npp, nnp, pnp
Medium vectors	pon, opn, npo, nop, onp, pno
Small vectors	poo, onn, ppo,oon, opo, non, opp, noo, opp,noo, pop, onn
Zero vectors	ppp, ooo, nnn

B. Principle of direct torque control and voltage vector selection

The fundamental equations set of an induction motor can be described as follows (in stationary reference frame):

$$\vec{V}_s = R_s \vec{I}_s + p\vec{\psi}_s , \qquad 0 = R_r I_r + p\vec{\psi}_r - j\omega\vec{\psi}_r , \quad (1)$$

$$\vec{\psi}_s = L_s \vec{I}_s + M\vec{I}_r , \qquad \vec{\psi}_r = L_r \vec{I}_r + M\vec{I}_s , \quad (2)$$

$$T = P(\vec{\psi}_s \otimes \vec{I}_s) . \quad (3)$$

where $\vec{V}_s$, $\vec{I}_s$, $\vec{\psi}_s$ are stator voltage, current and flux linkage vector respectively.

$\vec{I}_r$, $\vec{\psi}_r$ rotor current and flux linkage vector

R_s , R_r stator and rotor resistance

L_s , L_r stator and rotor self inductance

M , P mutual inductance and number of pole pairs

In a DTC drive, by the selection of optimum voltage vectors, stator flux linkage and electromagnetic torque are controlled directly [2][4]. The selection is made to restrict the flux linkage and torque error. The required vectors can be selected from an optimum look-up table, which can be obtained by knowing the position of stator flux linkage, the required torque and flux linkage.

Different from conventional two-level inverter, there is a problem that must be taken into account, i.e., the dv/dt of output voltage for each switching, for example, ΔV of two successive vectors in each bridge should not be over E/2 (where E is the dc link voltage).

Therefore, the principle of single vector in one sampling period, which is used in most DTC of two- level inverter, cannot be applied in some cases. i.e., when the flux is in the shadowed region (Fig. 1), and flux is to be decreased while torque should be increased, then vector npn, opo, non or npo is generally preferred. However, if the vector currently applied to the inverter is pon, none of these four vectors is allowed because vector npn, non or npo will lead to high ΔV in phase A, and vector opo will cause high ΔV in line voltage U_{AB}. It is one of the problems that must be solved to apply DTC in a three-level inverter.

Fortunately, the frequency of high ΔV occurrence are greatly reduced if one of the successive vectors is zero or small vector after all possible successive vectors have been reviewed, i.e. zero and small vector is the most preferable in vector selection. In other words, zero or small vectors can be used to reduce the high ΔV caused by successive vectors. In practice, multiple vectors are applied in one sampling period, and zero/small vectors are preferable at the beginning/end of each sampling period. The voltage vector selection method will be summarized in details in section IV, where the neutral-point voltage balance problem will be also taken into consideration.

Here, 3 principles are given first:

1) Select the vector (which should meet the flux and torque command) nearest to stator flux

2) The selected vector should not generate high dv/dt

3) Zero or small vector is preferred at the beginning/end of each sampling period.

III. DC LINK NEUTRAL-POINT VOLTAGE BALANCE

DC link neutral-point voltage shift is an intrinsic problem in an NPC inverter. Various PWM algorithms have been reported to solve this problem since the NPC inverter was firstly introduced in 1981[7]. However, these algorithms are generally based on open-loop space vector modulation (SVM) method, and are not suitable for the strategy of direct torque control which is based on an optimum vector table given by the closed-loop control of torque and flux. To solve this problem, the concept of virtual vector is developed, which can be easily applied to the conventional DTC scheme without any major modification.

A. Effects of space vectors on the neutral-point voltage

There is no effect on neutral-point voltage with large (eg. pnn) and zero vectors (defined in paper), and only small and medium vectors generate non-zero current into or out of the neutral point. It is this non-zero neutral point current that causes the neutral-point voltage-unbalance problem [5]. Table 2 shows the space vectors and their relative effects on neutral point currents.

B. The concept of virtual vectors

To solve the neutral-point voltage unbalance problem and to avoid the high ΔV problem between successive vectors, the concept of virtual vectors is introduced for the DTC strategy. A virtual vector is similar to a synthesized vector used in conventional space vector modulation, but its position is fixed. There are two types of virtual vectors: one is relative to medium vectors (such as pon), and the other is relative to large vectors (such as pnn).

TABLE 2

SPACE VECTORS AND THEIR RELATIVE NEUTRAL-POINT CURRENTS [5].

Positive small vectors	i_{NP}	Negative small vectors	i_{NP}	Medium vectors	i_{NP}
onn	ia	poo	-ia	pon	ib
ppo	ic	oon	-ic	opn	ia
non	ib	opo	-ib	npo	ic
opp	ia	noo	-ia	nop	ib
nno	ic	oop	-ic	onp	ia
pop	ib	ono	-ib	pno	ic

1) Virtual vectors relative to medium vectors

According to Table 2, if vector pon is selected for next sampling period, it will cause neutral point voltage unbalance because of its relative current i_b (generally non-zero). This problem may be solved if vector onn and ppo are added to the vector pon in the same sampling period with equivalent duty cycles (1/3). In this case, the position of the synthesized vector (synthesized by vectors onn, pon, and ppo) is the same as vector pon (Fig. 2), and the total relative neutral-point current i_{NP} is zero (ia+ib+ic=0). Therefore, it is possible to meet the flux and torque command while eliminating the neutral point current.

2) Virtual vectors relative to large vectors

In other cases, a large vector, such as pnn may be selected. Though it will not affect the balance of neutral-point voltage, virtual vector is also necessary because of the dv/dt problem that is mentioned in section II.

In this case, vector poo and onn are added to vector pnn in one sampling period, and these two vectors have equivalent duty cycles. Therefore the synthesized virtual vector is located at the same position of original vector pnn. But, in this case, its length is not fixed and can be adjusted by changing the duty cycle of small vector pair (such as vector poo and onn). Finally, a new diagram of space vectors based on virtual vectors can be summarized as in Fig. 2.

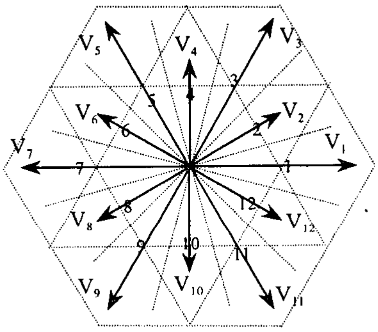


Fig.2 Virtual vectors in α - β plane

IV. DTC BASED ON VIRTUAL VECTORS

A. Vector selection method

With these 12 virtual vectors and zero vectors, an optimum look-up table similar to a conventional two-level one can be easily obtained, as shown in Table 3.

TABLE 3

OPTIMUM LOOK-UP TABLE BASED ON VIRTUAL VECTORS

Expectation	Required virtual vector
To increase flux and torque	V_{k+1}*
To increase flux and decrease torque	V_{k-1}*
To decrease flux and increase torque	V_{k+4}*
To decrease flux and torque	V_{k-4}*
To decrease flux and torque slightly	Zero vectors

* k is section number, and k=1~12, as shown in Fig. 2.

B. Synthesis of virtual vectors

The small and zero vectors can be divided into two groups: as is shown in Table 4, the adjacent small vectors in one group will not result in high dv/dt, eg, opo is next to ppo, and previous to opp, therefore vector opo is "adjacent" with vector ppo and opp. In some other cases, however, the preferred vectors are not always adjacent, so a zero vector should be inserted in order to avoid high dv/dt. A typical PWM pattern (symmetric PWM) is shown as follow:

```
***n | noppppon | ***
***o | nnopponn | ***
***n | nnnoonnn | ***
 Ts  |<---Ts--->|  Ts
```

TABLE 4

VECTOR GROUPS

Vector groups	Small/zero vectors
Group P	poo, ppo, opo, opp, oop, pop (ppp, ooo)
Group N	onn, oon, non, noo, nno, ono (nnn, ooo)

Neutral-point voltage variation in one sampling period can be greatly limited by applying the above techniques. However, problem still exists, i.e., the neutral-point voltage will shift slowly, which will cause great troubles in some cases. To solve this problem, an improved vector selection technique is introduced.

According to the PWM pattern above, it is clear that the vectors at the beginning/end of each sampling period are always in the same vector group (group P or N) (if not, high dv/dt will be inevitable). From the experimental result below, it can be seen that, if group P is used, the neutral-point voltage will slowly increase, and if group N is used, the neutral-point voltage will slowly decrease. Fortunately, note that zero vector ooo belongs to both group P and N, vector group P and N can be used respectively through zero vector ooo.

C. A typical DTC system based on virtual vectors

With the optimum vector look-up table (Table 3), a DTC strategy based on a three-level NPC inverter can be achieved by using the virtual-vector method. Fig. 3 illustrates a typical DTC system based on virtual vectors.

V. SIMULATION AND EXPERIMENTAL RESULTS

Simulations are implemented at starting of the induction motor without load and loaded suddenly at 0.5s. Simulation results show that the proposed DTC scheme has a very fast torque response (Fig. 4 (a)). Fig.4 (b) and (c) illustrate the output voltage and current waveforms. By using the proposed virtual vector technique, the variation of neutral-point voltage is greatly limited, and even without sensing the neutral-point voltage (Fig.4 (d)). Also the ΔV between two successive vectors will be never over E/2 (Fig.4 (e)).

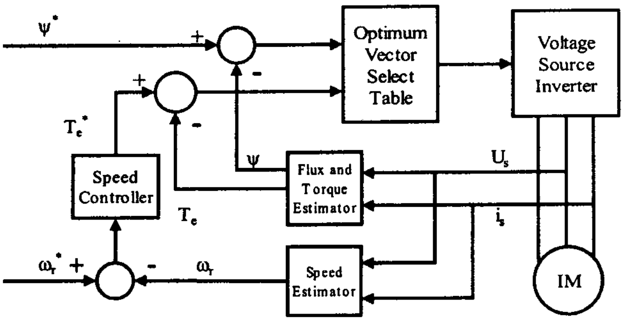
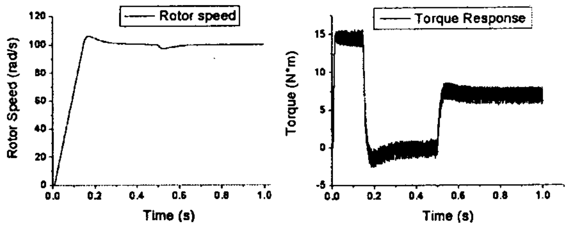
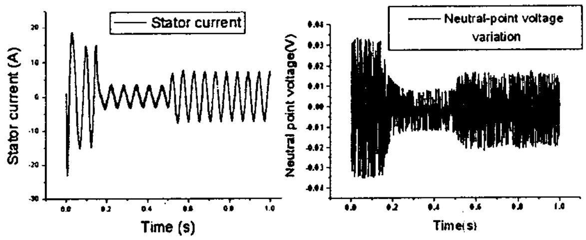


Fig. 3 Diagram of a typical speed sensor-less DTC strategy

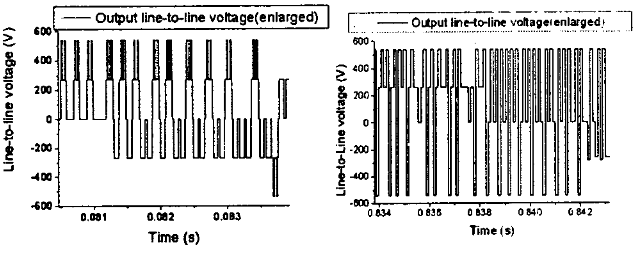
As a comparison, the simulation results of a DTC system with single vector method (i.e. only one vector is applied in a single sampling cycle) are reported. It can be seen that the high dv/dt problem emerges frequently (Fig.4 (f)), and the neutral-point voltage is shifting upward (Fig.4 (g)).



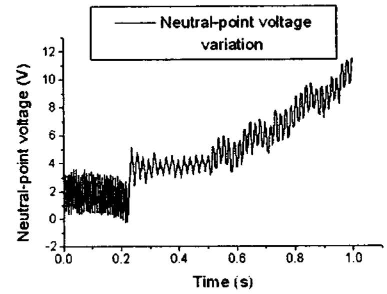
(a) Rotor speed (b) Torque response



(c) Stator current (d) Neutral-point voltage (with improved vector selection method)



(e) Line-to-line voltage (enlarged) (f) Line-to-line voltage (with single vector method)

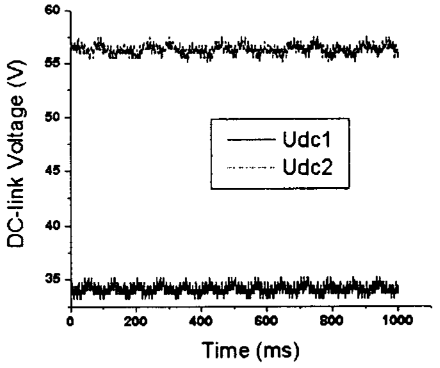


(g) Neutral point voltage variation (with single vector method)

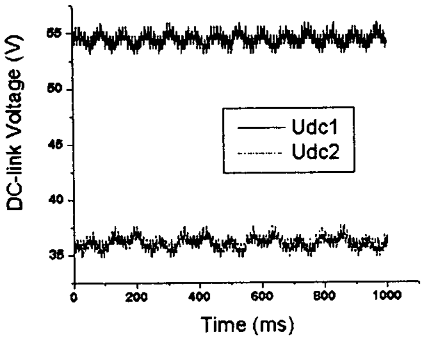
Fig. 4 Simulations results

A DSP (TMS320F240 DSP) based motor drive system is developed to verify the proposed control strategy. An MRAS (Model Reference Adaptive System) speed sensor-less method [10] is applied to the system. The sampling cycle is set at 100us, and the dead time is 4.5us.

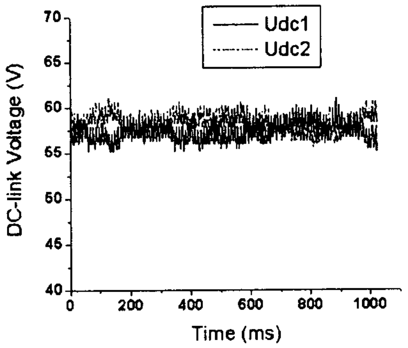
The experiments are carried on at 5Hz (31.4 rad/s) without load. The shifts of neutral-point voltage, as shown in Fig. 5(a) and (b) can be eliminated (Fig.5(c)). From Fig. 5(a) and (b), it is clear that the shifts of neutral-point voltage are in opposite directions with only vectors in Group P or N being used in the beginning/end of each sampling period. Hence, an improved vector selection method, which uses Group P and N alternately, can be obtained. In the experiments, the balance control of neutral-point voltage is in open-loop mode. The estimated rotor speed tracks the reference speed (31.4 rad/s) very well (Fig.5 (d)). And the output line voltage and stator current are presented in Fig. 5(e), (f) respectively. From the experiment results, it can be seen that the high dv/dt problem can be solved successfully with the proposed virtual-vector method.



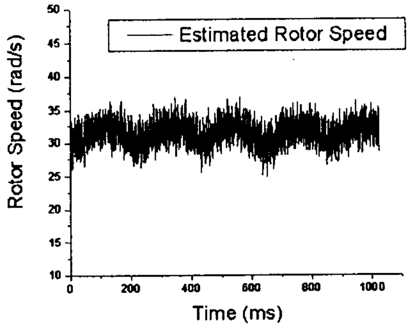
(a) DC-link voltage (Group N)



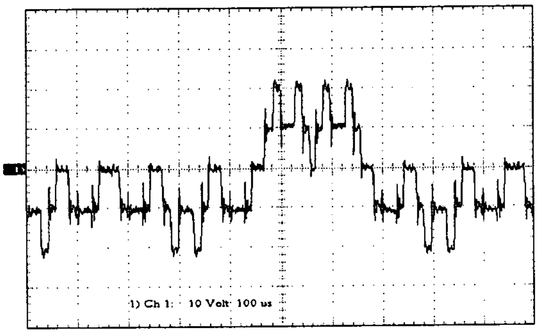
(b) DC-link voltage (Group P)



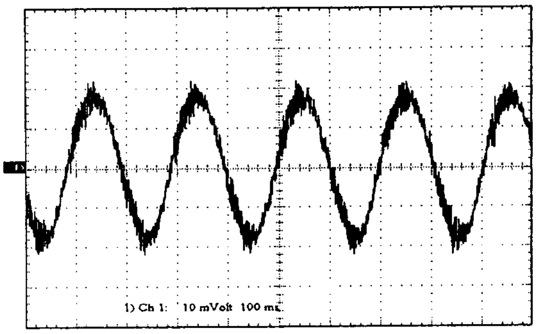
(c) DC-link voltage (with improved vector selection method)



(d) Estimated rotor speed



(e) Output line-to-line voltage (50V/div, 100us/div)



(f) Stator current (1A/div, 100ms/div)

Fig. 5 Experimental results

VII. CONCLUSIONS

The dc link neutral-point voltage unbalance problem can be solved in satisfactory way by using the proposed virtual-vector and the new vector selection techniques. The neutral-point voltage variation can be greatly limited and the voltage shift can be eliminated. A high performance DTC system is constructed on these techniques. Simulation and experimental results prove that the proposed methods are feasible and are suitable to a three-level DTC drive based on NPC inverter.

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