A New Direct Power Control of Three-level PWM Rectifier Based on Equivalent Space Vector

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Abstract. This paper analyzes basic principle of DPC of three-phase voltage-source PWM rectifier, and presents its shortcomings of high and unfixed switching frequency. On this base, it proposes the method of combining DPC and three-level voltage space vector pulse width modulation(SVPWM), which reduces and fixes switching frequency. To overcome the shortcomings of complex control and complicated calculations of traditional SVPWM algorithm, the paper proposes an equivalent three-level SVPWM algorithm of dual-carrier modulation, and in the d-q coordinates, and a control strategy of power feed forward decoupling control of traditional DPC, which realizes the dynamic decoupling of active and reactive power. The MATLAB/SIMULINK simulations verify the feasibility of this control strategy.

Keywords: direct power control; space vector pulse width modulation; dual-carrier modulation; constant switching frequency.

1. Introduction

The PWM rectifier has been widely used in the fields of AC speed regulation, uninterrupted power supply (UPS) and new energy, with its advantages of energy two-way flow, unity-power factor on grid side and good sine of input current [1][2]. Compared with the two-level, the three-level PWM rectifier has better output performance, low current harmonic, low pressure of the switching devices, higher energy density and has a better application prospect in the field of high power [3].

The direct power control (DPC) of the PWM rectifier has the advantages of high-power factor, low THD, simple algorithm and simple system structure. Therefore, the research and attention of scholars at home and abroad have been obtained [4][5][6]. Two-level DPC control has been more mature, while the switch table construction of three-level topology is difficult due to its large number of vectors.The traditional DPC algorithm has high switch frequency, requiring fast processor and AD converter chip, and because the switching frequency is not fixed, the filter design is complex. Therefore, this paper combines the space voltage vector pulse width modulation (SVPWM) and the direct power control, fixing the switching frequency, and simplifying the design of the filter.

For the three-level SVPWM algorithm, scholars at home and abroad have done many researches, and many simplified algorithms have also been proposed [7][8][9]. Literature [7] largely simplifies the three-level SVPWM algorithm to a level of two-level SVPWM. Literature [8] proposes a three level SVPWM algorithm using the 60-degree coordinate system. However, all these algorithms require sector estimation, vector selection and time computation, which are cumbersome and complicated. In this paper, an equivalent three-level SVPWM algorithm with dual carrier modulation is proposed, by adding zero sequence components in three-phase modulation wave, the same control effect is achieved as traditional SVPWM, and simplifying the cumbersome calculation. Through simulation, the equivalence of the algorithm compared with SVPWM is analyzed.

2. Mathematical model of three-level PWM rectifier

Fig.1 shows the main circuit topology of the three level PWM rectifier. The diode clamped structure is adopted in this paper. U_a, U_b, U_c are the three-phase grid voltages, i_a, i_b, i_c are the three-phase currents, i_{dc} is the load current, u_{dc} is the DC bus voltage, R_1, L are the resistance and inductance of the input filter, C_1, C_2 are the DC bus capacitors, R_L is the load resistance, U_{ra}, U_{rb}, U_{rc} are the input voltage of the rectifier bridge.

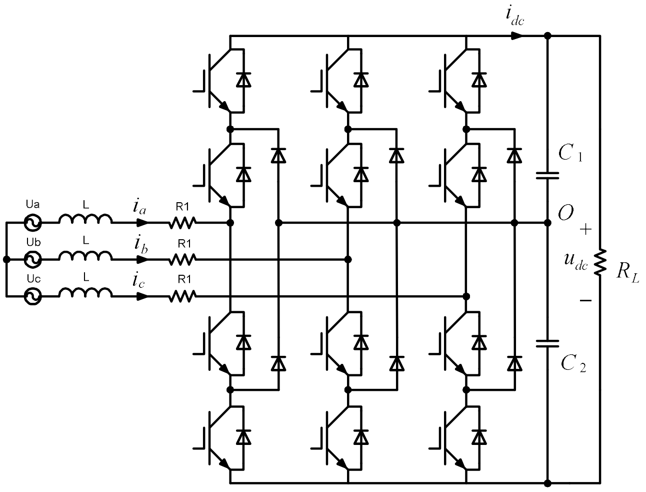

Fig.1. Main circuit of three-level PWM rectifier

According to its topology, the mathematical model of the three level-PWM rectifier in dq coordinate system is expressed as (1)

$$\begin{cases} L\dfrac{di_d}{dt} = u_d - u_{rd} - R_1 i_d + \omega L i_q \\ L\dfrac{di_q}{dt} = u_q - u_{rq} - R_1 i_q + \omega L i_d \end{cases} \tag{1}$$

In this formula, u_d, u_q, i_d, i_q and u_{rd}, u_{rq} are the d, q axis components of grid voltage, grid current and AC side voltage.

3. Dual carrier modulation algorithm based on equivalent three-level space vector

The three-level converter usually adopts sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation(SVPWM). Because of its high DC voltage utilization and good harmonic suppression capability, SVPWM is widely used in various industrial applications. Although the control effect of SPWM is not as good as that of SVPWM, its control effect can meet the requirements for general industrial applications, so it also has certain applications. At the same time, SPWM obtains switche signals directly through the comparison between carrier wave and modulation wave, so the algorithm is very simple, which can greatly save the hardware space of the control system.

By comparative analysis of the three-level SVPWM and SPWM[9], a carrier modulation algorithm equivalent to three-level SVPWM is obtained. By adding zero sequence component in the modulation wave, the algorithm has the same control effect as SVPWM, it simplifies the arithmetic and saves the arithmetic time.

The space distribution of the reference vector of the three-level converter is shown in Fig. 2. Fig. 3 is a dual carrier modulation diagram when the reference vector is located in I.1 area of the three-level vector diagram. According to the principle of volt-second equilibrium, the reference voltage can be expressed as:

$$V_{ref} = V_\alpha + jV_\beta = V_a + V_b e^{j\frac{2\pi}{3}} + V_c e^{-j\frac{2\pi}{3}} \quad (2)$$
$$\text{and } V_a + V_b + V_c = 0$$

In SVPWM algorithm, the output voltage vector is centrosymmetric. In Fig. 3, T_0, T_1, T_2 are the time of each combination vector in SVPWM, T_a, T_b, T_c are the time of A, B, C phase being 1 in the half modulation period in carrier modulation method, V_a^*, V_b^*, V_c^* are the value of intersection of three phase modulation wave and triangle carrier.

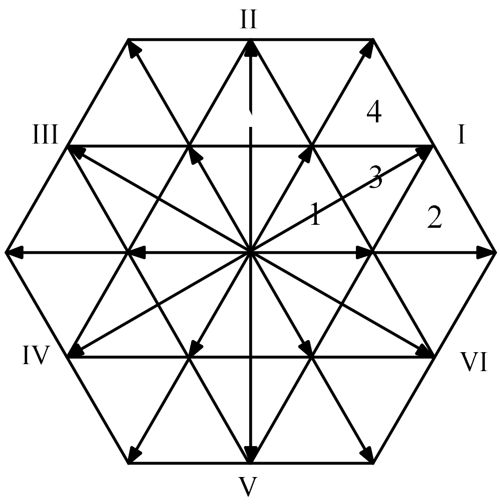

Fig.2 Space distribution of three-level converter reference vector

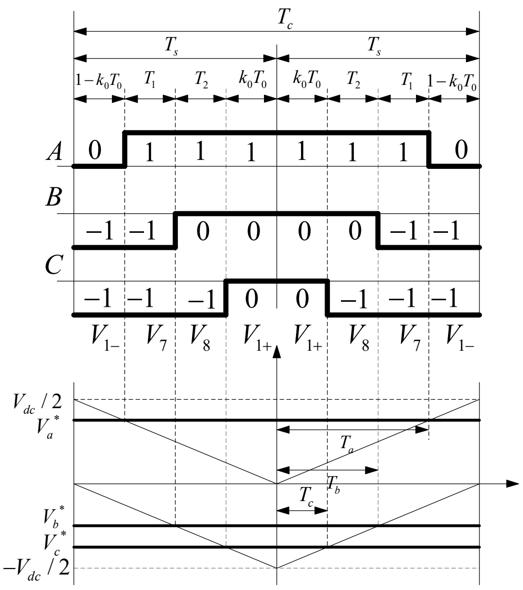

Fig.3 Equivalent carrier modulation of three-level space vector

Carrier modulation generally uses triangular carrier and modulation wave to compare. In the three level converter, because the converter outputs three level states, therefore, the output state is obtained by comparing the two carriers with the modulation wave, which is called positive and negative double carrier, as shown in the lower half of Fig. 3

$$T_a = k_0T_0 + T_2 + T_1 \quad (3)$$

$$T_b = k_0T_0 + T_2 \quad (4)$$

$$T_c = k_0 T_0 \tag{5}$$

The positive triangular carrier can be expressed as(when $V_{dc}/2=1$)

$$v_{t1} = \frac{1}{T_s} t,\ 0 \le t \le T_s \tag{6}$$

The negative triangular carrier can be expressed as

$$v_{t2} = \frac{1}{T_s} t - 1,\ 0 \le t \le T_s \tag{7}$$

Therefore

$$V_a^* = \frac{1}{T_s}(k_0 T_0 + T_2 + T_1) \tag{8}$$

$$V_b^* = \frac{1}{T_s}(k_0 T_0 + T_2) - 1 \tag{9}$$

$$V_c^* = \frac{1}{T_s}(k_0 T_0) - 1 \tag{10}$$

$$T_1 = T_s[(V_a - V_b) - 1] = T_s(V_{ab} - 1) \tag{11}$$

$$T_2 = T_s(V_b - V_c) = T_s V_{bc} \tag{12}$$

$$T_0 = T_s - T_1 - T_2 \tag{13}$$

The formula (11) ~ (13) substitution (8) ~ (10) can be obtained

$$V_a^* = V_a + V_{zs} \tag{14}$$

$$V_b^* = V_b + V_{zs} \tag{15}$$

$$V_c^* = V_c + V_{zs} \tag{16}$$

$$V_{zs} = -[(1 - 2k_0) + k_0 V_a + (1 - k_0) V_c] \tag{17}$$

V_{zs} is zero sequence component.

It can be seen from the above formula that the SVPWM modulation wave is actually formed by applying the zero-sequence component of the three-phase sinusoidal modulation wave in the carrier modulation. Therefore, the calculation of zero sequence components becomes the key of SVPWM algorithm based on carrier modulation. For this reason, according to the relationship between voltage vector phase and amplitude, we classify different regions according to the reference voltage. The polarity of voltage vectors remains unchanged in all regions. Thus, the three-phase reference voltage can be divided into:

region 1: $V_a > 0, V_b < 0, V_c < 0$

region 2: $V_c < 0, V_a > 0, V_b > 0$

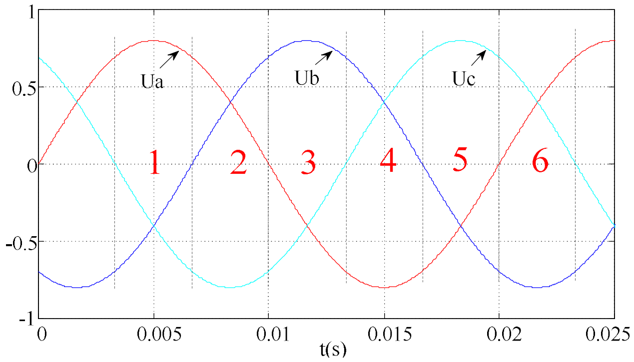

Fig.4 Partition of three phase reference voltages

region 3: $V_b > 0, V_a < 0, V_c < 0$

region 4: $V_a < 0, V_b > 0, V_c > 0$

region 5: $V_c > 0, V_a < 0, V_b < 0$

region 6: $V_b < 0, V_a > 0, V_c > 0$

In each region, the size order of the three-phase reference voltage needs to be determined in order to select $V_{\max}$, V_{mid}, $V_{\min}$ to form zero sequence components. The size of the reference voltage is in the following:

When the reference voltage is positive, the comparison value remains unchanged; when the reference voltage is negative, the reference voltage plus 1 is taken as the comparison value. Compare the order of size According to the above method, then Take each other into the original value, the size order of each phase vector can be determined. At the same time, according to the polarity of each phase vector, the zero sequence components in a variety of situations can be expressed as

$$\begin{aligned}
&(1) V_i > 0, V_{j,k} < 0 \qquad i,j,k \in (a,b,c)\\
&If\ V_i = V_{\max},\ V_{zs} = -[(1-2k_0) + k_0 V_{\max} + (1-k_0)V_{\min}]\\
&If\ V_i = V_{mid},\ V_{zs} = -[(1-k_0) + k_0 V_{\max} + (1-k_0)V_{\min}]\\
&If\ V_i = V_{\min},\ V_{zs} = -[k_0 V_{\max} + (1-k_0)V_{\min}]
\end{aligned} \tag{18}$$

$$\begin{aligned}
&(2) V_i < 0, V_{j,k} > 0 \qquad i,j,k \in (a,b,c)\\
&If\ V_i = V_{\max},\ V_{zs} = -[k_0 V_{\max} + (1-k_0)V_{\min}]\\
&If\ V_i = V_{mid},\ V_{zs} = -[-k_0 + k_0 V_{\max} + (1-k_0)V_{\min}]\\
&If\ V_i = V_{\min},\ V_{zs} = -[(1-2k_0) + k_0 V_{\max} + (1-k_0)V_{\min}]
\end{aligned} \tag{19}$$

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Generally, $k_0 = 0.5$ To achieve the best effect of SVPWM.

4. Direct power control(DPC) based on three-level SVPWM

As shown in formula (1), the mathematical model of the three level PWM rectifier contains only voltage and current, and does not contain power information directly. Therefore, it is necessary to transform the mathematical model of the three-level PWM rectifier to include the active power and reactive power of the grid side[10][11].

After Clarke transformation and Park transformation, the instantaneous phase voltage vector $\boldsymbol{u}$ and instantaneous phase current vector $\boldsymbol{i}$ in two phase synchronous rotating coordinate system are obtained as follows:

$$\boldsymbol{u} = (u_d \quad u_q)^T \qquad \boldsymbol{i} = (i_d \quad i_q)^T \tag{20}$$

The instantaneous active power p is defined as the scalar product of $\boldsymbol{u}$ and $\boldsymbol{i}$, and the instantaneous reactive power $\boldsymbol{q}$ is defined as the vector product of $\boldsymbol{u}$ and $\boldsymbol{i}$.

$$p = \boldsymbol{u} \cdot \boldsymbol{i} = (u_d i_d + u_q i_q) \qquad \boldsymbol{q} = \boldsymbol{u} \times \boldsymbol{i} = (u_d i_q - u_q i_d)\boldsymbol{k} \tag{21}$$

When the three-phase grid voltage is symmetrical, in the rotating coordinate system, the grid voltage is all located on the d axis based on grid voltage orientation, then $u_q = 0$, the following formulas are obtained:

$$p = u_d i_d , \quad q = -u_d i_q \tag{22}$$

Both ends of the formula (1) are multiplied by u_d, then:

$$\begin{cases} L\dfrac{dp}{dt} = u_d{}^2 - R_1 p - \omega L q - u_d u_{rd} \\ L\dfrac{dq}{dt} = R_1 q + \omega L p + u_d u_{rq} \end{cases} \tag{23}$$

Order $L_e = L / u_d$, $R_e = R_1 / u_d$, the following formula is obtained:

$$\begin{cases} L_e\dfrac{dp}{dt} = u_d - R_e p - \omega L_e q - u_{rd} \\ L_e\dfrac{dq}{dt} = R_e q + \omega L_e p + u_{rq} \end{cases} \tag{24}$$

It can be seen from the formula (24) that the active power and reactive power of the system are coupled to each other, which brings difficulties to the design of the controller. Therefore, compensation control can be carried out. After compensating the output of the power control loop, the given control voltage can be obtained as follows:

$$\begin{cases} u_{rd} = -(K_P + \frac{K_i}{s})(p^* - p) - \omega L_e q + e_d \\ u_{rq} = (K_P + \frac{K_i}{s})(q^* - q) - \omega L_e p \end{cases} \tag{25}$$

With the combination of (24) and (25), we can get the following formula:

$$\begin{cases} L_e \frac{dp}{dt} = (K_P + \frac{K_i}{s})p^* - [R_e + (K_P + \frac{K_i}{s})]p \\ L_e \frac{dq}{dt} = (K_P + \frac{K_i}{s})q^* + [R_e - (K_P + \frac{K_i}{s}]q \end{cases} \tag{26}$$

In the formula (26), the upper form contains only active power, while the lower one contains only reactive power. It is obvious that decoupling of active power and reactive power is achieved through compensation control. Combined with instantaneous power calculation and SVPWM algorithm, the block diagram of system control is obtained, as shown in Fig.5.

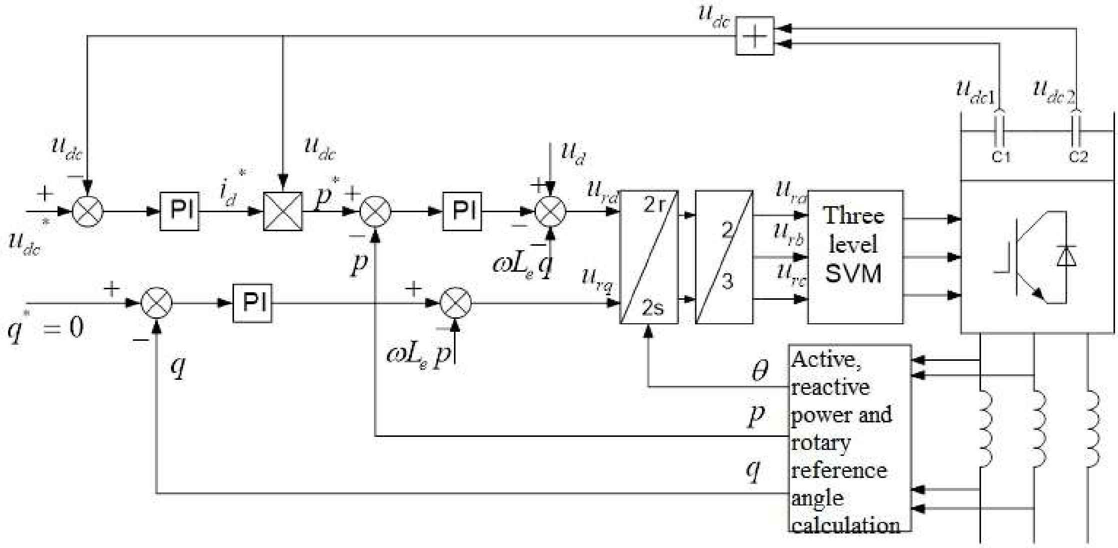


Fig.5 Block diagram of fixed-frequency DPC of three-level rectifier

The orientation angle is obtained from the three-phase grid voltage based on the grid voltage orientation. DC voltage control is achieved through external voltage loop to achieve DC voltage stability. Current control is achieved through a power inner loop. Through active reactive power theory, active and reactive power can be calculated, and then they are compared with the given value of active and reactive power. By the power loop and compensate control, the control voltage can be obtained. The control voltage is then passed to the SVPWM algorithm to get the pulse output of the rectifier, then the control of the whole converter is realized.

5. Simulation analysis

In this paper, the three-level equivalent space vector algorithm based on double carrier modulation is simulated on a three-level inverter. Fig.6 is the waveforms of zero sequence component, modulation wave superimposed on zero sequence component, output phase voltage and three-phase current under different modulation degree(m).

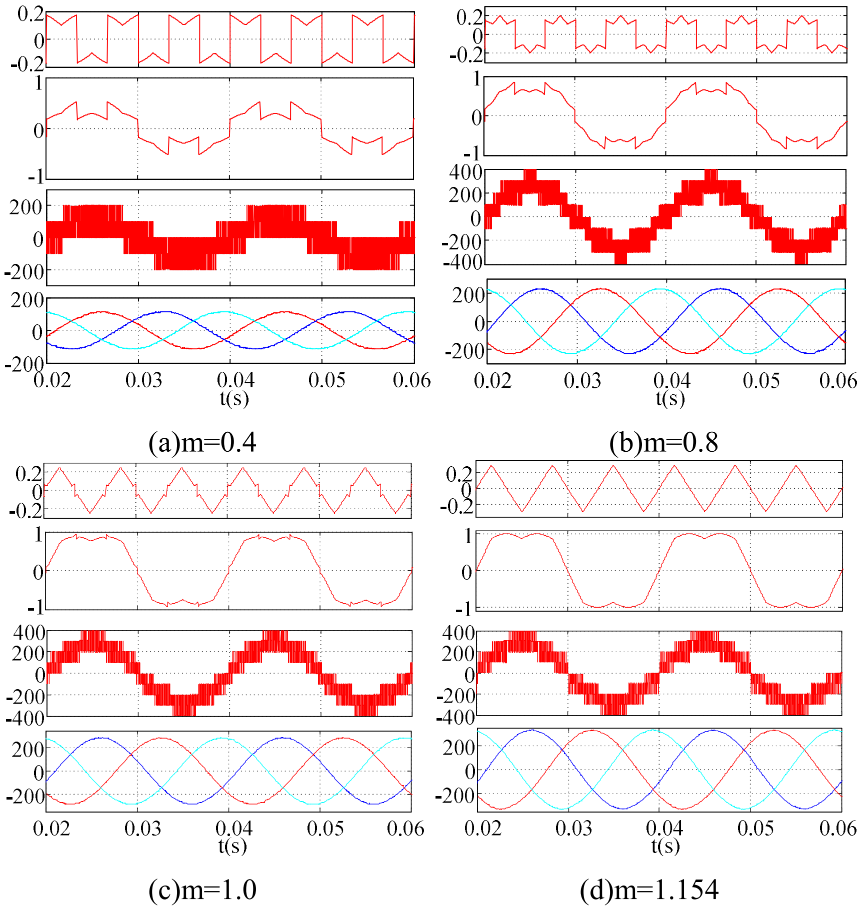


Fig.6 Waveforms of equivalent carrier modulation of three-level SVPWM

As shown in Fig.6, the zero-sequence component and the reference modulation wave change with the modulation degree when equivalent SVPWM based on carrier modulation is performed. And under different modulation degree, the effect of three-level SVPWM can be achieved. At the same time, compared with the SVPWM algorithm, the algorithm is based on SPWM, and the switch state can be obtained only by comparing the carrier wave with the modulation wave. The injection of zero sequence components in modulation wave is relatively simple, and there is no need for coordinate transformation and trigonometric function calculation. Therefore, in practical application, the algorithm is simple, and the hardware cost is low, so it has better practical value.

In order to verify the control effect of SVM-DPC algorithm, the algorithm is simulated in this paper. The load is a resistance load in the simulation model, The initial load resistance is $R = 30\Omega$, at 1s load doubles $R = 15\Omega$, The given value of the DC voltage is $u_{dc}^* = 600V$.

As shown in Fig.7, voltage dynamic response is fast, steady state fluctuation is small, basically no static error, it can be quickly recovered when the load is mutated. As shown in Fig.8, the grid voltage and current of the phase a are in the same phase, achieve the unit power factor operation, the current can also be quickly stabilized when the load is abrupt. As shown in Fig.9, the q is approximately zero and p can remain constant, and p can achieve stability quickly when the load changes. As shown in Fig.10, the harmonic distortion rate of the side current is very small.

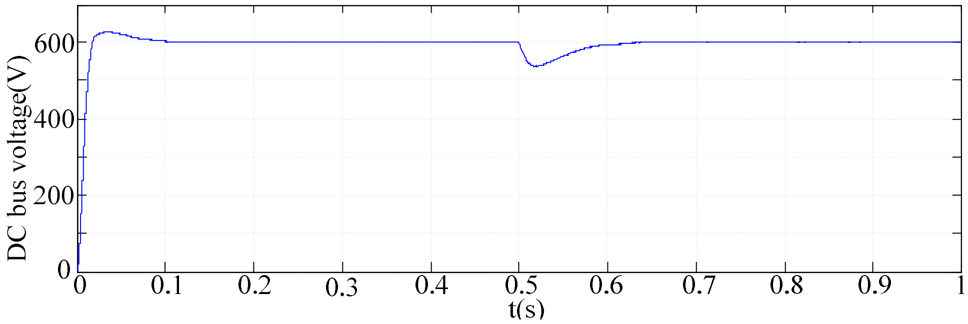


Fig.7 DC voltage waveform

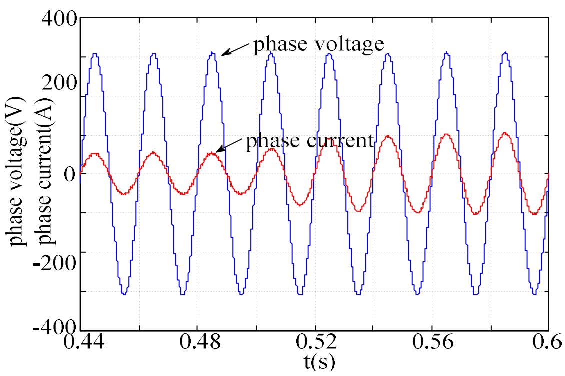


Fig.8 Waveforms of phase voltage and current

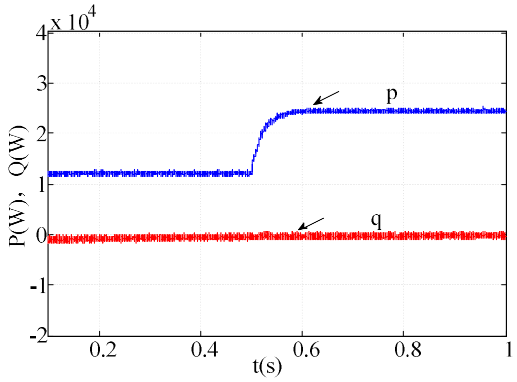
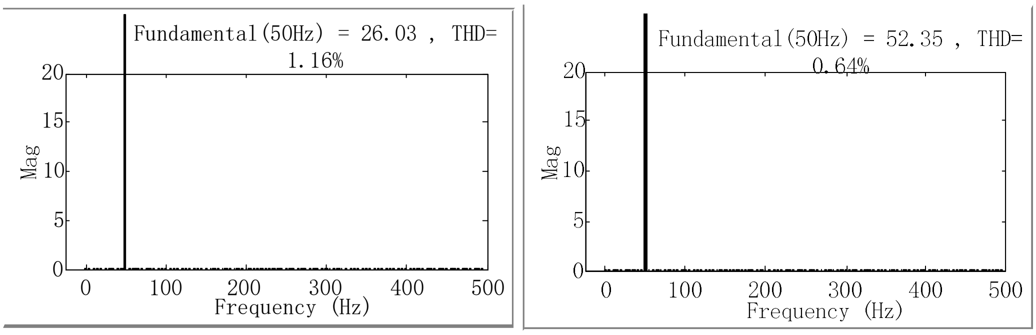


Fig.9 Waveforms of active power p and reactive power q



(a) $R = 30\Omega$ (b) $R = 15\Omega$

Fig.10 Current distortion of grid side

6. Conclusion

A new direct power control method with fixed switching frequency is proposed in this paper, which combining DPC and three-level voltage space vector pulse width modulation (SVPWM). To overcome the shortcomings of complex control and complicated calculations of traditional SVPWM algorithm, this paper proposes an equivalent three-level SVPWM algorithm of dual-carrier modulation, the equivalence between this algorithm and the three- level SVPWM is verified by simulation. DPC-SVPWM has good dynamic and static performance, unit power factor operation, low harmonic distortion rate, reactive power and reactive power decoupling, and switching frequency is fixed, simulation analysis shows that the control method is effective and feasible.

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