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Research on Control Strategy for Three-Phase PWM Voltage Source Rectifier

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Abstract –This paper first introduces the topology of Three-Phase PWM Voltage Source Rectifier (VSR). Then the mathematical models in three-phase static and two-phase rotary coordinate system are built. Based on that theory and the voltage-oriented vector control's idea, the paper introduces a dual-channel closed-loop control strategy with current-inner-loop and voltage-outer-loop. Active power channel is aim to make DC side voltage remain steady, and reactive power channel can regulate power factor by set current q-axis component reference. In order to prove that voltage-outer-loop is necessary, the paper builds a comparative model without a voltage loop. According to change current q-axis component reference value, illuminate reactive power channel's effect. In MATLAB/SIMULINK, the paper sets up simulation models for above cases. The simulation results show that the voltage-outer-loop is essential, and prove that current q-axis component can regulate power factor. The Three-Phase PWM Voltage Source Rectifier dual-channel double-closed-loop control strategy is effect.

Keywords - Three-Phase PWM Voltage Source Rectifier, voltage-oriented; dual-channel closed-loop control, voltage-outer-loop, current q-axis component.

I. INTRODUCTION

Conventional rectifying method adopts phase-control method or passive diode rectifier. They have has some disadvantages, including slower dynamic respond, passive diode rectifier can absorb harmonic current from power grid and the DC-side energy can not feed back to power grid[1]. Three-Phase PWM Voltage Source Rectifier (VSR) applies Pulse Width Modulation (PWM) technology, it can overcome the phase-control method and passive diode rectifier's drawbacks, and has higher power factor, lower harmonic current and rapid dynamic respond, so Three-Phase PWM Voltage Source Rectifier is a developing rectifying method [2].

Three-Phase PWM voltage source Rectifier is applied in normal and large power converter field, it also can be used in large UPS supply system, in order to achieve unit power factor and eliminate harmonic current. It is a new important focus in power quality field [3]. This paper will study the control strategy for VSR in particular, and prove the control performance in MATLAB/SIMULINK.

II. THE BASIC THEROY FOR VSR

A. Topology for VSR

The main circuit topology is showed in Fig.1. AC-side inputs are ideal three-phase symmetrical voltage source, which are filtered by resistance R and inductor L, then connected to three-phase rectifier consist of IGBT and diode. The output load is composed of capacitance and resistance. Suppose that the power switch is ideal, its fundamental wave equivalent circuit is showed in Fig.2. The input side for PWM rectifier can be equaled to three ideal symmetrical voltage sources, and the output side can be replaced by three ideal current sources [4].

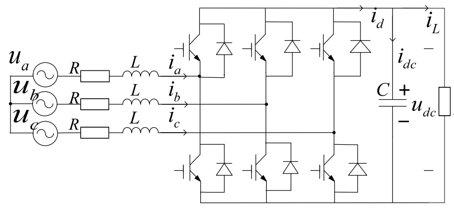

Fig.1. VSR circuit topology

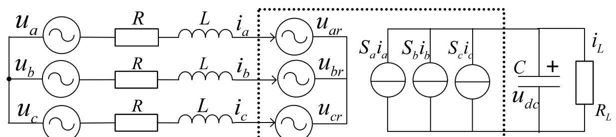

Fig.2. VSR fundamental wave equivalent circuit

B. Mathematical Models for VSR

Base on the topology and equivalent circuit for VSR, we can get (1).

$$\begin{cases} u_a - i_a R - L\dfrac{di_a}{dt} - S_a u_{dc} \\ = u_b - i_b R - L\dfrac{di_b}{dt} - S_b u_{dc} \\ = u_c - i_c R - L\dfrac{di_c}{dt} - S_c u_{dc} \\ C\dfrac{du_{dc}}{dt} = i_d - i_L = S_a i_a + S_b i_b + S_c i_c - i_L \end{cases} \qquad (1)$$

Where: S_a, S_b, S_c are switch functions, when S_k =1, equals the up-arm switch is closed, and the down-arm switch is open. When S_k =0, equals an opposite result (where k = a,b,c). It is three-phase three –wire system, so we can get (2).

$$\begin{cases} i_a + i_b + i_c = 0 \\ u_a + u_b + u_c = 0 \end{cases} \qquad (2)$$

Linking (2) into (1) is (3):

$$\begin{cases} L\dfrac{di_a}{dt} = u_a - Ri_a - \left(S_a - \dfrac{S_a + S_b + S_c}{3}\right)u_{dc} \\ L\dfrac{di_b}{dt} = u_b - Ri_b - \left(S_b - \dfrac{S_a + S_b + S_c}{3}\right)u_{dc} \\ L\dfrac{di_c}{dt} = u_c - Ri_c - \left(S_c - \dfrac{S_a + S_b + S_c}{3}\right)u_{dc} \\ C\dfrac{du_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_L \end{cases} \qquad (3)$$

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The mathematical model in three-phase coordinate system can be converted to the model in dq rotary coordinate system through 3s/2r coordinate transformation [5]; the two-phase model is showed in (4).

$$\begin{cases} L\dfrac{di_d}{dt} = -Ri_d + \omega L i_q - S_d u_{dc} + u_d \\ L\dfrac{di_q}{dt} = -Ri_q - \omega L i_d - S_q u_{dc} + u_q \end{cases} \quad (4)$$

Where:

$$\begin{cases} u_{dr} = S_d u_{dc} \\ u_{qr} = S_q u_{dc} \end{cases} \quad (5)$$

u_{dr} , u_{qr} are control variables, S_d, S_q are switch functions in dq coordinate system. From (4), dq axis current is affected by cross-coupling variables $\omega_1 L i_q$, $-\omega_1 L i_d$, and the power grid voltage u_d,u_q also influence the current. Based on (5), make $\Delta u_{dr} = \omega_1 L i_q$, $\Delta u_{qr} = \omega_1 L i_d$, we can get (6):

$$\begin{cases} u_{dr} = -u'_{dr} + \Delta u_{dr} + u_d \\ u_{qr} = -u'_{qr} + \Delta u_{qr} + u_q \end{cases} \quad (6)$$

Where:

$$\begin{cases} u'_{dr} = L\dfrac{di_d}{dt} + Ri_d \\ u'_{qr} = L\dfrac{di_q}{dt} + Ri_q \end{cases} \quad (7)$$

u_{dr}' and u_{qr}' are the decoupling variables for current dq components, $\omega_1 L i_q$, $-\omega_1 L i_d$ are the compensations for eliminating cross-coupling between the current dq components. Dividing the variables into the decoupling component and the compensation can simplify the control process, which make model control the current independently.

III. CONTROL STRATEGY FOR VSR

A. Grid-Voltage-Oriented Vector Control

To simplify the control arithmetic, applying the vector coordinate transformation, the infinite power grid can be regarded as constant approximately. So we orient the d-axis by grid voltage vector u_s, $\theta_u = \omega_1 t$ is the phase angle of grid voltage[6], the voltage dq components of power grid can be showed in (8).

$$\begin{cases} u_d = u_S \\ u_q = 0 \end{cases} \quad (8)$$

The power flow from power grid to VSR can be described in (9):

$$\begin{cases} P = u_d i_d + u_q i_q = u_s i_d \\ Q = u_q i_d - u_d i_q = -u_s i_q \end{cases} \quad (9)$$

From (9), we can see that active power and reactive power can be controlled independently through Grid-Voltage-Oriented vector control strategy. Dq components i_d,i_q are active power and reactive power component for VSR respectively. Regulating them can achieve the active and reactive power's decoupling control [7].

Linking (8) into (6), we can get (10), which is the basis for dual-channel closed-loop control model.

$$\begin{cases} u_{dr} = -u'_{dr} + \Delta u_{dr} + u_s \\ u_{qr} = -u'_{qr} + \Delta u_{qr} \end{cases} \quad (10)$$

B. The Dual-channel Closed-loop Control Model

According to (10) and Grid-Voltage-Oriented vector control strategy, a dual-channel closed-loop control strategy for VSR is present. i_d, i_q are active power and reactive power component, so dual channels are named by active power control channel and reactive power control channel.

For active power control channel, the voltage control loop is regarded as outer-loop. The error between DC voltage command and feedback voltage passes PI regulator, the result is active power current command i_d^*. The active power control channel controls VSR DC-side voltage, and makes it remain constant.

For reactive power control channel, it is aim to accomplish that the system's input power factor remain unit, that is, input voltage and current has the same phase. In order to fulfill it, the reactive current should be controlled to zero all the time [8].

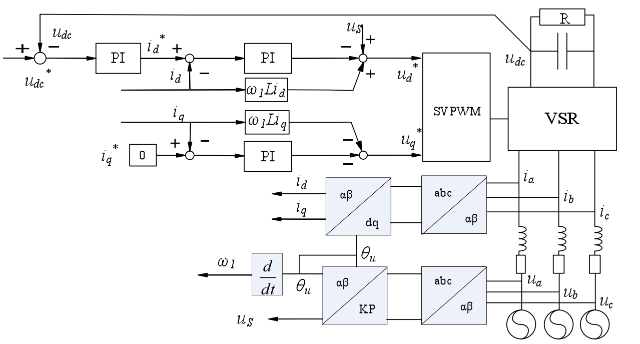

Fig.3 VSR dual-channel closed-loop control structure

The active component i_d^* and the reactive component i_q^* are compared with their feedback values, then the error are calculated by current PI regulator, the output values are the voltage component $u_d^{'}$, $u_q^{'}$. According to (10), $u^{'}_d$, $u^{'}_q$ add $\omega_1 L i_q$, $-\omega_1 L i_d$ and power grid voltage disturb compensation u_s, the result are command control signal u_d^*, u_q^*, which can generate the necessary signals for controlling the switch order of VSR [9]. The whole control structure is showed in Fig.3.

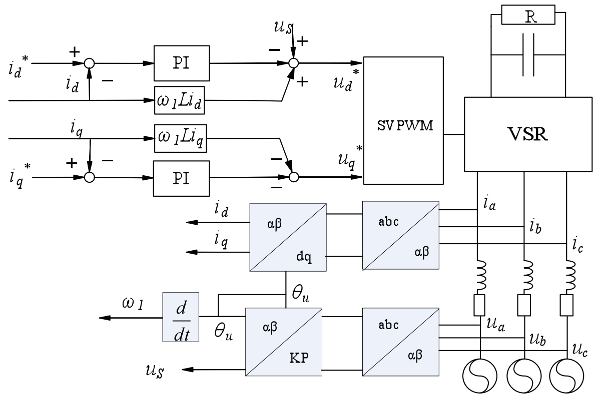

Fig.4 VSR single-closed-loop control structure

C. The Single-Closed-loop Control Model

In order to prove the effect of voltage-outer-loop for dual-closed-loop control model, the primary model is changed to single-closed-loop model, which remains dual-channel structure. The DC-voltage-loop is removed in new model's active power channel, current d-axis component command value i_d^* is given, and reactive power channel is the same as former. In MATLAB/SIMULINK, the simulation model will be built to prove the single-closed-loop model's control performance. Its structure is showed as Fig.4.

To prove the effect of reactive power channel, the current q-axis component command value i_q^* can be regulated. In MATLAB/SIMULINK, we can see how i_q^* affects the power factor.

IV. SIMULATION

A. Simulation Model.

In MATLAB/SIMULINK, the dual-closed-loop model and single-closed-loop model are built respectively. Simulation time is 0.3s. The model's parameter is set as follows: power grid phase voltage's RMS is 110V, L=5mH, R=5Ω, C=2.2mF, i_L =20A, u^*_{dc} = 300V. Dual-closed-loop model is showed in Fig.5; its inner-current-loop model is showed in Fig.6.

Single-closed-loop model is showed in Fig.7, the current command value is set as follows: i_d^* = 30A, i_q^* = 0A. Its inner-loop parameter is as same as dual-loop model.

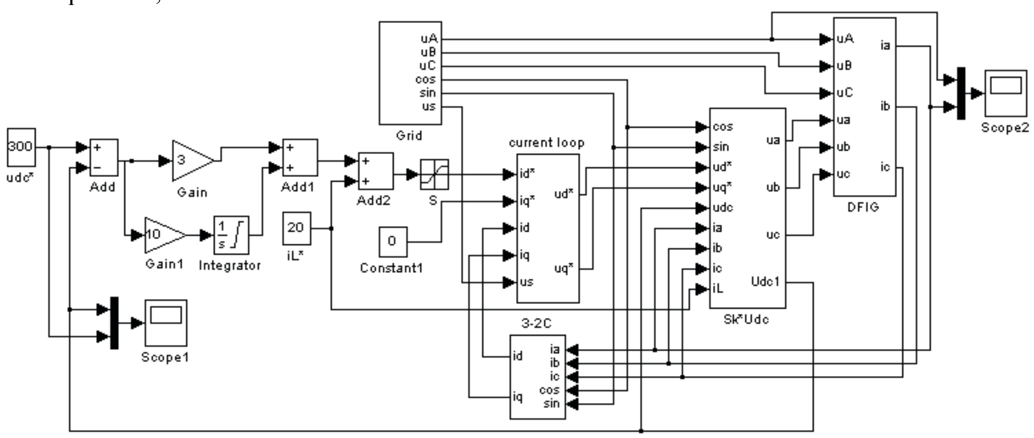

Fig.5 VSR dual-closed-loop simulation model

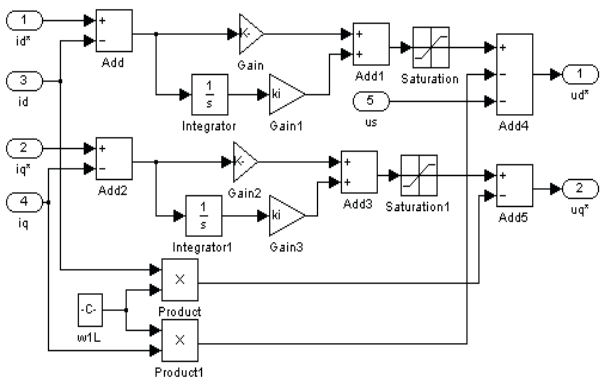

Fig.6 VSR inner-loop simulation model

B. Simulation Result

1) When i_q^* = 0A, dual-loop simulation results are showed in Fig.8-9. Fig.8 is the DC-side voltage simulation result; Fig.9 is one phase simulation result for power grid voltage and input current. From Fig.8, u_{dc} can follow the command signal u_{dc}^*, which proves that the VSR DC-side voltage can be controlled as constant steadily. From Fig.9, the result show that input grid voltage and input current have same phase, which illuminates that the dual-closed-loop model can make system run in unit power factor.

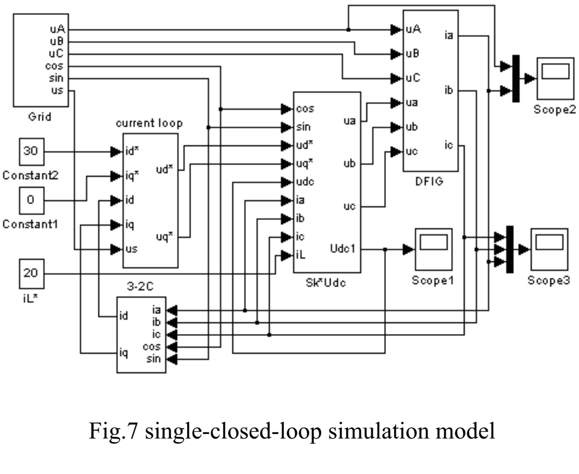

Fig.7 single-closed-loop simulation model

2) when iq* = 20A, dual-loop simulation results are showed in Fig.10-11. Fig.10 is the DC-side voltage simulation result; Fig.11 is one phase simulation result for power grid voltage and input current. Compared with Fig.8-9, the result shows that u_{dc} also can follow the command signal u_{dc}^*, which is similar to Fig.8. From fig.11, we can see that the phase of input voltage leads the phase of current, and the power factor is not equal to unit. It proves the i_q^* affects the power factor indirectly.

3) The single-closed-loop simulation results are showed in Fig.12-13. Fig.12 is the DC-side voltage simulation result; Fig.13 is one phase simulation result for power grid voltage and input current. The simulation results show that u_{dc} can't follow the command signal u_{dc}^*, its value can't be controlled to be steady. Current wave has high harmonic, its performance can't satisfy control demand, which proves that the DC-voltage-loop is necessary.

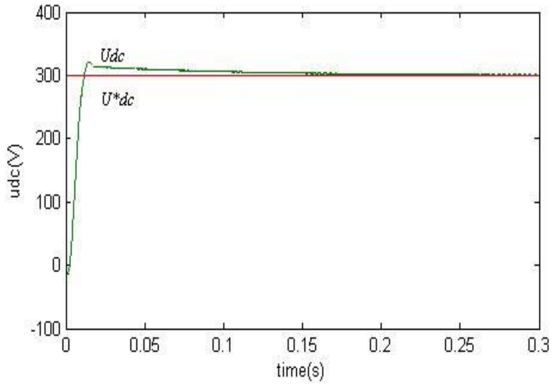

Fig.8 dual-loop u_{dc} simulation result（i_q^*=0A）

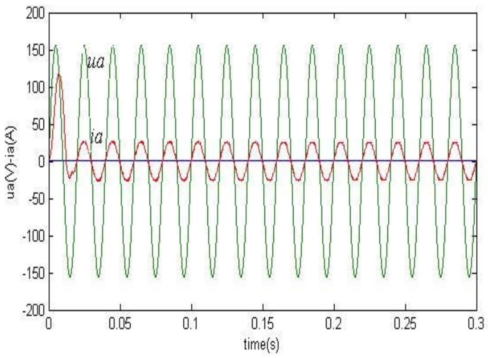

Fig.9 dual-loop u_a, i_a simulation result（i_q^*=0A）

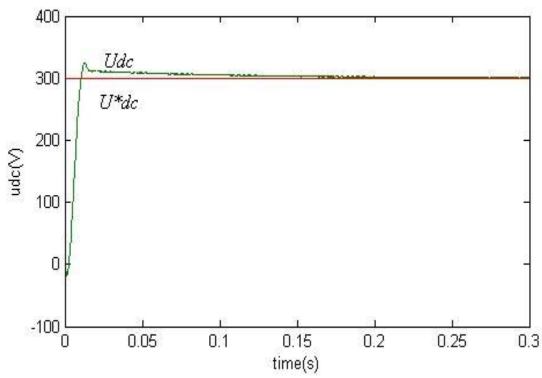

Fig.10 dual-loop u_{dc} simulation result（i_q^*=20A）

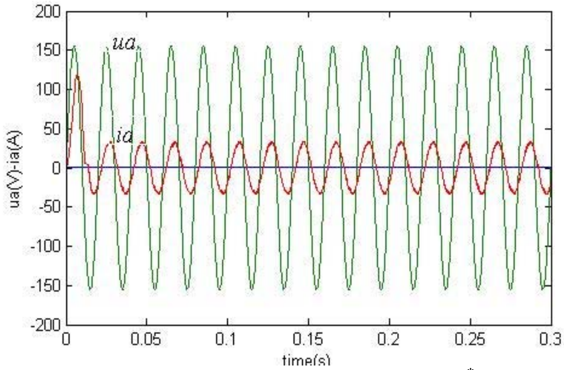

Fig.11 dual-loop u_a, i_a simulation result（i_q^*=20A）

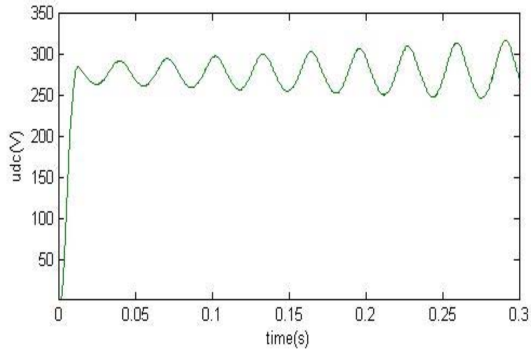

Fig.12 single-loop u_{dc} simulation result

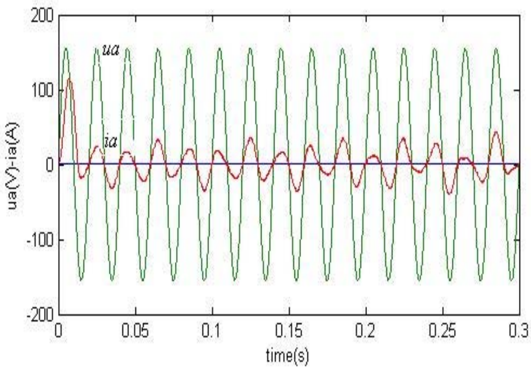

Fig.9 single-loop u_a, i_a simulation result

V. CONCLUSION

The simulation results show that the dual-channel closed-loop strategy has good control effect. Active power channel can control DC-side voltage to be constant for VSR. In reactive power channel, the power factor can be changed by regulating i_q^*. To make system run in unit power factor, we can set $i_q^*=0$. Compared with dual-closed-loop model, the simulation results of single-loop model is not ideal. Without DC-voltage-loop, u_{dc} can't be steady, which shows that DC-voltage-loop is essential in active power channel. According to compare the simulation results, it proves that the dual-channel closed-loop control strategy for Three-Phase PWM Voltage Source Rectifier is correct.

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