SVM Algorithm of Three-Level NPC Inverter

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***Abstract*-On the basis of presenting the principles of Space Vector Modulation (SVM) of three-level Neutral Point Clamped (NPC) inverter, an approach to implementation of SVM is proposed. The dwell times of vectors are calculated according to the volt-second balancing. A triangle is adopted to compare with three switching points. The three switching points are determined by the dwell times. According to the comparing results and the location of the triangles that the reference vector falls in, the switching sequences can be arranged. The control of the neural point voltage is realized by adjusting the switching points. The simulation results verify that the proposed approach is correct and feasible.**

I. INTRODUCTION

For high power application, multilevel inverter structures have the outstanding advantages. Compared with the traditional two-level voltage inverter, the main advantage of multilevel converters is their smaller output voltage steps, which results in higher power quality, lower harmonic components, better electromagnetic compatibility, and lower switching losses. There are three common voltage synthesis-based multilevel inverters: diode-clamp, flying-capacitors, and cascaded-inverters with separated dc sources. Due to the great control complexity and number of capacitors for flying-capacitors converter and separate DC sources for the cascaded-inverter, the diode-clamped topology is found to be more suitable for the high-power applications [1,2].

Pulse width modulation schemes used in the conventional inverter can be modified to use in the multilevel converters. The three main multilevel PWM methods most discussed in the literature have been multilevel carrier-based PWM, selective harmonic elimination, and multilevel space vector PWM, all are extensions of the conventional two-level PWM schemes to multilevel converters. Among these schemes, space vector modulation is an attractive scheme due to its easy digital implementation, optimal switching sequence, and higher usage of DC rail voltage. There have been a few attempts to provide a fast, simple, general switching algorithms for multilevel inverter using SVM. Amit Kumar Gupta presented the algorithm based on the two-level SVM algorithm [3]. The computations based on the two-level SVPWM do not increase with level. The algorithm can be easily implemented by available microcontroller or DSP, which normally supports two-level modulation. The main advantage is that it can be used directly in the existing torque or speed system. Sanmin Wei presented a SVM algorithm realized in the 60° coordinate system [4]. The algorithm substantially simplifies the calculation of space vectors and their corresponding dwell times. Subrata K. Mondal proposed a feedforward ANN-based SVM implementation of a three-level voltage-fed inverter [5]. A 1-24-12 BP neural network for the SVM implementation of the three-level inverter was adopted. The performance of the ANN-based modulator is excellent. Unfortunately, the scheme is not suitable for the practical application.

This paper describes a practical SVM implementation of a three-level voltage-fed inverter. At first, SVM basic principle for three-level inverter is reviewed briefly. The general expressions of time dwells of space vector are derived. The switching sequences are given in order to get symmetrical pulse and neutral-point voltage balancing. Then the practical SVM algorithm is proposed. The algorithm is implemented easily by microcontroller or DSP. Simulation results are provided to prove the proposed SVM algorithm.

II. BASIC PRINCIPLE OF SVM

Fig. 1 is a circuit diagram of a three-level voltage-fed inverter and the switching states of each bridge of the inverter are list in Table 1. There are three kinds of switching states P, O, and N in each bridge, so there exist 27 kinds of switching states in three-phase three-level inverter [6].

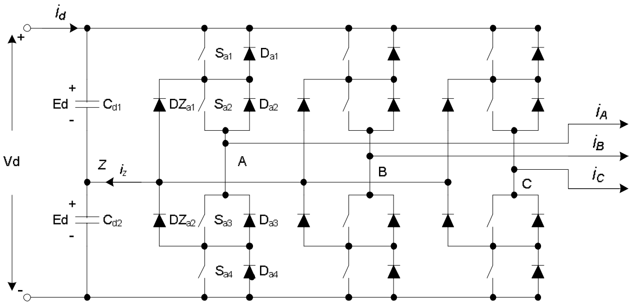

Fig. 1 Circuit diagram of three-level inverter

Table 1
Definition of switching states

Switching State	Device Switching Status				Terminal Voltage
	S1	S2	S3	S4	
P	on	on	off	off	Ed
O	off	on	on	off	0
N	off	off	on	on	-Ed

The space vector diagram is showed in Fig. 2. The 27 switching states of the three-level inverter correspond to 19 space vectors. Based on their magnitude, these space vectors can be divided into four groups: zero vector, small vectors, medium vectors, and large vectors. Zero vector has three

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switching states, each small vector has two switching states, and each medium and large vector only has one switching states. In the small vectors, the vector containing switching state P is called P-type small vector, the vector containing switching state N is called N-type small vector. These vectors have different effect on neutral point voltage deviation. Small vectors have a dominant effect on neutral point voltage, the P-type small vectors make NP voltage rise, while the N-type small vectors make NP voltage decline. The medium vectors also affect NP voltage, but the direction of the voltage deviation is undefined. Zero vector and large vectors do not affect the NP voltage.

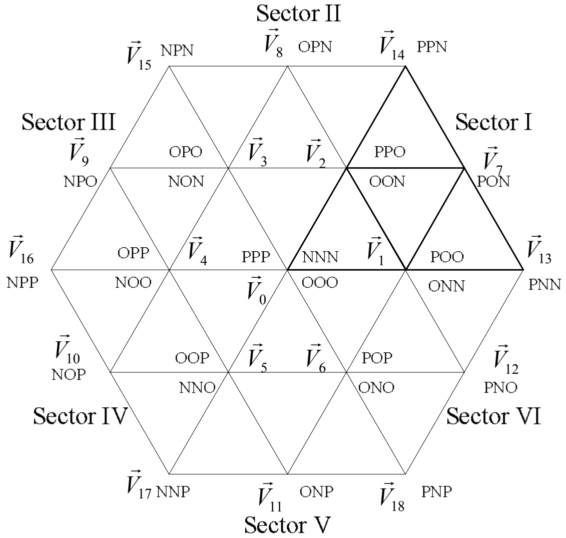

Fig. 2 The space vector diagram of three-level inverter

To calculate the dwell time of space vectors, the space vector diagram can be divided into six triangle sectors (Ⅰ~Ⅵ) as showed in Fig. 2, each of which can be further divided into four triangle regions (1~4) as showed in Fig. 3.

In the three-level NPC inverter, the reference vector $\vec{V}_{ref}$ can be synthesized by the nearest three space vectors based on the volt-second balancing principle. The nearest three vectors are chosen to reduce harmonic distortion in the inverter output voltage. If $\vec{V}_{ref}$ falls into region 3 of sector Ⅰ as shown in Fig. 3, the three nearest vectors are $\vec{V}_1$, $\vec{V}_2$, and $\vec{V}_7$. The following expressions can be gotten based on the volt-second balancing.

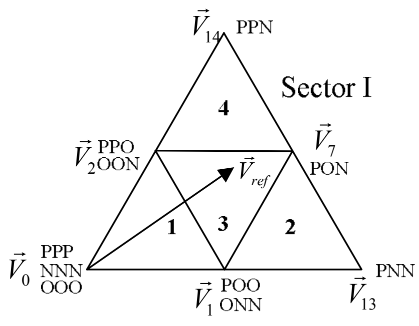

Fig. 3 Space vectors and their dwell times

$$\vec{V}_1 t_1 + \vec{V}_2 t_2 + \vec{V}_7 t_7 = \vec{V}_{ref} T_s \tag{1}$$

$$t_1 + t_2 + t_7 = T_s \tag{2}$$

Where t_1, t_2, and t_7 are the dwell times for $\vec{V}_1$, $\vec{V}_2$, and $\vec{V}_7$, respectively.

In stationary α-β plane, $\vec{V}_{ref}$ can be expressed as following

$$\vec{V}_{ref} = V_\alpha + jV_\beta \tag{3}$$

Solve three equations (1), (2), and (3) for dwell times

$$t_1 = T_s - \frac{2\sqrt{3}V_\beta}{V_d} T_s$$

$$t_2 = T_s - \frac{3}{V_d}(V_\alpha - \frac{V_\beta}{\sqrt{3}})T_s$$

$$t_7 = -T_s + \frac{3}{V_d}(V_\alpha + \frac{V_\beta}{\sqrt{3}})T_s$$

Define three variables X, Y, Z

$$X = \frac{2\sqrt{3}V_\beta}{V_d}$$

$$Y = \frac{3}{V_d}(V_\alpha + \frac{V_\beta}{\sqrt{3}})$$

$$Z = \frac{3}{V_d}(V_\alpha - \frac{V_\beta}{\sqrt{3}})$$

The following expressions can be achieved

$$t_1 = (1 - X)T_s$$

$$t_2 = (1 - Z)T_s$$

$$t_7 = (-1 + Y)T_s$$

When $\vec{V}_{ref}$ falls into other regions in Sector 1, the dwell times are as following

In region 1,

$$t_0 = (1 - Y)T_s$$

$$t_1 = ZT_s$$

$$t_2 = XT_s$$

In region 2,

$$t_1 = (2 - Y)T_s$$

$$t_{13} = (-1 + Z)T_s$$

$$t_7 = XT_s$$

In region 4,

$$t_2 = (2 - Y)T_s$$

$$t_7 = ZT_s$$

$$t_{14} = (-1 + X)T_s$$

The dwell times can be calculated as above when reference vector is in other sectors.

The neutral point voltage varies with the switching states of the NPC inverter, so the switching sequencing should be taken into account to control the neutral point voltage. When the reference vector falls into different regions, there are two cases for the selected three vectors. One is that there are two small vectors among the three vectors, such as in region 1, 3; the other is that there is only one small vector, such as in region 2, 4. The switching sequencing is different for these two cases.

In region 1, the switching sequencing is

$$\vec{V}_{1N}-\vec{V}_{2N}-\vec{V}_{0}-\vec{V}_{1P}-\vec{V}_{0}-\vec{V}_{2N}-\vec{V}_{1N}$$

In region 2, the switching sequencing is

$$\vec{V}_{1N}-\vec{V}_{13}-\vec{V}_{7}-\vec{V}_{1P}-\vec{V}_{7}-\vec{V}_{13}-\vec{V}_{1N}$$

If the dwell times of the P-type small vector and N-type small vector are equally distributed, it can make the neutral point voltage balance.

III. ALGORITHM

According to the basic principle of SVM, when the inputs are the reference voltage $\vec{V}_{ref}$, the proposed algorithm of SVM is as following.

A. Determination of sector

It is easy to determine in which sector the reference voltage falls in by V_α and V_β. The value N is calculated by the following expression.

$$N = sign(V_\beta) + 2sign(V_\alpha \sin 60° - V_\beta \sin 30°) + 4sign(-V_\alpha \sin 60° - V_\beta \sin 30°)$$

Where sign(x) is sign function. When x is greater than zero, the value is 1; otherwise, it is zero.

The relationship between N and the sector S as in Fig. 2 is showed in Table 2.

Table 2
The relationship between N and sector S

S	I	II	III	IV	V	VI
N	3	1	5	4	6	2

B. Determination of triangles

In each sector, there are four triangles defined as in Fig. 3. The calculation of the dwell times for the three nearest space vectors is different. The determination of the triangles is judged by three rules.

Rule1: $V_\alpha + \frac{\sqrt{3}}{3}V_\beta \le \frac{V_d}{3}$

Rule2: $V_\alpha - \frac{\sqrt{3}}{3}V_\beta \ge \frac{V_d}{3}$

Rule3: $V_\beta > \frac{\sqrt{3}}{6}V_d$

The judgement of the triangles is showed in Table 3. The value M of the triangles is determined by the three rules.

Table 3
The judgement of the triangles

Triangle		Rule 1	Rule 2	Rule 3
M	1	YES	--	--
	2	NO	YES	--
	3	NO	NO	YES
	4	NO	NO	NO

The location of the triangles is easy to get by the sector N and triangle M.

$$K = (S-1)\times 4 + M$$

Where $S = 1 \sim 6$, $M = 1 \sim 4$.

C. Calculation of the dwell times

In the last section, the dwell times are calculated in sector Ⅰ. If the dwell times in all triangles are listed, some rules will be found. So the dwell times can be calculated by look-up. In the proposed SVM algorithm, only two dwell times t_1 and t_2 are calculated according to the location of the triangles. The third dwell time need not to calculate. The calculation of the dwell time t_1 and t_2 is as following.

For the dwell time t_1

$$U_1 = XT_s[1,0,0,0,-1,0,1,0,0,1,-1,1,0,-1,0,-1,0,0,0,0,0,0,0,0]^T$$

$$V_1 = YT_s[0,0,0,0,0,0,0,0,-1,0,0,0,1,0,-1,0,0,-1,1,-1,0,1,0,1]^T$$

$$W_1 = ZT_s[0,1,-1,1,0,-1,0,-1,0,0,0,0,0,0,0,0,1,0,0,0,-1,0,1,0]^T$$

$$C_1 = T_s[0,-1,1,0,1,0,-1,-1,0,-1,1,0,1,0,-1,-1,0,-1,1,0,1,0,-1,-1]^T$$

$$t_1 = U_1 + V_1 + W_1 + C_1$$

For the dwell time t_2

$$U_2 = XT_s[1,1,0,1,0,0,0,0,0,0,0,0,-1,0,0,0,1,0,-1,0,0,-1,1,-1]^T$$

$$V_2 = YT_s[0,0,1,0,0,1,-1,1,0,-1,0,-1,0,0,0,0,0,0,0,0,1,0,0,0]^T$$

$$W_2 = ZT_s[0,0,0,0,-1,0,0,0,1,0,-1,0,0,-1,1,-1,0,1,0,1,0,0,0,0]^T$$

$$C_2 = T_s[0,0,-1,-1,0,-1,1,0,1,0,-1,-1,0,-1,1,0,1,0,-1,-1,0,-1,1,0]^T$$

$$t_2 = U_2 + V_2 + W_2 + C_2$$

$U_1 \sim C_1$ and $U_2 \sim C_2$ are calculated by K. After calculating the dwell times t_1 and t_2, three switching points can be achieved. A triangle which period is T_s is given to compare with three switching points t_a, t_b, and t_c.

$$t_a = \frac{T_s - t_1 - t_2}{4}$$

$$t_b = t_a + \frac{t_1}{2}$$

$$t_c = t_b + \frac{t_2}{2}$$

The switching points are arranged by the location of the triangles. Table 4 depicts this arrangement.

Table 4
The arrangement of switching points

Triangle				Phase A	Phase B	Phase C
Ⅰ-1	Ⅰ-3	Ⅱ-3	Ⅲ-4	t_c	t_a	t_b
Ⅰ-2	Ⅰ-4	Ⅴ-1	Ⅵ-3	t_a	t_b	t_c
Ⅱ-2	Ⅱ-4	Ⅲ-2	Ⅵ-1	t_b	t_a	t_c
Ⅱ-1	Ⅲ-3	Ⅳ-2	Ⅳ-4	t_c	t_b	t_a
Ⅲ-1	Ⅳ-3	Ⅴ-2	Ⅴ-4	t_b	t_c	t_a
Ⅴ-3	Ⅵ-1	Ⅳ-2	Ⅵ-4	t_a	t_c	t_b

D. Determination of switching sequence

The switching sequence is determined by the location of the triangles K and switching points t_a, t_b, and t_c. The output values of comparing between switching points and the triangles are different when the triangles value K varies. For phase A, when K varies from 8 to 19, the output values are 1 or 0; otherwise, the output values are 0 or –1. For phase B, when K varies from 4 to 15, the output values are 1 or 0; otherwise, the output values are 0 or –1. For phase C, when K varies from 12 to 23, the output values are 1 or 0; otherwise, the output values are 0 or –1. For each inverter bridge, according to the output value –1, 0, and 1, one of three switching states N(0011), O(0110), and P(1100) are chosen. For the three-phase inverter, the desired symmetrical switching sequence is achieved. The switching sequence in sector Ⅰ is showed in Table 5.

Table 5
Switching sequence in sector Ⅰ

Sequence	1	2	3	4
1st	ONN	ONN	ONN	OON
2nd	OON	PNN	OON	PON
3rd	OOO	PON	PON	PPN
4th	POO	POO	POO	PPO
5th	OOO	PON	PON	PPN
6th	OON	PNN	OON	PON
7th	ONN	ONN	ONN	OON

E. Control of neutral point voltage

Generally, the neutral point voltage can be controlled by adjusting the dwell time distribution between the P-type small vectors and the N-type small vectors. In this paper, a switching points' adjustment method is proposed in the proposed SVM algorithm. The basic idea is that the three switching points are modified according to the deviation of the neutral point voltage. The modified switching points are given by

$$t_a' = t_a(1+ke)$$

$$t_b' = t_a' + \frac{t_1}{2}$$

$$t_c' = t_b' + \frac{t_2}{2}$$

Where e is the deviation of the neutral point voltage, k is the adjusting coefficient.

In the method, switching points are modified by the deviation of the neutral point voltage, but the dwell times t_1 and t_2 are not modified. It means that the dwell times of the P-type small vectors and the N-type small vectors are changed by this method.

IV. SIMULATION RESULTS

In order to verify the proposed SVM algorithm, the algorithm is constructed by MATLAB /SIMULINK and Simpowersystems tools. An induction motor is adopted as load of three-phase voltage-fed three-level inverter. Table 6 gives the parameters of the induction motor and the inverter for simulation study.

Table 6
Parameters of motor and inverter

DC link voltage:	540V
Sampling time:	1ms
Induction motor:	3phase, 2.2Kw, 380V, 2-pole
	Frequency range: 0~50Hz
	Stator resistance: 2.92ohm
	Rotor resistance: 1.92ohm
	Stator leakage inductance: 5.71mH
	Rotor leakage inductance: 5.71mH
	Magnetizing inductance: 95.8mH

Fig. 4 shows the machine line voltage and current waveforms when the frequency of the machine is 50Hz. Fig. 5 shows the machine line voltage and current waveforms when the frequency of the machine is 10Hz. Fig. 6 shows the machine speed waveform when the frequency of the machine is 50Hz. Fig. 7 shows the machine speed waveform when the frequency of the machine is 10Hz. Fig. 8 shows the waveform of neutral point voltage deviation. In Fig.8, at t=2.5s, the control of the neutral point voltage begins to be applied.

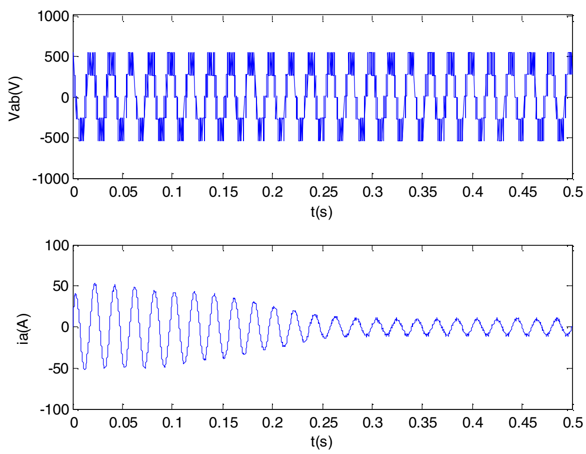

Fig. 4 The machine line voltage and current waveforms (50Hz)

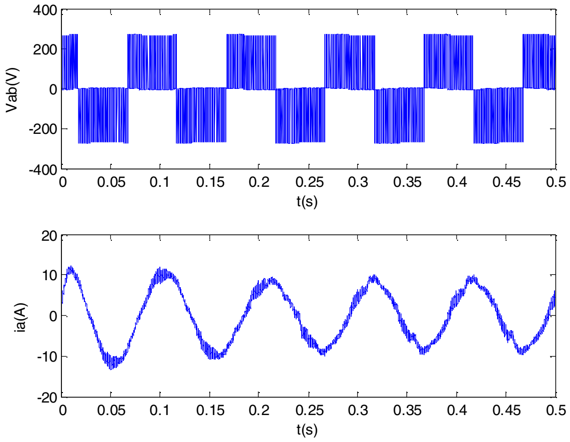

Fig. 5 The machine line voltage and current waveforms (10Hz)

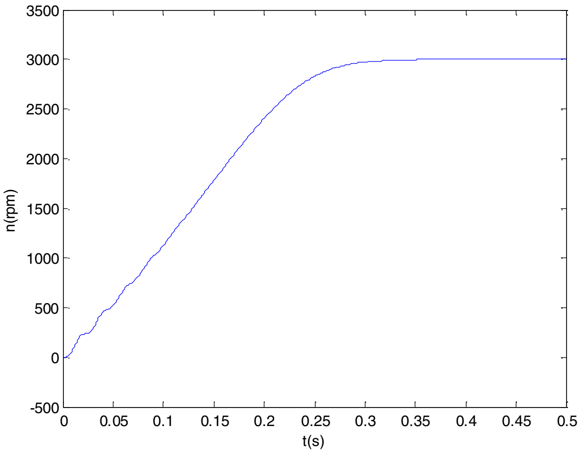

Fig. 6 The machine speed waveforms (50Hz)

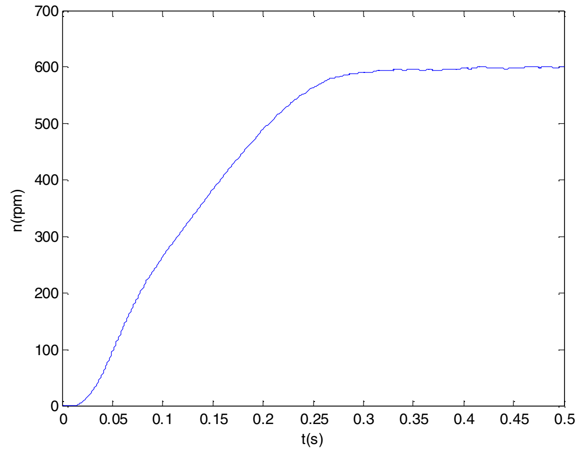

Fig. 7 The machine speed waveforms (10Hz)

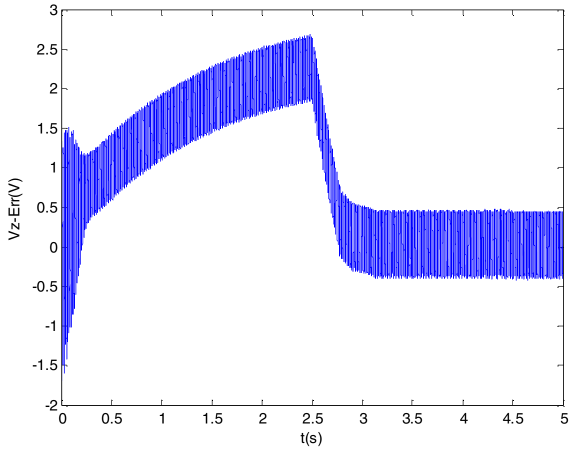

Fig. 8 The waveform of neutral point voltage deviation

V. CONCLUSION

A simple algorithm of SVM for voltage-fed three-level NPC inverter has been proposed. In the algorithm the location of the triangles determines the calculation of the dwell times for space vectors and switching sequences. A triangle is adopted to compare with three switching points to generate desired PWM signals. At the same time, the control of neutral point voltage can be achieved by adjusting the switching points. The algorithm is verified through the MATLAB simulation. This paper shows some waveforms of induction motor fed by three-level NPC inverter. These waveforms show that the proposed algorithm is correct and is easy to implement.

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