Research on control strategy of a buck-type harmonic injection three-phase rectifier

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Abstract. This paper proposes a buck-type harmonic injection three-phase rectifier to mitigate the high voltage stress of the rear switch of the conventional boost-type power factor correction (PFC) circuit. It develops a control strategy composed of improved double loop control pattern and voltage feedforward pattern. Firstly, the working principle of the buck-type harmonic injection three-phase rectifier is described. Then, it demonstrates the advantage of improved control strategy. Afterwards, the controller’s corresponding involved parameters are optimized. Finally the theoretical analysis and simulation results show that the circuit can output the stable low ripple voltage with increased power factor and decrease the harmonic content of input side current.

1. Introduction

At present, with the development of power electronics, various converter equipment has caused serious harmonic pollution to the power grid, and the harmonic pollution will cause serious damage to the electrical equipment [1-2]. Therefore, the PFC technology is generated, which make the input side current tend to be sinusoidal and improve the power factor of the circuit. Common PFC circuits are mainly divided into boost-type and buck-type [3]. Boost-type PFC Circuit inductor on the input side, with boost characteristics, continuous inductor current, simple control, but its high output voltage, the post-stage switch tube stress requirements, power consumption is not conducive to the design of the rear stage circuit, these limit its development [4-6]. Buck-type PFC is able to achieve low voltage output, low stress requirements for post-stage pipes, and inrush current protection, which are becoming more and more interesting with increasing power requirements [7-8].

The article [9] describes in detail the feasibility and effectiveness of the three harmonic midpoint injection principle, which provides the idea for the following research, but the paper does not combine with the specific circuit to further study. Literature [10] in the traditional three-phase six-switch PWM rectifier circuit be based on the addition of two-way switch tube, three harmonic injection to achieve the PFC, but the circuit controllable devices too much, difficult to control. The principle and control strategy of Buck-type harmonic injection rectifier are studied in literature [11], but its control strategy is larger and the response speed is slower when the load changes.

Based on the detailed analysis of the above literatures, this paper mainly analyzes the working principle and current injection circuit of three-phase buck harmonic injection rectifier, and puts forward an improved double closed-loop control mode, which is verified by simulation, the control effect is better, the unit power factor can be realized, the input current harmonic content is improved, achieves low ripple voltage output.
2. Main circuit topological structure

The topology of the three-phase Buck-type harmonic injection rectifier is shown in Figure 1. It mainly includes input \( LC \) filter part, harmonic current injection part and buck rectifier part. The main function of the input filter is to filter out the high frequency harmonic components in the input current, and to achieve the purpose of harmonic current injection through reasonable control of the conduction timing of the three sets of bidirectional switching tubes, and to realize the sinusoidal input current and improve the power factor of the circuit. The buck rectifier part can achieve buck and stabilize the low ripple voltage by controlling the high frequency switching tube output.

![Fig1 Topological structure of three-phase buck-type harmonic injection rectifier](image)

3. principle Analysis

For the rectifier circuit, the injection current acquisition is mainly two channels, namely the external supply and the internal supply of the circuit itself. The former is more intuitive but complex and cost-efficient, and the second method is chosen here [12]. It is found that for three-phase Buck-type harmonic injection rectifier, the current at point \( E \) is an ideal three harmonic source, which can be used as the pulsation source of three harmonic circulations injected into the input terminal.

To facilitate analysis, the following assumptions are made:

1. Both the active switching element and the diode are considered ideal switches, ignoring their conduction pressure drop;
2. Ignore the low-frequency voltage drop on the input filter inductor, that \( v_{a,b,c} \equiv v_{a,b,c} \);
3. The output inductor current is constant.

The current injection path of the rectifier is analyzed using interval \( v_a > v_b > v_c \) as an example. Figure 2 is a simplified equivalent circuit diagram.

![Fig.2 Three-phase buck-type harmonic injection rectifier Equivalent circuit at \( v_a > v_b > v_c \)](image)

For three-phase Buck-type harmonic injection rectifier, its output voltage \( v_o \) is the function of two-phase line voltage, the output voltage of the rectifier bridge is not controlled by the minimum value of the effect, therefore, according to the following formula can be seen, three-phase buck harmonic injection rectifier output voltage can achieve a full range of voltage adjustable.

\[
0 < v_o < \frac{3}{2} V_{1-l,rm} \]  \hspace{1cm} (1)

In the formula 1, \( V_{1-l,rm} \) is the effective value of the line voltage, therefore, the Formula 1 can be further simplified as the phase voltage peak form, that:
In the formula 2, $v_{\text{phase}}$ is the phase voltage of the three-phase supply, and $\hat{v}_{\text{phase}}$ is the phase voltage peak.

Available from the formula 2:

$$0 < v_o < \frac{3}{\sqrt{2}} v_{l-rms} = \frac{3}{\sqrt{2}} v_{\text{phase}} = \frac{3}{2} \hat{v}_{\text{phase}}$$  \hspace{1cm} (2)

As a result, the $2v_o / 3\hat{v}_{\text{phase}}$ in the formula 3 can be defined as the modulation ratio $M$, that:

$$M = \frac{2}{3} \frac{v_o}{\hat{v}_{\text{phase}}}, \quad 0 < M < 1$$  \hspace{1cm} (4)

Assuming that the admittance of the three-phase circuit is $G$, the three-phase input current is:

$$\begin{align*}
i_a &= Gv_{aN} = I_m \sin(\sigma_0 t) \\
i_b &= Gv_{bN} = I_m \sin(\sigma_0 t - \frac{2\pi}{3}) \\
i_c &= Gv_{cN} = I_m \sin(\sigma_0 t + \frac{2\pi}{3})
\end{align*}$$  \hspace{1cm} (5)

For a three-phase buck rectifier, the output current ripple is ignored, and the output filter inductor current is:

$$I_{DC} = \frac{3}{2} \frac{V_m^2}{v_o}$$  \hspace{1cm} (6)

Where $V_m$ is the amplitude of the phase voltage and $v_o$ is the output voltage.

The duty ratios of the switching Tubes $V_{T+}$ and $V_{T-}$ are $d_1$ and $d_2$, respectively:

$$d_1I_{DC} = i_a, \quad d_2I_{DC} = -i_c$$  \hspace{1cm} (7)

Integrated the formula 5,6,7 can get:

$$\begin{align*}
d_1I_{DC} &= \frac{2}{3} v_o v_{aN} \\
d_2I_{DC} &= \frac{2}{3} v_o v_{aN}
\end{align*}$$  \hspace{1cm} (8)

For symmetric three-phase Y-junction circuits, $i_a + i_b + i_c = 0$, so the injected current $i_c$ is:

$$i_c = (1-d_2)I_{DC} - (1-d_1)I_{DC} = i_a + i_c = -i_b$$  \hspace{1cm} (9)

From the above analysis can be obtained, the circuit can be achieved by the e-point generated three harmonic current injected into the input current, so that the input current continuous, as long as the use of reasonable control strategy and modulation method can be very good to achieve the input current sinusoidal.

4. System control strategy improvement and design

4.1 Traditional system control strategy

The traditional three-phase Buck-type harmonic injection rectifier control system structure can be divided into two parts, based on the double closed-loop pi adjustment as a negative feedback error signal, the rectifier bridge arm ends of the voltage as a feedforward signal, then the two do poor, and then the triangular wave modulated high-frequency switch control signal, the structure of the diagram shown in Figure 3(a).
Through analysis and simulation, it is found that the control mode can modulate the control signal of the switch tube, and realize the function of three-phase Buck-type harmonic injection rectifier, but the control mode mainly has the following disadvantages:

1. This control mode is the Rectifier bridge arm at both ends of the voltage of the unit ratio $\frac{2}{3}V_M^2$ to the double closed-loop PI control negative feedback signal, this way will greatly reduce the negative feedback error signal amplitude, not very good to play the advantages of double closed-loop PI control;

2. Under this control mode, the output voltage will have a large ripple, and the output voltage is not stable;

3. Through the simulation found that the negative feedback signal and the feedforward signal to do poor, to control the high-frequency switching tube, the modulation signal produced in this way and the bidirectional switch control performance is poor, so that the AC side input current harmonic content is higher.

4.2 Improved system control strategy
Based on the shortcomings of the traditional control strategy, this paper improves the double closed-loop control strategy of three-phase Buck-type harmonic injection rectifier. The structure of the control system presented in this paper is shown in Figure 3(b).

The proposed control methods mainly include the following improvements:

1. The rectifier bridge arm end voltage to the unit ratio $\frac{1}{V_M}$ to the double closed-loop PI control negative feedback signal multiplication, this way is the rectifier bridge arm end voltage unit, which will better use the double closed-loop PI control feedback signal, play the advantages of PI control, so that the dual closed-loop PI control participate in the adjustment of the dynamic, The performance of static characteristics is superior;

2. The signal generated by the Feedforward control signal and the double closed loop control is changed from the traditional control to the multiplication, the improvement after simulation shows that the ripple of the DC output inductor current will be greatly reduced, thus the output voltage is more stable and its ripple is almost zero;

3. Improve the modulation of high-frequency switching tube, and according to the different duty ratio led to different circuit working state, respectively, the interleaving modulation and synchronous modulation method, the simulation found that interleaving modulation can better reduce the output voltage ripple, synchronous modulation can better reduce the input current harmonic content.

4.3 Control system Design
1. Feedforward Network Design

After sampling the voltages at both ends of the rectifier bridge arm in this design, the voltage at both ends of the bridge arm of the rectifier bridge must be normalized according to the sawtooth Crest.
Peak $V_T$ which is involved in modulation, where it is divided by the amplitude $V_M$ of the three-phase phase voltage.

2. Double closed loop design

Combined with Figure 3(b), and the circuit of the two-way switching tube part of the simplification, you can obtain a double-loop control system schematic diagram, as shown in Figure 4.

$$\hat{V}_o(s) = \frac{G(s)}{G_V G_1 K_{PWM}}$$

(10)

According to the open-loop transfer function, the characteristic root equation of closed loop transfer function can be obtained:

$$D(s) = A_4 s^4 + A_3 s^3 + A_2 s^2 + A_1 s + A_0$$

(11)

Which:

$$\begin{align*}
A_4 &= LC' \\
A_3 &= K_{PWM} K_{ip} BC' s^3 \\
A_2 &= K_{PWM} K_{ip} K_{i} (1 + \alpha) \\
A_1 &= K_{PWM} K_{ip} K_{i} (1 + \alpha) + K_{PWM} K_{ip} K_{i} \alpha + K_{PWM} K_{ip} K_{i} + 1 \\
A_0 &= K_{PWM} K_{ip} K_{i} (1 + \alpha)
\end{align*}$$

(12)

The stability of closed-loop system is mainly determined by the distribution of its closed-loop poles on the S-plane [13], and the dominant poles of the system are:

$$s_{1,2} = \frac{-\xi \sigma_n \pm j \sigma_n \sqrt{1 - \varepsilon^2}}{n}$$

(13)

For a 4-order system, the further two poles are farther away from the dominant poles, the more stable the system, and the two non-dominant poles of the system are:

$$s_{3,4} = -n_{2,5} \xi \sigma_n \quad n_{2,5} \in 5-10$$

(14)

According to the desired ideal pole and non-dominant pole, the ideal characteristic root equation of the system can be obtained:

$$D(s) = \left(s^2 + 2 \xi \sigma_n s + \sigma_n^2\right)(s + n_{2,5} \xi \sigma_n)\left(s + n_2 \xi \sigma_n\right)$$

$$= s^4 + B_3 s^3 + B_2 s^2 + B_1 s + B_0$$

(15)

The overshoot $\sigma$ and rise time $t_p$ of the system can be expressed separately as:

$$\sigma = e^{-\frac{\sigma_n}{\xi} \sqrt{1 - \varepsilon^2}}$$

$$t_p = \frac{\pi}{\sigma_n \sqrt{1 - \varepsilon^2}}$$

(16)
According to the actual experience of the project, set the system's overshoot \( \sigma = 0.05 \), rise time \( t_r = 0.001 \), the damping ratio of the system according to the upper formula is \( \xi = 0.7 \), the natural oscillation frequency is \( \omega_n = 4350 \). Take two non-dominant pole coefficients \( n_1 = 5 \), \( n_2 = 8 \), take the DC output filter inductance \( L = 305 \mu H \), filter capacitance \( C = 470 \mu F \), the above parameters into the formula 16, and according to the ideal characteristics of the root equation and the actual characteristics of the relationship between the root equation, you can find the voltage outer ring and the current internal loop PI controller parameters are: the current inner loop proportional control, \( K_i = 8.7 \times 10^{-3} \), the voltage outer ring is proportional integral control \( K_{pi} = 78.33 \), \( K_{qi} = 9.33 \times 10^4 \).

5. Simulation Results Analysis

Based on the principle analysis of three-phase Buck-type harmonic injection rectifier and the parameters shown in the table below, the three-phase Buck-type harmonic injection rectifier is simulated by Simulink under power frequency sinusoidal three-phase voltage input.

The parameters of the circuit are selected as: Switching frequency \( f_p = 36 \) kHz, Output voltage \( v_o = 400V \), filter inductance \( L = 200 \mu H \), filter capacitance \( C = 4 \mu F \), DC inductance \( L = 305 \mu H \), output capacitance \( C = 470 \mu F \).

The output voltage waveform and the input voltage and input current waveform of a phase of the system are shown in Figure 5.

![Output Voltage Waveform](image1)

(a) The output voltage waveform (b) The input voltage and input current waveform of a phase

Fig.5 The output voltage waveform and the input voltage and input current waveform of a phase

As can be seen from Figure 5(a), when the output power is 8kW, the output voltage can be stabilized in 400V, the output voltage ripple is \( \pm 0.06 \), for the output voltage of 400V, the ripple can be completely ignored, to achieve a low ripple voltage output, and its overshoot is 3.75\%, the adjustment time is 0.01s, with good dynamic response. As can be seen from Figure 5(b), harmonic injection realizes the improvement of power factor, reduces the input current harmonic content, the phase-a input current is realized by FFT, its harmonic content is 3.5\%, satisfies the industry standard. However, because the two-way switch operation in the low-frequency state, in the two-phase switching of the moment, the injection current will be interrupted, so that in each injection instantaneous current fluctuations.

In order to verify the correctness of the control mode and the rationality of the controller design, the circuit load is changed at 0.05s, the power of the circuit is changed from 8kW to 5.3kW, and the output voltage is shown in Figure 6(a). As can be seen from the diagram, when the load changes, the voltage overshoot is 0.002s, can quickly stabilize in 400V, and the adjustment time is only E, indicating that the circuit has a good fast recovery characteristics and strong stability. As can be seen from Figure 6(b), the input current can also be very small fluctuations in the fast recovery of the sine, the unit power factor, the phase a input current FFT analysis of its harmonics accounted for the fundamental percentage is 3.45\%.
6. Conclusion

Aiming at the problem of large voltage stress of the rear switch in the traditional three-phase boost-type PFC Circuit, a three-phase Buck-type harmonic injection rectifier is studied, and an improved control mode of double closed-loop control and voltage Feedforward is proposed, which realizes the voltage regulation control of the rectifier and improves the overall performance of the rectifier. The simulation results show that the power factor of the circuit is higher, the harmonic content of the AC side is low, the stable low ripple voltage can be output, and the dynamic response characteristic is better when the load is changed.

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