Research on Three-phase PWM Rectifier based on Double Closed-loop Feedforward decoupling control

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Abstract. For rectifier link widely used traditional diode rectifier circuit and brake pipe phased rectifier circuit, resulting in net side current, voltage distortion, problem of higher harmonic and low power factor, and put forward a double closed-loop feed-forward decoupling control strategy, used in three-phase voltage source PWM rectifier was established in Matlab/Simulink simulation model, compared with traditional SVPWM control of three-phase PWM rectifier, verifies the correctness of the proposed control strategy. From the simulation results, it can be seen that the voltage on the grid side is nearly consistent with the phase of the current, which realizes the operation of unit power factor and makes the voltage on the DC side reach steady-state rapidly, thus reducing the harmonic pollution and improving the power quality, which has a good practical application effect in the power transformation.

1. Introduction

Power electronic devices in the development as well as a variety of clean energy under the background of the emergence, performance of rectifier and inverter circuit has been widely applied, the traditional rectifier link widely used diode uncontrollable rectifier circuit and brake pipe phased rectifier circuit, although have strong robustness, the advantages of low cost, but to give the power injected into the non-sinusoidal current and higher harmonic, pollute the power grid, the serious influence the quality of electric energy[1-3]. Therefore, scholars at home and abroad have carried out extensive research on PWM rectifier that can realize two-way flow of energy, get output current close to sinusoidal wave and output unit power factor, and its control strategy has become a research hotspot[4-5].

The control objects of three-phase PWM rectifier are generally ac side current and DC side output voltage, among which AC side current control is the core of rectifier system. At present, there are many kinds of PWM modulation techniques, such as sinusoidal pulse width modulation (SPWM), space vector pulse width modulation (SVPWM), time optimal control and so on[6-7]. In view of the traditional electrical equipment use the components such as diodes, silicon controlled rectifier front-end power supply, resulting in net voltage to current power factor to reduce the single-phase flow, energy and other issues[8-10]. have designed a feedforward decoupling control of double closed loop control system, with the actual current with a given current error as input of regulator, regulator for three-phase PWM rectifier ac voltage vector of instructions, to control the conduction of the switch tube, realize the stable operation of the system. The control strategy also realizes the characteristics of approximate sinusoidal current, low harmonic content and stable DC output voltage.
2. Mathematical model of three-phase voltage-sourced PWM rectifier

The main circuit topology of the three-phase voltage type PWM rectifier (VSR) is shown in figure 1.

In the three-phase voltage-sourced PWM rectifier circuit shown in the figure above, \( e_a, e_b, e_c \) represented as the three-phase voltage of the AC power supply with star connection; L is the AC side filter inductance; R is the equivalent resistance on the AC side; C is the DC side capacitor.

Assuming the following ideal conditions: the power supply is three-phase stable and symmetrical, the AC side inductance is linear, the resistance of the VSR power switch tube and the AC side filter inductor is combined as R, the switch tube is an ideal device, and there is no switch dead zone.

Using the switching function, the general mathematical model of the VSR circuit in the three-phase static coordinate system can be obtained as shown in formula (1):

\[
\begin{align*}
L \frac{di_a}{dt} + Ri_a &= e_a - (v_{dc} s_a - \frac{v_{dc}}{3} \sum_{k=a,b,c} s_k) \\
L \frac{di_b}{dt} + Ri_b &= e_b - (v_{dc} s_b - \frac{v_{dc}}{3} \sum_{k=a,b,c} s_k) \\
L \frac{di_c}{dt} + Ri_c &= e_c - (v_{dc} s_c - \frac{v_{dc}}{3} \sum_{k=a,b,c} s_k) \\
C \frac{dv_{dc}}{dt} &= i_a s_a + i_b s_b + i_c s_c - i_L
\end{align*}
\]

(1)

According to the above mathematical model in the three-phase \( abc \) static coordinate system, there is a coupling between the three-phase grid voltage \( e_a, e_b, e_c \) and the three-phase grid current \( i_a, i_b, i_c \). Therefore, by coordinate transformation, Convert the three-phase \( abc \) static coordinate system into a rotating two-phase coordinate system with the same frequency as the fundamental wave of the power grid, which can realize no static error control. Then the mathematical model of the VSR in the two-phase rotating coordinate system is shown in formula (2):

\[
\begin{align*}
L \frac{di_q}{dt} - wLi_q + Ri_q &= e_q - v_{dc} s_q \\
L \frac{di_d}{dt} + wLi_d + Ri_q &= e_q - v_{dc} s_q \\
C \frac{dv_{dc}}{dt} &= \frac{3}{2} (i_d s_d + i_q s_q) - i_L
\end{align*}
\]

(2)

3. Research and Design of VSR Control Strategy

It can be seen from formula (2) that there is a problem of mutual coupling of the \( dq \) components of the inner loop current in the two-phase rotating coordinate system after coordinate transformation; and
the inductance and grid electromotive force in the two-phase rotating coordinate system affect the current $i_d$ and $i_q$, so the negative feedback decoupling control cannot realize the independent control of $i_d$ and $i_q$. Feedforward decoupling control can be used, as shown in equation (3):

$$
\begin{align*}
V_d &= -(K_{v_d} + \frac{K_{v}}{s})(i_d^* - i_d) + wL_i + e_d \\
V_q &= -(K_{v_q} + \frac{K_{v}}{s})(i_q^* - i_q) + wL_i + e_q
\end{align*}
$$

(3)

The $i_d^*, i_q^*$ in the above formula is the command value of the current inner loop $i_d,i_q$. The model diagram shown in figure 2 realizes the decoupling control of the rectifier.

![Figure 2. Feedforward decoupling control in two-phase rotating coordinate system.](image)

It can be seen from figure 2 that the rectifier has realized the independent control of the $dq$ axis current, realized the decoupling of the control mode, and brought convenience to the control. In order to achieve unity power factor control, the current value on the shaft can be set to zero when the control system is set. The value of $e_d^*$ is the maximum amplitude of the phase voltage during the process of controlling the power input value of the rectifier. The given value of $e_q^*$ is 0. This ensures that the rectifier works in the unit power factor state during the control process.

3.1. Current inner loop parameter design

After the feedforward decoupling, the $i_d$ and $i_q$ on the $dq$ axis are independent and symmetrical. The $i_d$ calculation process can be selected to calculate the parameter size. The control parameter design of $i_q$ is the same. Figure 3 shows the current inner loop control structure after feedforward decoupling.

![Figure 3. Current control structure diagram of the current inner loop $i_d$.](image)

In figure 3, $T_s$ is the operating switching frequency of the rectifier, and $K_{PWM}$ is the equivalent gain of the rectifier. Therefore, the transfer function of the system is obtained as Equation (4):
Simplify and merge the above equations, and convert the transfer function of the PI controller into a zero-pole expression, as shown in equation (5):

$$G(s) = \frac{K_p + \frac{K_i}{s}}{s(1.5T_s + 1)}$$

The inner loop of the rectifier is designed according to a typical I-type system, so that the inner loop of the current has a good followability, and then make:

$$\tau_i = L/R$$

Incorporating into equation (4), the simplified expression of the inner loop can be obtained as:

$$G(s) = \frac{K_pK_{PWM}}{R\tau_i}$$

It can be seen from the parameter setting relationship of the typical type I system that when the damping ratio $\xi$ is 0.707, the system performance is the best, then:

$$\frac{1.5T_sK_pK_{PWM}}{R\tau_i} = \frac{1}{2}$$

The setting coefficient of PI control is calculated as:

$$\begin{aligned}
K_p &= \frac{3T_sK_{PWM}}{2R\tau_i} \\
K_i &= \frac{\tau_i}{3T_sK_{PWM}}
\end{aligned}$$

3.2. Voltage outer loop parameter design

According to the circuit topology diagram of the PWM rectifier, formula (10)

$$i_{dc} = S_a i_a + S_b i_b + S_c i_c$$

Taking into account the low frequency component of the switching function, we can get equation (11)

$$\begin{aligned}
S_a &= 0.5m \cos(wt - \theta) + 0.5 \\
S_b &= 0.5m \cos(wt - \theta + 120^\circ) + 0.5 \\
S_c &= 0.5m \cos(wt - \theta - 120^\circ) + 0.5
\end{aligned}$$

In equation (11), $\theta$ is the initial phase angle of the fundamental wave of the switching function, and $m$ is the modulation ratio of PWM.

When the VSR runs at unity power factor, the three-phase symmetrical current can be obtained as:

$$\begin{aligned}
i_a &= I_m \sin(wt) \\
i_b &= I_m \sin(wt + 120^\circ) \\
i_c &= I_m \sin(wt - 120^\circ)
\end{aligned}$$

Combining formulas (10) (11) (12) to obtain the input current of the rectifier is:

$$i_{dc} \approx 0.75mI_m \cos\theta$$

Since the formula (13) is variable, but in the design, a fixed value is generally adopted, and a constant 0.75 is used to replace the time-varying link. In addition, considering the delay of the voltage sampling signal of the voltage outer loop, the voltage outer loop control system is shown in Figure 4:
Figure 4. Voltage outer loop control diagram.

Figure 4 considers the sampling delay of the voltage outer loop, adding the sampling delay of the voltage outer loop and the sampling time of the current inner loop together, ignoring the disturbance of the load current, and deducing the voltage outer loop control equation as formula (14):

$$v_p(s) = \frac{(4 \tau_v + 1) K_s G_s}{\tau_v s + 1} \frac{3(\tau_v s + 1)}{4(4 \tau_v + 1) \tau_v s + 1}$$

When designing the voltage loop, consider the anti-load disturbance ability of the voltage outer loop, which can make the system quickly recover to the steady-state value when it is disturbed. According to the type II system design, derive formula (15)

$$\frac{3K_v}{4C} = \frac{h_v + 1}{32h_v T_i}$$

In formula (16), $h_v = \tau_v / 4T_i$ represents the intermediate frequency width of the voltage outer loop, and the PI parameter of the voltage outer loop is obtained as:

$$K_v = \frac{C}{5T_i}, \quad K_i = K_v \frac{20T_i}{20T_i}$$

The design method of the double closed-loop voltage outer loop and the current inner loop, and the parameter design method derived above, design and control the control parameters of the inner and outer loops according to the parameters of the circuit, which simplifies the workload and achieves fast and effective parameter setting.

4. Simulation model and experimental analysis
Using Matlab/Simulink, a simulation model based on the feedforward decoupling double closed-loop controller was established to verify the performance of the rectifier described by the model. The simulation model is shown in Figure 5.
Figure 5 shows the simulation model of the VSR system. The main simulation parameters of the system are shown in Table 1.

| Parameter                        | Value  |
|----------------------------------|--------|
| Three-phase AC line voltage peak value | 311V   |
| Input line voltage               | 220V   |
| DC side output voltage           | 700V   |
| AC side inductance               | 2mH    |
| AC side resistance               | 0.5Ω   |
| DC side resistance               | 30Ω    |
| DC side capacitor                | 2000μF |

In the feedforward control, the DC voltage is set to 700V, and the simulation is performed to obtain the DC voltage waveform as shown in Figure 6. It can be seen from Figure 6 that the system responds to a stable output DC voltage and current in a very short time.

5. Concluding Remarks

This paper proposes a control strategy for a three-phase PWM rectifier based on feedforward decoupling and double closed-loop control. This strategy aims to improve the anti-interference and dynamic response characteristics of the overall system. And built a three-phase voltage-type rectifier simulation model with feedforward decoupling double closed-loop control in MATLAB/Simulink. It can be seen from the simulation results that the control strategy achieves separate control of the active and reactive power.
power of the rectifier, which improves the utilization rate of the DC voltage. In addition, the output voltage of the rectifier begins to stabilize after 0.1s after being added to the load. In 0.15s, the robust performance is better, and the phase of the grid-side voltage and current is consistent. The current waveform is close to a sine wave after 0.02s, and unity power factor control is realized. And compare with the traditional control method to verify the correctness of the control strategy.

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