A Novel SVPWM Algorithm Considering Neutral-Point Potential Balancing for Three-Level NPC Inverter

Chen Yongchao, Li Yanda, and Zhao Ling.

***Abstract*—For three-level inverter, complexity of control strategy and neutral-point potential imbalance problem of DC side is the bottleneck restricting its application. In order to solve the problem, a simplified implementation of three-level space vector pulse width modulation (SVPWM) considering neutral-point potential balancing is proposed in this paper. The proposed SVPWM algorithm is based on judging of three phase voltages and voltage-second balance principle, which does not need to perform the sine and cosine calculations, and thus it is more convenient and effective than traditional SVPWM algorithm. Also, the neutral-point potential balancing can be realized conveniently and effectively. The proposed algorithm can not only effectively simplify the calculation and reduce calculation time greatly, but also achieve the same control effect as traditional SVPWM. It has certain reference significance and can be used to shorten sampling time and improve the inverter performance. Finally, the proposed SVPWM algorithm is verified by simulation and experimental results.**

***Index Terms*—Three-level Inverter, SVPWM, Voltage-second balance, Neutral-point potential.**

Original Research Paper
DOI: 10.7251/ELS1620069Y

I. Introduction

RECENTLY, industry has begun to demand more and more high-voltage and high-power equipments, such as large AC motor drives, HVDC, UPFC and STATCOM. Therefore, multilevel inverters particularly the three-level one, have received great attention due to their significant advantages in high-power and high-voltage applications. Comparing with two-level inverter system with the same capacity, three-level inverters can reduce the voltage stress on switches, diminish the harmonic distortion of output voltage and increase the rate of voltage and power [1, 2].

The modulation method is a key technology in the research of three-level inverters, which directly determine the performance of inverter. Among so many methods, SPWM and SVPWM are used most frequently. For the method of SPWM, the fatal disadvantage is low DC voltage utilization. As for SVPWM, even though it has the advantages of high DC voltage utilization ratio, low ripples and less number of power device switching [3, 4]. However, as the number of the level increases, more complicated control strategy is needed in an effort to choose proper switching states from increased amount of redundant states. Moreover, the neutral-point (NP) potential variation is another thorny problem for three-level inverter. The traditional SVPWM algorithm needs sine and cosine calculations. Its large amount of complicated calculation leads to waste of time. For this reason it becomes very difficult to shorten the sampling time. A great deal of work has been done to find out a better modulation algorithm and all kinds of simplified SVPWM algorithms have been proposed in many literature. But these algorithms mostly focus on offsetting unnecessary inverse operation and changing multiplication into shift operation, often with very little effect [5]. In fact the essence of SVPWM is based on the principle of voltage-second balance. According to this principle, a simplified SVPWM algorithm is proposed in this paper, which can avoid sine and cosine calculations, and thus sampling period can be shortening. And this can be used to improve the controlling effect of three-level inverter.

II. Fundamental of Three-Level SVPWM

Among all multi-level topologies, the most popular at present is three-level neutral-point-clamped inverter (NPC) [6, 7]. Fig.1 presents the scheme of three-level NPC inverter.

Each leg of the NPC inverter consists of four power switches, four freewheeling diodes and two clamping diodes that limit the voltage excursions across each device to half the input dc-bus voltage. For three-level NPC inverter, each bridge leg has three different switching states P, O or N corresponding to three kinds of output phase voltage respectively.

Manuscript received on March 1, 2016. Received in revised form on June 28, 2016. Accepted for publication on September 6, 2016.

(This work was supported by Henan province scientific and technological brainstorm project 152102210294).

Chen Yongchao is with the Department of Physics & Electrical Engineering, Anyang Normal University, Anyang, Henan, P.R. China (phone: +8613569051580; e-mail: randy827@163.com).

Li Yanda is with the Department of Physics & Electrical Engineering, Anyang Normal University, Anyang, Henan, P.R. China (phone: +8613849256675; e-mail: liyd@aynu.edu.cn).

Zhao Ling is with the Department of Research and development, Xu Ji Power Company LIMI TED, Xuchang, Henan, P.R. China (e-mail: zhaolingdy@126.com).

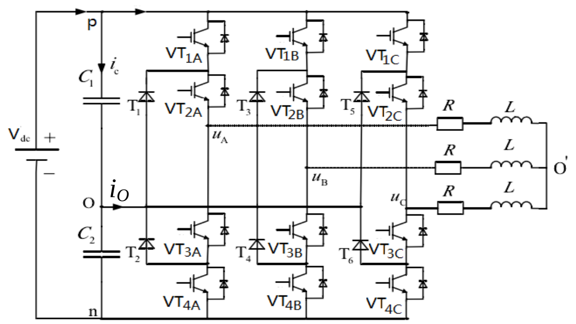


Fig.1 Three-level NPC inverter.

Take three phase reference voltages as:

$$u_a = E_m \sin wt \tag{1}$$

$$u_b = E_m \sin(wt - \frac{2}{3}\pi) \tag{2}$$

$$u_c = E_m \sin(wt + \frac{2}{3}\pi) \tag{3}$$

Define the voltage space vector corresponding to the three-phase reference voltage as:

$$V_{ref} = \frac{2}{3}(u_a + u_b e^{j\frac{2\pi}{3}} + u_c e^{-j\frac{2\pi}{3}}) = E_m e^{jwt} \tag{4}$$

The three phase positive sequence voltage is corresponding to the counter clockwise rotating reference vector. Take three-phase into consideration, the total switching states consist of 3^3=27 different states corresponding to 27 standard voltage space vectors, as shown in Fig.2. According to magnitude, these 27 vectors are classified by four categories, that is, zero vectors, small vectors (vertices of inner hexagon), medium vectors (mid-points of sides of outer hexagon) and large vectors (vertices of outer hexagon). Each small vector has two redundant switching states respectively.

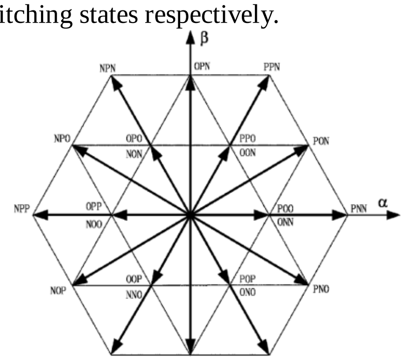


Fig. 2 Space vector with their switching states.

And these 27 standard voltage space vectors divide the space vector diagram into six triangle sections. Start from the large voltage vector PNN, the whole region can be defined as sectors I, II… and VI every 60 degrees. And each sector is divided into six sub triangles as shown in Fig.3. Sector I is usually analyzed firstly. Then the result of the whole 360 degree region can be achieved according to its symmetry characteristic.

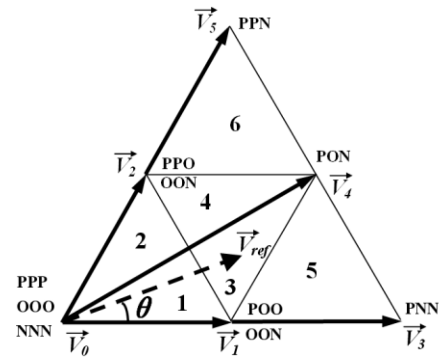


Fig.3 Vector approach for desired vector in sector I.

The main idea of SVPWM is to find out which sector and sub triangle the target reference vector V_{ref} falls into, and then, form the target reference vector by its nearest three vectors (NTV) according to voltage-second balance principle [8~10].

III. Conventional SVPWM Algorithm

A. Location Judgment of Reference Vector

In order to form the target reference vector V_{ref}, we must find out which sector and sub triangle the target reference vector falls into. It is determined by the target vector's amplitude and phase.

As for the conventional SVPWM algorithm, coordinate transformation is needed in order to find out where V_{ref} is. Assume that the reference vector falls in the sector I, there is $0 < \theta < \frac{\pi}{3}$.

When the reference vector falls into sector I, the judgment of the sub angle where it is located can be determined by rules listed in Table I.

TABLE I
JUDGING RULES FOR SUB ANGLES

Sub angle	Judgment rule
1	$\theta < \frac{\pi}{6}$ and $m \le \frac{1}{2\sin(\frac{2\pi}{3} - \theta)}$
2	$\theta \ge \frac{\pi}{6}$ and $m \le \frac{1}{2\sin(\frac{2\pi}{3} - \theta)}$
3	$\theta < \frac{\pi}{6}$ and $\frac{1}{2\sin(\frac{2\pi}{3} - \theta)} < m \le \frac{1}{2\sin(\frac{\pi}{3} - \theta)}$
4	$\theta \ge \frac{\pi}{6}$ and $\frac{1}{2\sin(\frac{2\pi}{3} - \theta)} < m \le \frac{1}{2\sin\theta}$
5	$\theta < \frac{\pi}{6}$ and $m > \frac{1}{2\sin(\frac{\pi}{3} - \theta)}$
6	$\theta \ge \frac{\pi}{6}$ and $m > \frac{1}{2\sin\theta}$

In TABLE I, m is the modulation degree:

$$m = \frac{\sqrt{3}E_m}{V_{dc}} \quad (5)$$

When the reference vector falls into sector N, the sub angle judgment rules can be obtained by using ($\theta - (N-1)*\frac{\pi}{3}$) instead of θ.

B. Synthesizing of Reference Voltage Vector

Assume that the reference vector is located in the third sub angle of sector I, as shown in Fig.3. Therefore, the target reference vector V_{ref} can be synthesized by its three nearest standard vectors, that is, V_1, V_2 and V_4.

Define t_1, t_2 and t_4 to be the operating time of V_1, V_2 and V_4 respectively, T_s to be the sampling period. According to the voltage-second balance principle, the following two equations should be met:

$$V_1 t_1 + V_2 t_2 + V_4 t_4 = V_{ref} T_s \quad (6)$$

$$t_1 + t_2 + t_4 = T_s \quad (7)$$

By solving the above complex equations, there is:

$$t_1 = T_s[1 - 2m\sin\theta] \quad (8)$$

$$t_2 = T_s[1 - 2m\sin(\frac{\pi}{3} - \theta)] \quad (9)$$

$$t_4 = T_s[2m\sin(\frac{\pi}{3} + \theta) - 1] \quad (10)$$

In the same way, the operating time of each standard vector can be calculated when the reference vector falls into other sub angles.

C. Shortage of Conventional SVPWM Algorithm

From the above calculation process of the traditional SVPWM algorithm, it can be seen that the calculation of sine and cosine is inevitable which is with high computational overhead. Therefore, it is difficult to shorten the sampling period when using conventional algorithm, which restrict the performance of inverter.

Moreover, as shown in Fig.2, we have redundant switching states of small vectors that can provide same output voltage. Small vectors made of P and O are called positive vectors, and those made of O and N are called negative vectors. These two kinds of different vectors with same output affect NP potential oppositely. NP voltage balance problem is an inherent problem of three-level NPC topology. It restricts the development and application of three-level NPC inverter greatly. In order to solve the problem of imbalance NP potential, the operating time of positive and negative vectors have to be timely redistributed, which makes the SVPWM even more complicated and time-consuming.

IV. IMPROVED SVPWM ALGORITHM

A. Judgment of Reference Vector Location

When using SVPWM control, we only need to determine that which region the reference vector falls into roughly. There is no need to find out the accurate location of reference vector. In order to avoid sine and cosine calculations, we can judge the location directly through three reference phase voltage.

The waveform of three positive sequence reference voltages is shown in Fig.4. It can be seen from Fig.4 that there exists following rules: The amplitude of the three reference phase voltage take turns as the biggest one for 120 degrees. In each 120 degrees, the smaller two phase voltages take turns as the smallest one for 60 degrees. Sorting the three reference phase voltage by the amplitude, we can get $P_3^3 = 3! = 6$ different kind of statuses. And these 6 different statuses are corresponding to 6 different sectors into which the reference vector may fall. Since the reference vector is synthesized by the three-phase reference voltage, the changing of positive sequence voltage lead to counter-clockwise rotation of the synthetic vector. Actually, comparing the amplitude of phase voltage is equivalent to identifying into which sector the reference vector falls [11].

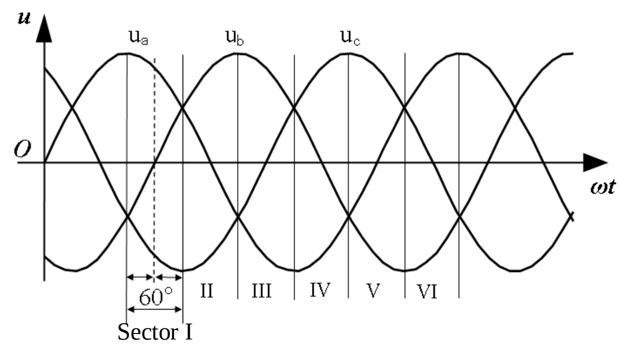


Fig.4 Three-phase reference voltage

For convenience of discussion, the range of ωt is set within 90°~150° in order to illustrate the fundamental of improved SVPWM. As shown is Fig.4, if three phase voltage is sorted, we can get $U_a > U_b > U_c$. At the same time, the reference vector phase angle ranges between 0°~60° because of $\theta = wt - \frac{\pi}{2}$, which means that the reference vector falls into sector I. Furthermore, according to the symmetry of U_B, this 60 degree can be divided into two parts, $U_b \geq 0$ and $U_b < 0$, each part occupies 30 degrees. Therefore, based on the value of three-phase reference voltage, it can be recognized that weather sub angle 1, 3, 5 or 2, 4, 6 the corresponding reference vector falls into. In order to find out exactly which sub angle the reference vector falls into, a few more judgments must be carried out. And new judging rules for the value of three-phase reference voltage can be obtained from TABLE I. For example, when the reference vector falls into sub angle 3, the corresponding judging rules can be deduced as following.

According to TABLE I, there is $\theta < \frac{\pi}{6}$, which is equivalent to $U_b < 0$. Also, there is $\frac{1}{2\sin(\frac{2\pi}{3} - \theta)} < m \leq \frac{1}{2\sin(\frac{\pi}{3} - \theta)}$

Which can be replaced by:

$$\frac{1}{2\sin(\frac{7\pi}{6}-wt)} < \frac{\sqrt{3}E_m}{V_{dc}} \le \frac{1}{2\sin(\frac{5\pi}{6}-wt)} \tag{11}$$

$$\sin(\frac{7\pi}{6}-wt) > \frac{V_{dc}}{2\sqrt{3}E_m} \ge \sin(\frac{5\pi}{6}-wt) \tag{12}$$

$$\sqrt{3}E_m\sin(wt-\frac{\pi}{6}) > \frac{V_{dc}}{2} \ge \sqrt{3}E_m\sin(wt+\frac{\pi}{6}) \tag{13}$$

$$U_{ac} > \frac{V_{dc}}{2} \ge U_{ab} \tag{14}$$

Makes $E=\frac{V_{dc}}{2}$, there is $U_{ac} > E \ge U_{ab}$.

In the same way, new judging rules can be deduced while the reference vector falls into other sub angles, as shown in TABLE II. From the rules in TABLE II, it is clear that the new judging method is very simple and it is much easier to operate. Calculation with complex trigonometric function is avoided, which reduce the computational overhead.

TABLE II
New judging rules for sub angle

Sub angle	Judgment rule
1	$U_b < 0$ and $U_{ac} \le E$
2	$U_b \ge 0$ and $U_{ac} \le E$
3	$U_b < 0$ and $U_{ab} < E \le U_{ac}$
4	$U_b \ge 0$ and $U_{bc} < E \le U_{ac}$
5	$U_b < 0$ and $U_{ab} > E$
6	$U_b \ge 0$ and $U_{bc} > E$

B. Pulse Transmission Sequence

In this paper, the seven segment pulse transmission sequence is adopted. It started with the nearest small negative vector, and then passes through all of the standard vectors determined by NTV rule clockwise. After that, it returns back to the nearest positive vector in the original way counterclockwise. The vector operating sequence is ONN→OON→PON→POO→PON→OON→ONN. The timing diagram of vector is shown in Fig.5.

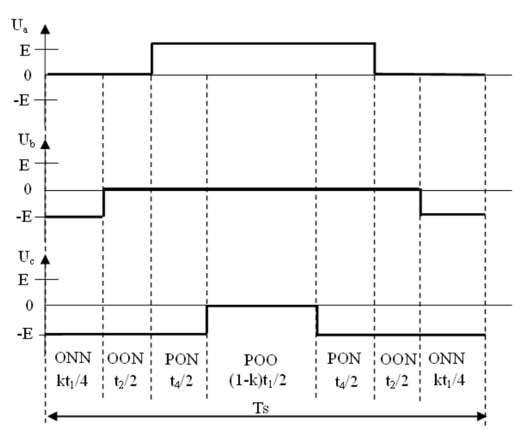


Fig.5 Switch states and timing for voltage vectors

In Fig.5, k is a scale factor which is used to adjust the NP potential. It can be seen from Fig.5 that only one phase switch state changes when the vector is changing and the switch state only changes between P, O or O, N. Therefore, the stable operating of inverter is guaranteed. Moreover, when the reference vector is rotating from one sector to another, three phase switch states remains unchanged and the transition is much more smoother [12].

As can be seen from the pulse sequence, the standard vector V_2 is always operating as one switch state OON, whose redundant switch state PPO is never been used. It is because that when the reference vector falls into sub angle 3, the distance between V_{ref} and V_2 is bigger than that of V_{ref} and V_1.

Thus, the operating time of V_2 is much shorter than that of V_1. This means that the NP potential adjusting ability of V_2 is weaker than that of V_1 contrarily [13]. So, only the redundant switch state of V_1 is used to adjust NP potential.

If the operating time of V_2 is also separated proportionally to the two redundant states OON and PPO, the pulse transmission sequence would become nine segments instead of seven segments. Although it can make full use of the redundant switching state to adjust NP potential, it would lead to complexity of the control and bigger switching loss of the device.

C. Calculation of Vector Operating Time

Actually, the fundamental of SVPWM is voltage-second balance principle. The following formula can be obtained directly from Fig.5 according to voltage-second balance principle.

$$\begin{cases} U_{ab}T_s = E(t_1+t_4) \\ U_{bc}T_s = E(t_2+t_4) \\ U_{ca}T_s = -E(t_1+t_2)-2Et_4 \end{cases} \tag{15}$$

Combined with $t_1+t_2+t_4=T_s$, there is:

$$t_1 = T_s(1-\frac{U_{bc}}{E}) \tag{16}$$

$$t_2 = T_s(1-\frac{U_{ab}}{E}) \tag{17}$$

$$t_4 = -T_s(1+\frac{U_{ca}}{E}) \tag{18}$$

In order to verify the correctness of above formula, we can compare the results with that of the traditional algorithms. According to the relationship between phase voltage and line to line voltage, and notice that $\theta = wt-\frac{\pi}{2}$, there is:

$$t_1 = T_s[1-\frac{\sqrt{3}E_m\sin(wt-\frac{\pi}{2})}{E}] \tag{19}$$

$$t_1 = T_s(1-\frac{\sqrt{3}E_m}{E}\sin\theta) \tag{20}$$

$$t_1 = T_s(1-2m\sin\theta) \tag{21}$$

It can be found that formula (21) is as same as formula (8). Similarly, t_2 and t_4 can also be testified to be exactly equal to the results obtained by conventional SVPWM. Furthermore, the results can also be testified when the reference vector falls into other sub angles and sectors. Thus, the validity of the proposed improved algorithm is verified.

D. Adjusting of Neutral-Point Potential

As is known form Fig.1, when the neutral point current i_O is not equal to zero, one of the two DC side capacitors would be charged while the other discharged. And this, leads to variation of neutral-point (NP) potential. The NP current is affected by the three-phase load current of the inverter. When the switch state of a certain phase is P or N, it will not affect the NP current. On the opposite, when the phase switch state is O, the contribution to the NP current is phase current.

While synthesizing the reference vector, the NP potential will not be affected by zero vectors and large vectors. Once the medium vector plays a role in synthesizing, one phase output load current is connected to neutral point, which will result in the neutral-point current disturbing the NP voltage variation [14~17]. The NP current would be the output current of a certain phase. Therefore, imbalance of the NP potential which is inevitable when medium vector is involved in the synthesis. So, in order to balance the NP potential, it is necessary to choose properly from the two redundant states of small vectors, which with the same output voltage but have opposite influence on the NP potential [18~20].

Split the small vector operating time into two parts according to a scale factor k, it is convenient to balance the NP potential by adjusting k [21]. Assume that the NP potential offset ΔU and three phase current i_a, i_b and i_c have been obtained by sampling. In order to pull back the NP potential to the balanced position in a sampling period, appropriate NP current should be injected into NP producing ($-\Delta U$) to help offset imbalance voltage. Therefore, the average value of the NP current in a sampling period should meet the following equation:

$$I_O^* = -C\frac{\Delta U}{T_s} \tag{22}$$

According to Fig.5, the average NP current can also be calculated as:

$$I_O^* = \frac{1}{T_s}[(2k-1)t_1 i_a + t_4 i_b - t_2 i_c] \tag{23}$$

Combine (22) and (23), and eliminating I_O^*, there is:

$$k = \frac{t_1 i_a - t_4 i_b + t_2 i_c - C\Delta U}{2t_1 i_a} \tag{24}$$

Where the scale factor k ranges between 0~1. While the result obtained according to formula (24) fall outside the range, the boundary value should be taken at 0 or 1. At this point, the NP potential could not be balanced in one sampling period. However, the NP potential will attempt to move toward the balanced position, and after several sampling period, it will be balanced eventually.

V. Simulation and Experiment

A. Simulation

Simulation study is carried out under the symmetrical three-phase load condition, where the resistance of load is 2.5Ω. The output phase to phase voltage is 315V, the output frequency is 50 Hz and the switching frequency is 12.5 kHz. The inverter DC bus consists of two capacitors in series with 4100uF each, and the DC bus voltage is 600V.

Fig. 6 shows the output phase to phase voltage and Fig.7 shows the three phase output current of inverter. Form these two figures we can see obviously that the waveform distortion rate is satisfying. Fig. 8 shows the dynamic average value of current i_o which directly affect the fluctuation of NP potential. As shown in Fig.9, it can be seen that the NP potential variation is suppressed successfully. Also, the waveform of scale factor k is shown in Fig.10.

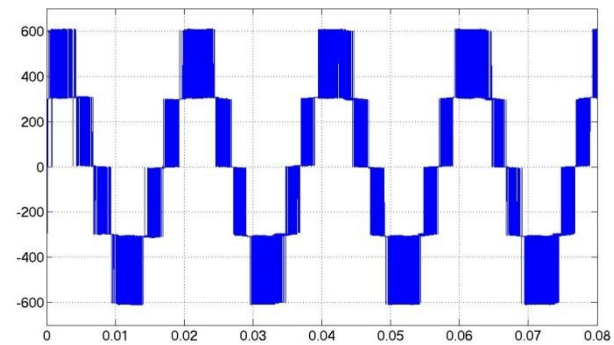


Fig.6 Phase to phase output voltage of inverter

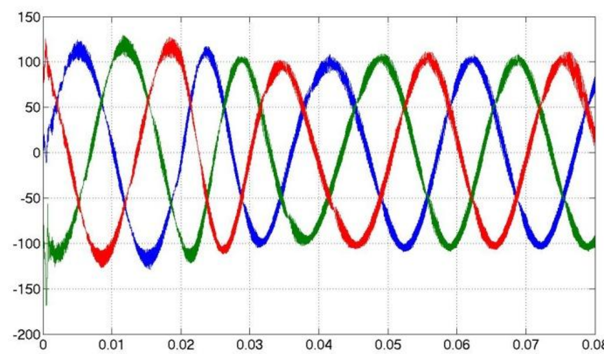


Fig.7 Three phase output current of inverter

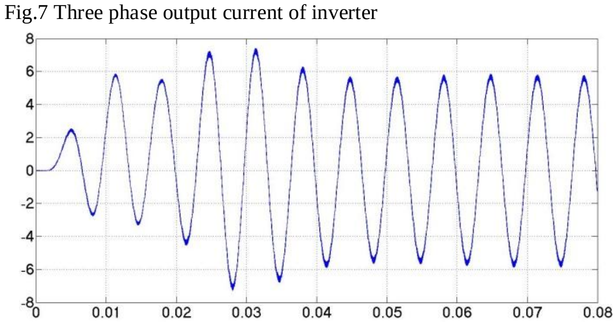


Fig.8 Dynamic average value of current i_o

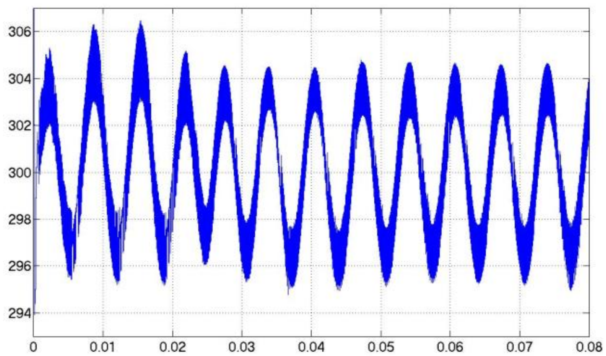


Fig.9 Neutral-point potential of DC bus

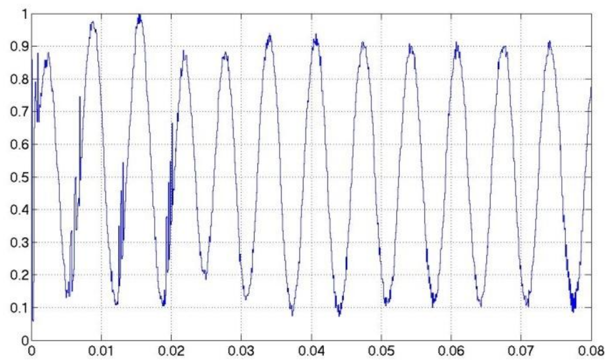
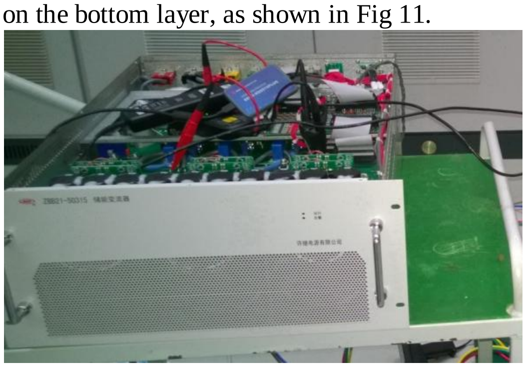


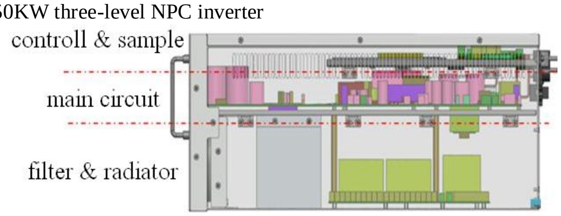
Fig.10 Scale factor *k*

B. Experiment Device and Results

In order to go a step further to verify the correctness of the design method, a set of experimental platform is set up. The three-level NPC inverter use DSP-CPLD as the control core. The controlling and sampling board is placed on the top layer, while the main circuit board on medium layer, filter and radiator on the bottom layer, as shown in Fig 11.



(a) 50KW three-level NPC inverter



(b) Structure design of inverter

Fig.11 Experimental device.

The DC bus of inverter is linked to a 600V DC source, and islanding detection device is employed to provide the symmetrical three-phase loading condition for fully loaded test. The waveforms of output phase current and phase to phase voltage are shown in Fig.12, and voltage variations of the two DC bus capacitors are shown in Fig.13. As can be seen clearly from Fig.13, the effect of NP potential balancing is pretty well.

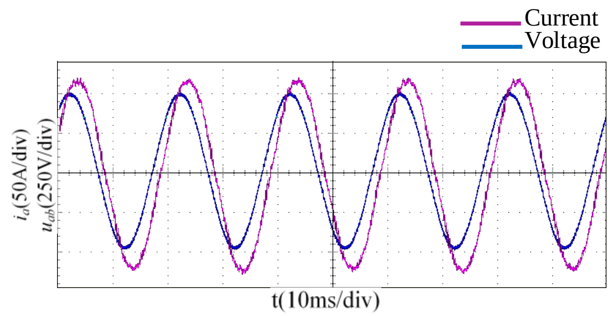


Fig.12 Waveforms of output current and voltage.

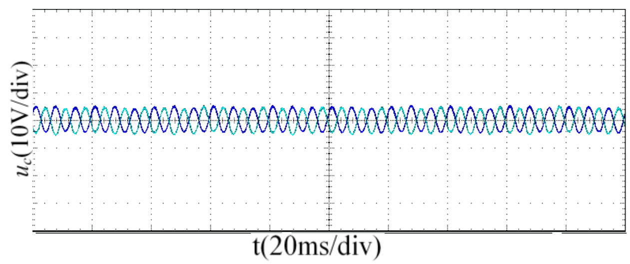


Fig.13 Waveforms of DC capacitor voltage

VI. Conclusions

In this paper, a novel SVPWM algorithm for the three-level neutral-point-clamped inverter has been proposed. Compared with conventional SVPWM, the proposed algorithm is simple to implement and does not need to perform sine and cosine calculations. And thus it is more convenient and effective than the conventional SVPWM algorithm. Besides, the neutral-point potential balancing can be implemented readily by adjusting redundant scale factor of small vectors. Only the information of DC-link capacitor voltages and three-phase load currents is required, which is convenient to apply and is compatible of digital computer realization. Because the proposed SVPWM is also based on voltage second balance principle, the control effect is same as the conventional one. Owing to low computational overhead of improved SVPWM, the sampling period can be shortening and can be used to improve the controlling effect of three-level inverter.

References

[1] S.R.Bowes, Y.S.Lai. “The Relationship Between Space-Vector Modulation and Regular-Sampled PWM”, IEEE Trans. on Industrial Electronics, Vol.44, No.5, 1997, pp.670-679.

[2] CHEN Yongchao, Gao Xiangming, etc. “An Improved SVPWM Algorithm With Low Computational Overhead for Three-Level Inverter”, 7th International Power Electronics and Motion Control Conference, Harbin, China, 2012.

[3] Lai J S, Peng F Z. “Multilevel converters–a new breed of power converters”, IEEE Transactions on Industry Applications, Vol.23, No.3, 1996, pp.509-517

[4] Steinke J K. “Switching frequency optimal PWM control of a three-level inverter”, IEEE Transactions on Power Electronics, Vol.7, No.3, 1992, pp.487-496.

[5] WANG Hongyan. "Multilevel inverter PWM methods and relative techniques", Doctoral Dissertation of Zhejiang University, 2004.

[6] Kim D H, Kang D W. "The analysis and comparison of carrier-based PWM methods for 3-level inverter", IECON 2000, 26th Annual Conference of the IEEE. Vol.2, 2000, pp.1316-1321, Nagoya, Japan.

[7] Martin Jones, Obrad Dordevic, Nandor Bodo, and Emil Levi. "PWM Algorithms for Multilevel Inverter Supplied Multiphase Variable-Speed Drives", Electronics, Vol. 16, No. 1, 2012, pp. 22-31

[8] Brendan Peter McGrath, Donald Grahame Holmes, and Thomas Lipo. "Optimized Space Vector Switching Sequences for Multilevel Inverters", IEEE Transaction on power electronics, Vol. 18, No. 6, 2003, pp. 1293-1301.

[9] Obrad Dordevic, Martin Jones, and Emil Levi. "A Comparison of Carrier-Based and Space Vector PWM Techniques for Three-Level Five-Phase Voltage Source Inverters", IEEE Transaction on industrial informatics, Vol. 9, No. 2, 2013, pp. 609–619.

[10] E. Levi, I. N. W. Satiawan, N. Bodo, and M. Jones, "A space-vector modulation scheme for multilevel open-end winding five-phase drives", IEEE Trans. Energy Convers., Vol. 27, No. 1, 2012, pp. 1–10.

[11] CHEN Yongchao, MIAO Fengdong, etc. "An improved SVPWM control algorithm for three-level inverter", Chinese Journal of Power Sources， Vol.137, No.8, 2013, pp.1435-1438.

[12] Wang Jian-ze, XUE Chang, HU Xi-jin, et al. "Simplified Algorithm for Accurately Adjust Neutral Point Potential of Three-Lvevl Inverter", Proceedings of the CSU-EPSA, Vol.22, No.1, 2010, pp.54-58.

[13] Zhang Weifeng, Yu Yuehui, Liu Lu. "A SVPWM control algorithm for three-level inverter and its simulation", Chinese Journal of Power Electronics, Vol.40, No.1, 2006, pp.3-5.

[14] JIANG Wei-dong, SHI Xiao-feng, WANG Hong-tao. "SVPWM Algorithm for NPC Three-level VSI Considering Unbalance Neutral Point Voltage", Proceedings of the Chinese Society for Electrical Engineering, Vol.28, No.30, 2008, pp.20-26.

[15] Hu Cungang, Feng Jigui, Jiang Weidong, etc. "A Neutral-Point Potential Balancing Algorithm for Three-Level Inverter Based on Virtual-Space-Vector", Transactions of China Electro technical Society, Vol.24, No.5, 2009, pp.100-106.

[16] Pou J, Pindado R, Boroyevich D, et al. "Limits of the neutral-point balance in back-to-back connected three-level converters", IEEE Transaction on power electronics, Vol.19, No.3, 2004, pp. 722-731.

[17] Celanovic N, Boroyevich D. "A Comprehensive Study of Neutral-point Voltage Balancing Problem in Three-level Neutral-point-clamped Voltage Source PWM Inverters", IEEE Transactions on Power Electronics, Vol.15, No.2, 2000, pp.242-249.

[18] Z. Mohzani, B. P. McGrath, and D. G. Holmes, "Natural balancing of the neutral point voltage for a three-phase NPC multilevel converter", in Proc. IEEE IECON, 2011, pp. 4445-4450.

[19] Z. Mohzani, B. P. McGrath, and D. G. Holmes, "The balancing properties of DC link compensation for 3-phase Neutral Point Clamped (NPC) Converter", in Proc. ECCE Asia (IPEC), 2012, pp. 574-579.

[20] E. Levi, D. Dujic, M. Jones, and G. Grandi, "Analytical determination of DC-bus utilization limits in multiphase VSI supplied AC drives", IEEE Trans. Energy Convers., Vol. 23, No. 2, 2008, pp. 433–443.

[21] LI Ning, WANG Yue, et al. "Overview of Neutral Point Potential Fluctuation Control Strategies in NPC Three-level Converters", Chinese Journal of Power Electronics, Vol.45, No.10, 2011, pp.78-80.