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Research Article

Research on Three-phase Voltage Type PWM Rectifier System Based on SVPWM Control

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Abstract: The fundamental principle of SVPWM is introduced in this study. The design on the structure of three-phase voltage type PWM rectifier system based on SVPWM control was also discussed. Then we calculate the DC capacitor and AC side inductance. The computer simulation tool MATLAB/Simulink is taken and the result is shown in the end. The result indicates that the design of such platform is feasible.

Keywords: Power factor, PWM rectifier, space voltage vector, three-phase voltage

INTRODUCTION

Space Vector PWM (SVPWM) control strategy is a control strategy with novel thoughts on the basis of controlling the converter by converter space voltage (current) vector switchover. Space vector PWM control strategy was put forward for the purpose of frequency conversion driving of AC motor in early stage. The main thought lies in discarding original Sinusoidal wave Pulse Width Modulation (SPWM) and more directly controlling rotating magnetic field of AC motor so as to obtain quasi-circular rotating magnetic field in static and transient state by adopting inverter space vector switchover and make AC motor obtain better properties than that of SPWM control. Main manifestations include: SVPWM improves the voltage use ratio of voltage type inverter and dynamic response property of the motor and meanwhile it also reduces torque pulsation of the motor. In addition, it is easier to realize single chip micro-processing by simple vector mode switchover.

Sangshin and Hamid (2005) study the design and rating comparisons of PWM voltage source rectifiers and active power filters for ac drives with unity power factor. Vladimir and Vikram (1999) study a new mathematical model and control of a three-phase ac-dc voltage source converter. Wu *et al*. (1991) give the analysis of an ac to dc voltage source converters using PWM with phase and amplitude control. Boon and Xiao (1990) shows the voltage angle lock loop control of the boost type PWM converter for HVDC application. Fujita *et al*. (1998) shows the control and ana1ysis of a unified power flow controller. Marian and Luigi (1998) give the current control techniques for three-phase voltage-source PWM converters. Thomas (1993) has a study of the space vector-based rectifier regulator for AC/DC/AC converters. Mariusz *et al*. (2004) analyze the simple direct power control of three-phase PWM rectifier using space-vector modulation. Li *et al*. (2006) study the review on nonlinear control strategies of three phase boost-type PWM rectifiers.

In this study, the fundamental principle of SVPWM is introduced. The design on the structure of three-phase voltage type PWM rectifier system based on SVPWM control was also discussed. Then we calculate the DC capacitor and AC side inductance. The computer simulation tool MATLAB/Simulink is taken and the result is shown in the end. The result indicates that the design of such platform is feasible.

SPACE VECTOR CONTROL PRINCIPLE

Distribution and interval division of space voltage vector: Three-phase VSR space voltage vector describes the space distribution of three-phase VSR AC-side phase voltage (v_{a0}, v_{b0}, v_{c0}) on the complex plane, meeting the following relation:

$$v_{a0} = \left[s_a - \frac{1}{3}\left(s_a + s_b + s_c\right) \right] v_{dc}$$

$$v_{b0} = \left[s_b - \frac{1}{3}\left(s_a + s_b + s_c\right) \right] v_{dc}$$

$$v_{c0} = \left[s_c - \frac{1}{3}\left(s_a + s_b + s_c\right) \right] v_{dc}$$

where, S_a, S_b and S_c = three-phase unipolarity two-valued logic switch function. Substitute 2^3 = 8 switch function combinations into the above formula and get

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Table 1: Voltage values in different switch combination

S_a	S_b	S_c	v_{a0}	v_{b0}	v_{c0}	V_k
0	0	0	0	0	0	V_0
0	0	1	$-\frac{1}{3}v_{dc}$	$-\frac{1}{3}v_{dc}$	$-\frac{2}{3}v_{dc}$	V_5
0	1	0	$-\frac{1}{3}v_{dc}$	$\frac{2}{3}v_{dc}$	$-\frac{1}{3}v_{dc}$	V_3
0	1	1	$-\frac{2}{3}v_{dc}$	$\frac{1}{3}v_{dc}$	$\frac{1}{3}v_{dc}$	V_4
1	0	0	$-\frac{2}{3}v_{dc}$	$-\frac{1}{3}v_{dc}$	$-\frac{1}{3}v_{dc}$	V_1
1	0	1	$\frac{1}{3}v_{dc}$	$-\frac{2}{3}v_{dc}$	$\frac{1}{3}v_{dc}$	V_6
1	1	0	$\frac{1}{3}v_{dc}$	$\frac{1}{3}v_{dc}$	$-\frac{2}{3}v_{dc}$	V_2
1	1	1	0	0	0	V_7

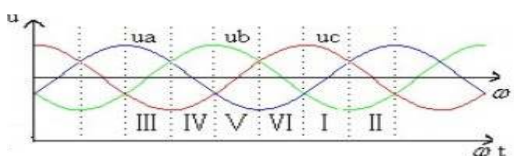


Fig. 1: The phase sectors district chart

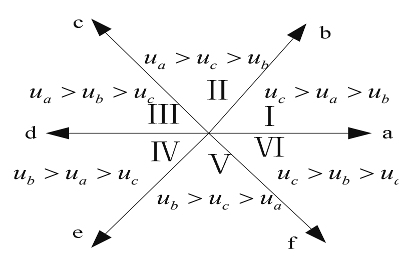


Fig. 2: The district condition of space voltage vector

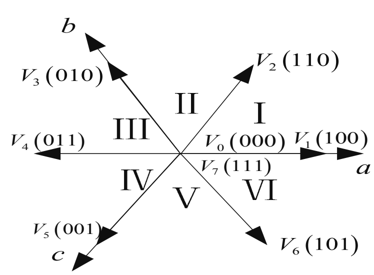


Fig. 3: The space voltage vector district

corresponding three-phase VSR AC-side voltage values, as shown in Table 1.

It can be found from Table 1 that AC-side voltage under different switch combinations of three-phase VSR can be expressed with $2v_{dc}/3$ space voltage vector on the complex plane. Obviously, a switch combination corresponds to a space vector. v_{a0}, v_{b0} and v_{c0} under this switch combination are the projection of the space vector on triaxial (a, b and c).

Thus, three-phase VSR space voltage vector V_k can be expressed as:

$$\begin{cases} V_k = \frac{2}{3} v_{dc} e^{j(k-1)\pi/3} & (k = 1,\ldots, 6) \\ V_{0、7} = 0 \end{cases} \tag{1}$$

The above formula can also express as a switch function, i.e.:

$$V_j = \frac{2}{3} v_{dc} (s_a + s_b e^{j2\pi/3} + s_c e^{-j2\pi/3}) \tag{2}$$

(j = 0, …, 7)

Traditional SVPWM control scheme divides intervals of three-phase VSR switching input voltage. Each 60° as an interval and a wave form cycle is divided into 6 intervals, as shown in Fig. 1.

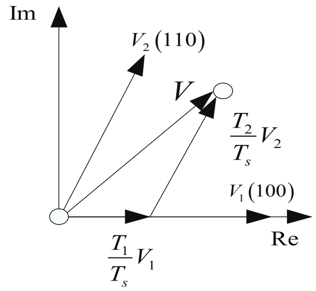
According to control principles of space vectors, rectifier switching input voltage with symmetrical three-phase can be regarded as a space voltage vector V. Synthesize the space voltage vector V with the same amplitude and different phases by use of 8 different combinations of basic voltage space vectors V_0~V_7 of the rectifier. According to Fig. 1, it can be known that the interval location of the voltage vector V is determined by the values of u_a, u_b and u_c.

Figure 2 shows interval division conditions. Line segment ad is the boundary line of "$u_a = u_b$". The first half area of ad line segment means $u_a > u_b$ and $u_a < u_b$ for the second half area. Analogously, line segment be is the boundary line of "$u_a = u_c$" and line segment cf is the boundary line of "$u_b = u_c$". The relation between interval division and basic voltage space vector is shown in Fig. 3.

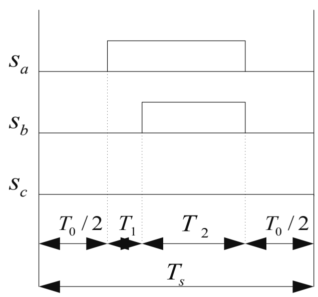
Synthesis of space voltage vector: Voltage space vector is synthesized by use of combinations of basic voltage space vectors. Proper selection of basic voltage space vector is the key to the control scheme.

After the interval location of voltage space vector V is determined, it is required to select adjacent non-zero vectors and zero vectors to synthesize. There are three common synthesis methods:

- Adopt V_0 (000), V_1 (100) and V_2 (110) combination as shown in Fig. 4a. This combination meets the principle that only a power device conducts switch changing-over during each operating mode changing-over. The changing-over time is 4, reducing switch loss. However, since the wave form of the switch function is asymmetric as shown in Fig. 4b, PWM harmonic wave is relatively large.
- Still adopt V_0 (000), V_1 (100) and V_2 (110) combination, but the insertion way of zero vector is

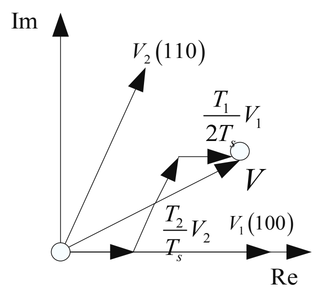


(a) V synthesis

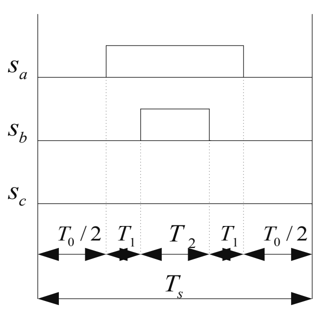


(b) Switch function diagram

Fig. 4: The method one of V synthesis



(a) V synthesis



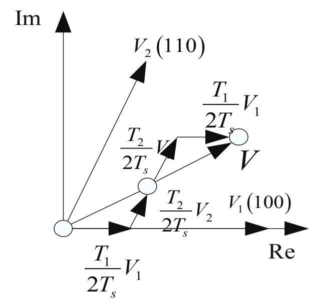
(b) Switch function diagram

Fig. 5: The method two of V synthesis

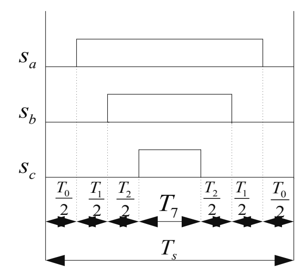
changed as shown in Fig. 5a. The changing-over time is still 4, so the switch loss remains unchanged. However, the wave form of the switch function is symmetrical as shown in Fig. 5b, thus reducing PWM harmonic wave.

Table 2: Different voltage vector synthesis sequence

Interval	Vector sequence
I	V_0 V_1 V_2 V_7 V_2 V_1 V_0
II	V_0 V_3 V_2 V_7 V_2 V_3 V_0
III	V_0 V_3 V_4 V_7 V_4 V_3 V_0
IV	V_0 V_5 V_4 V_7 V_4 V_5 V_0
V	V_0 V_5 V_6 V_7 V_6 V_5 V_0
VI	V_0 V_1 V_6 V_7 V_6 V_1 V_0



(a) V synthesis



(b) Switch function diagram

Fig. 6: The method three of V synthesis

- To make PWM harmonic wave as small as possible, add another sequence on the basis of the sequence in the first method and this sequence is inverted sequence of the previous sequence, i.e., the complete sequence is V_0 (000), V_1 (100), V_2 (110), V_7 (111), V_2 (110), V_1 (100) and V_0 (000), as shown in Fig. 6a. At the moment, the wave form of the switch function is shown in Fig. 6b. Further reducing PWM harmonic wave, but the changing-over time is 6, increasing the switch loss.

Control algorithm: According to the third vector synthesis method, it can be seen from Table 2 that four vectors among the basic vectors V_0~V_7 are required to act jointly in order to space vector V in any interval, i.e., output PWM wave form with the same amplitude and different widths. Assume voltage space vector Vin interval I, basic voltage vectors V_1, V_2 and $V_{0,7}$ are required to act jointly, according to parallelogram law:

$$\frac{T_1}{T_s}V_1 + \frac{T_2}{T_s}V_2 = V \quad (3)$$

In the formula (3),

T_1 & T_2: The time of duration of the vectors v_1 and v_2 in a switch cycle
T_s : PWM switch cycle

Make the time of duration of zero vector $V_{0,7}$ as $T_{0,7}$ and then:

$$T_1 + T_2 + T_{0,7} = T_s \tag{4}$$

The included angle between V and V_1 is θ, due to $|V_1| = |V_2| = 2v_{dc}/3$ and:

$$\begin{cases} T_1 = \dfrac{\sqrt{3}\,|V|\,T_s \sin\left(\dfrac{\pi}{3} - \theta\right)}{v_{dc}} \\ T_2 = \dfrac{\sqrt{3}\,|V|\,T_s \sin(\theta)}{v_{dc}} \end{cases} \tag{5}$$

In formula (5), v_{dc} = Output DC voltage.

SVPWM CONTROL SYSTEM DESIGN

Three-phase VSR adopts SVPWM current control based on fixed switching frequency, i.e., space voltage vector instruction output by current regulator in synchronous rotating reference frame (*d*, *q*) is adopted and SVPWM is used to make space voltage vector of PWM rectifier trace voltage vector instruction so as to reach the purpose of current control. Aiming at DC control, adopt the design thought of double closed-loop (outer voltage loop and inner current loop) control and take the sample of network-side current instantaneous value. Active component and reactive component of network-side current are obtained through 3s/2r coordinate transformation to directly control the phase and amplitude of network-side current.

Three-phase VSR control block diagram is shown in Fig. 7. In the figure, L_a, L_b and L_c are network-side incoming inductance; i_a, i_b and i_c are actual three-phase current value at the network side; U_{dc} and U^*_{dc} are DC-side voltage detection value and given value respectively. The D-value of the two is adjusted by PI to output active component current instruction value i_q^*. Since rectification and inversion of unit power factors are studied, reactive component current instruction value $i_d^* = 0$. Actual detection current values at network side i_a, i_b and i_c output actual current components i_d and i_q of d axis and q axis under dq coordinate system through coordinate rotating conversion. Then, calculate the D-value between actual current components i_d and i_q and current instruction values i_d^* and i_q^*. The D-value outputs instruction voltage values V_d^* and V_q^* under coordinate system trough PI adjustment. Then, instruction voltage values V_α^*, V_β^* under αβ coordinate are obtained through dp/αβ coordinate inverse transformation. The pulse is controlled through output power tube of Phase A and SVPWM control algorithm.

Selection of DC-side voltage: In PWM rectifier, DC-side output voltage U_{dc} both meets voltage requirements of the load and controls the current wave form through filtering inductance L as sinusoidal waves. This rewires certain restriction for U_{dc}. In terms of supply current control, excessively low U_{dc} will lead to serious AC-side current distortion and the current even cannot follow the given value. Thus, the purpose of current control cannot be reached. Excessively high U_{dc} will improve the withstand voltage quota and increase system cost and meanwhile reduce the reliability of the system.

It can be known from the working principle of three-phase voltage PWM rectifier that given DC voltage needs to meet certain conditions in order to

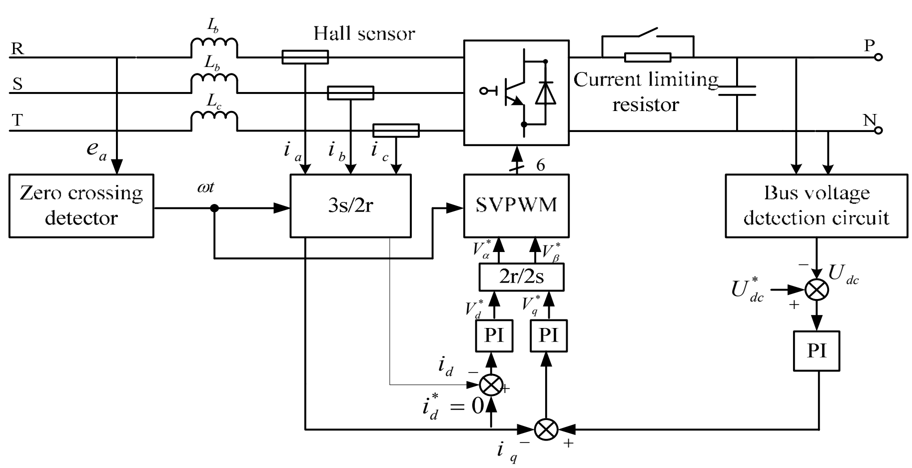


Fig. 7: The three phase PWM rectifier voltage fixed vector control diagram

make the line voltage at the input end of the rectifier exclude low-order harmonic waves. Space vector modulation needs to meet: $T_1 + T_2 \leq T_s$. Thus, it can be deduced that:

$$U_{dc} \geq \sqrt{3} U_m \tag{6}$$

where, U_m is the maximum of phase voltage, i.e., in the control system where voltage space vector PWM control is adopted, actual DC-side voltage must exceed the peak value of line voltage.

Design of AC-side inductance: In the design of three-phase VSR system, the value of AC-side inductance not only influences dynamic and static responses of current loop, but also restricts VSR output power, power factor and DC voltage. If AC-side resistance R of VSR is ignored and Phase a voltage is considered, the equation is:

$$L\frac{di_a}{dt} = e_a - v_{dc}\left(s_a - \frac{1}{3}\left(s_a + s_b + s_c\right)\right) \tag{7}$$

where, v_{dc} = Output DC voltage. The above formula can be rewritten as the incremental equation:

$$\Delta i_a = \frac{T_s}{L}(e_a - v_{dc}\left(s_a - \frac{1}{3}\left(s_a + s_b + s_c\right)\right)) \tag{8}$$

where, T_s = Switch cycle

In the process of current tracking reference signal, current fluctuation amount Δi_a cannot exceed the maximum given fluctuation value Δi_{amax} in each switch cycle. The pulse of harmonic current is the most serious near the peak value of current. Thus, the inductance shall be large enough. At this moment:

$$\Delta i_a = \frac{T_s}{L}\left(\sqrt{2}e_a + \frac{2}{3}v_{dc}\right) \leq \Delta i_{a\max} \tag{9}$$

And get:

$$L \geq \frac{T_s\left(\sqrt{2}e_a + \frac{2}{3}v_{dc}\right)}{\Delta i_{a\max}} \tag{10}$$

In formula (10),

e_a : The effective value of Phase A voltage

Δi_{amax} : Allowable maximum pulse of Phase A current -20% I_{amax} generally

I_{amax} : The peak value of Phase A current

When the inductance L is too large, the tracking performance of actual current for the given current will become poor. When the current exceeds zero, the rate of current change is maximum. The tracking performance index requirement can be met only when the inductance L is small enough. At this time, the tracking speed of current shall exceed the rate of current change of current. Thus, the following relational expression can be obtained:

$$\frac{\Delta i_a}{T_s} = \frac{\frac{2}{3}v_{dc}}{L} \geq \frac{I_{a\max}\sin(\omega T_s)}{T_s} \tag{11}$$

In the above formula, ω is angular frequency of AC power supply and get:

$$L \leq \frac{\frac{2}{3}v_{dc}T_s}{I_{a\max}\sin(\omega T_s)} \tag{12}$$

when current exceeds zero:

$$L \leq \frac{\frac{2}{3}v_{dc}T_s}{I_{a\max}\sin(\omega T_s)} \approx \frac{\frac{2}{3}v_{dc}}{I_{a\max}\omega} \tag{13}$$

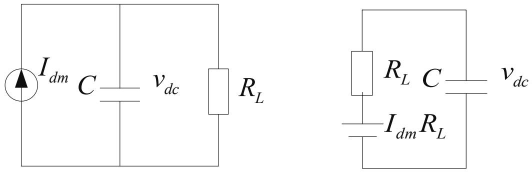
In fact, in actual engineering, in view of manufacturing cost and the rectifier volume, the numerical value of the inductance is expected to be small, so generally the minimum value of the inductance is considered during selection of inductance.

Assume that the effective value of AC-side input voltage is 220V; the given voltage at DC side is 620V; the switching frequency is 10K; the effective value of input current is 30A and the peak value is about 42A and the allowable maximum pulse current value is about 8.4A. According to formula (10), L is about 9 mH. Since three-phase symmetrical voltage is input, the three inductance values connected to the power supply are all 9 mH.

Design of DC-side capacitance: During parameter design of VSR main circuit, except AC-side inductance parameter design, another important parameter design is VSR DC-side capacitance design. Generally speaking, in terms of meeting tracking performance index of voltage loop control, VSR DC-side capacitance shall be as small as possible so as to ensure rapid tracking control of VSR DC-side voltage. In view of meeting tracking performance index of power supply, the dynamic process of three-phase VSR from the minimum value of DC voltage steady state to the rated value of DC voltage is discussed now. When the voltage is not adjusted in power switching tube, the effect of fly-wheel diode in the power tube is equivalent to three-phase diode rectification now. The average minimum of the rectified voltage is:

$$V_{do} = 1.35V_1 \tag{14}$$

In the above formula, V_1 is the effective value of three-phase VSR network-side voltage. The rated value of DC voltage output is:



(a) Constant current (b) Constant voltage

Fig. 8: The equivalent circuit when DC voltage step

$$V_{de}=\sqrt{p_e R_{Le}} \quad (15)$$

In the above formula,
P_e = Rated output power at VSR DC side
R_{Le} = Rated DC load resistance
V_{de} = VSR rated DC voltage

When three-phase VSR DC voltage instruction phase step is set to rated DC voltage instruction, if voltage regulator adopts PI regulator, the output of voltage regulator has been saturated before actual current of three-phase VSR does not exceed the instruction value. Since the output of voltage regulator means current amplitude instruction at three-phase VSR AC side, if the inertia of inner current loop is ignored, the capacitor will be charged at the maximum current I_{dm} at three-phase VSR DC side so as to make DC voltage rise at the fastest speed. The equivalent circuit of this process is shown in Fig. 8.

If the initial value of DC voltage is V_{d0}, the following can be obtained from Fig. 8b:

$$v_{dc}-V_{d0}=\left(I_{dm}R_L-V_{d0}\right)\left(1-e^{-\frac{t}{\tau_1}}\right) \quad \tau_1 = R_L C \quad (16)$$

Make $v_{dc} = V_{de}$, substitute it into the above formula and simplify it and then get:

$$t=\tau_1 \ln\frac{I_{dm}R_L-V_{d0}}{I_{dm}R_L-V_{de}} \quad (17)$$

According to tracking performance index, if the rise time for output DC voltage stepping to rated DC current is required no more than t_r and:

$$R_L C \ln\frac{I_{dm}R_L-V_{d0}}{I_{dm}R_L-V_{de}} \le t_r \quad (18)$$

Generally, take the following values in terms of engineering:

$$\begin{cases} I_{dm}=1.2\dfrac{V_{de}}{R_L} \\ V_{de}=\sqrt{3}V_1 \end{cases} \quad (19)$$

Substitute formula (19) into (18), simplify it and get:

$$C \le \frac{t_r}{0.74 R_L} \quad (20)$$

Thus it can be seen that the upper limit value of DC-side capacitance can be calculated according to the tracking performance index controlled by three-phase VSR DC-side voltage. In consideration of tracking performance of voltage, DC-side capacitance should be as small as possible. However, if anti-interference index of DC-side voltage is considered, the lower limit of DC-side capacitance should be limited. In view of the dynamic process of three-phase DC-side voltage from no-load to full-load disturbance, the lower limit value of DC-side capacitance can be deduced as follows:

$$C > \frac{1}{2\Delta V_m R_L} \quad (21)$$

where,
ΔV_m : The relative value of the maximum dynamic decline of DC voltage and $\Delta V_m = \Delta V_{max}/V_{de}$
ΔV_{max} : The maximum decline value of DC voltage

the ratio of capacitance and lower limit value is obtained according to formula (20) and (21):

$$\lambda_c=\frac{2\Delta V_m t_r}{0.74} \quad (22)$$

Obviously, in order to make the value of VSR DC-side capacitance meet DC voltage tracking performance and anti-interference control performance indexes, λ_c must meet $\lambda_c>1$. Actually, the conditions in formula (22) often cannot be met, so DC voltage tracking performance and anti-interference control performance indexes are considered comprehensively according to actual demands in the process of capacitance parameter design.

Since complex energy exchange process exists between intermediate circuit and the converters at both ends, capacitance selection is related to load power changes, adjustment time of the voltage loop and inertia time delay of the rectifier and other factors. The capacitance can be calculated according to energy balance in the dynamic process. Assume the maximum variable quantity of the load power ΔP = 10 KW, the maximum inertia time of the rectifier T = 1.5 ms and the maximum of voltage fluctuation amount ΔV_{max} = 20V, the maximum energy supplied by the output capacitance at DC side in the dynamic process is:

$$\Delta W \approx \frac{\Delta PT}{2} \quad (23)$$

The capacity of output capacitance is:

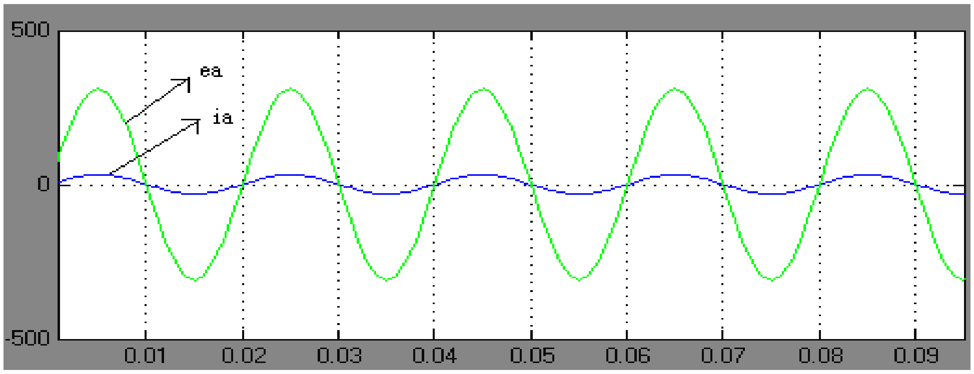


Fig. 9: The voltage and current waves of A phase in the condition of rectifying

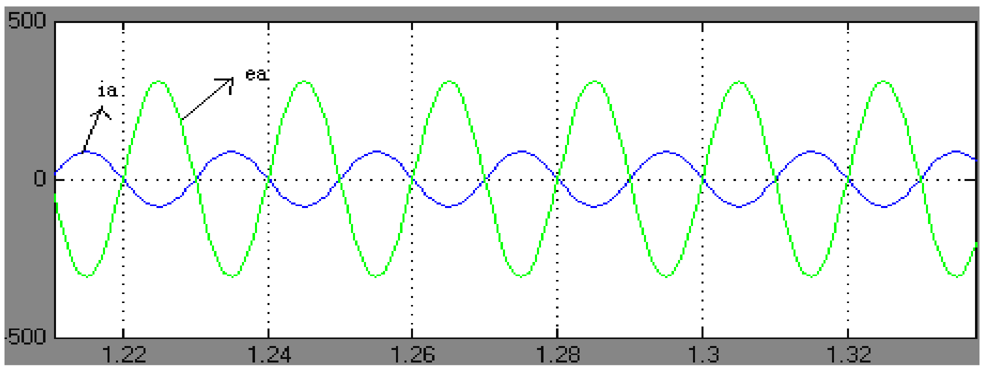


Fig. 10: The network side voltage and current waves of A phase in the condition of active inversion

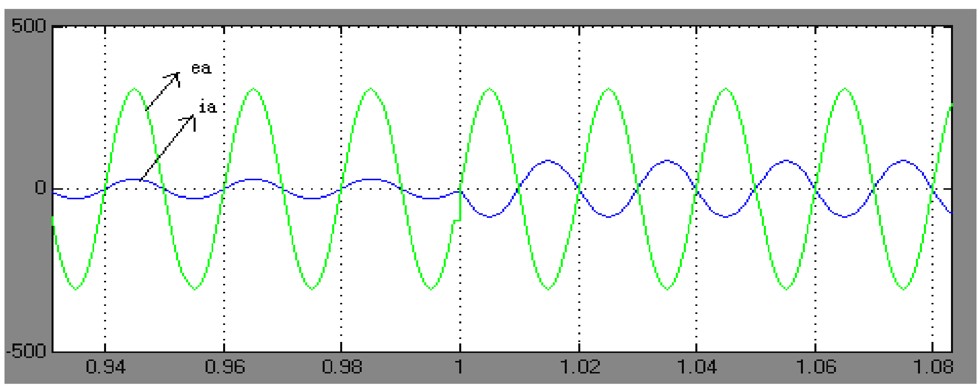


Fig. 11: The voltage and current waves of A phase from rectifying to inversion

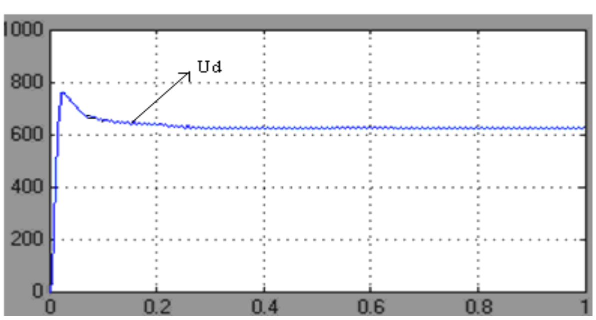


Fig. 12: The DC side voltage wave from rectifying to inversion

$$C \geq \frac{\Delta W}{v_{dc} \Delta V_{\max}} \tag{24}$$

Substitute the above value into formula (23) and get the minimum capacitance value is about 605 uf. The electrolytic capacitor in this design is 680 uf/800V.

SYSTEM SIMULATION TEST

System simulation parameters are set as: the effective value of three-phase AC-side supply voltage is 220V, with the frequency of 50 Hz; the give value at DC side is 620V, with back electromotive force at DC side of 220V, support with back electromotive force at DC side of 220V, support capacitance at DC side is of 605 uF and DC load of 40 Ω; the AC-side inductance is 9 mH and the AC-side resistance is 0.5 Ω; the switching frequency is 10 KHz.

Figure 9 to 12 are wave forms of the whole system simulation results of three-phase voltage-type PWM rectifier controlled by SVPWM; the vertical coordinate is the amplitude value (voltage unit: V; current unit: A) and the horizontal ordinate is the time (unit: s). It can be seen from the figures that when PWM rectifier operates stably in synchronous rectification state, the network-side current and voltage phase are basically consistent. In addition, the sine degree of network-side current wave form is good and network-side power factor approaches 1, with the energy transmitting to the load from the power grid. When PWM rectifier operates stably in active inversion state, network-side current and voltage phase are opposite.

CONCLUSION

This study introduces SVPWM control principles and adopts three-phase PWM rectifier digital control system based on SVPWM control on the basis of this. Besides, AC-side incoming inductance and DC-side capacitance are calculated and selected. Then, each simulation module is established for the whole system by use of simulation software MATLAB/Simulink and simulation researches are conducted. The simulation result shows the digital control system designed is feasible.

ACKNOWLEDGMENT

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