Compound Control Scheme Based on Repetitive Controller And Proportional Controller In Building Distribution Grid

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Abstract: This paper proposes a compound control scheme of three-Phase four-Leg (3P4L) SVG based on the combination of repetitive controller and proportional controller, for the purpose of independently compensating the zero-sequence current under the conditions of load imbalance. To begin with, the overall control scheme of the system is given, in which the repetitive controller and P-controller are connected in parallel. Then, we concluded the recommended scheme is completely equivalent to the series scheme, hence the proportional controller and the repetitive controller can be designed independently. After that, a step-by-step design example of open-loop proportional controller and closed-loop repetitive controller are described. Moreover, the grid voltage feed-forward block is adopted for suppressing the influence of harmonics voltage in grid. Last but not least, Simulation experiments are carried out, and the results demonstrate that the proposed scheme can effectively improve the dynamic performance and stability of 3P4L-SVG under the conditions of load imbalance or grid voltage imbalance.

1. INTRODUCTION

Problems such as harmonic current pollution caused by a large number of non-linear loads in the building distribution network and unbalanced three-phase currents caused by single-phase loads are becoming increasingly prominent. It will cause line overload and pose a great threat to the safety of the power system when the neutral sequence zero-sequence current exceeds 25% of the rated current. Therefore, it is meaningful to study the end treating methods of power quality.

The static reactive power generator (SVG) based on power electronics technology is a promising control device. SVG has the advantages of remarkable continuity of reactive power output, wide range of reactive power regulation, fast response, high control accuracy and reliable operation. The traditional three-phase three-leg SVG fail in mitigating the problem of midline over current due to lacking middle line. It is worthwhile to mention that the 3P4L-SVG has a fast dynamic response in compensating for zero-sequence current and negative-sequence current, which is considered as a prospective scheme to solve the problem of three-phase current imbalance in low-voltage distribution grid[1].

At present, the research on SVG control strategy is mainly focused on two categories. One is the traditional control scheme, for instance, hysteresis current control (HCC) which doesn’t need a carrier and just needs to set the threshold value. The reference current is compared with the actual compensation current to generate the signal of the control bridge arm. Nevertheless, the selection of threshold is very cumbersome and the switching frequency fluctuates greatly, so it is difficult to balance the relationship
between control accuracy and switching frequency [2-4].

The other is a popular control strategy at the present stage. Proportional resonance control (PR) has infinite gain at the fundamental frequency. In practical application, several PR controllers are connected in parallel so as to compensate harmonic current, which leads to system instability and only for selective harmonics [5-6]. The work in [7]-[8] implements predictive current control, not only its switching frequency is not fixed, but also it has high requirements for parameters, and the process of control and programming is sophisticated. Furthermore, deadbeat control (DBC) can quickly track the current change, but it relies on the system parameters and has a large overshoot. The calculation process is complex and the robustness is poor[9-11]. The PI control has an extraordinary dynamic response. However, it suffers from inferior performance in completely eliminating the steady-state error of the system due to the limitation of bandwidth. Accordingly, it is unable to track the sinusoidal reference signal containing periodic components with multiple frequencies, which will result in a large steady-state tracking error [14-15]. A control scheme based on repetitive controller has been reported in [16]-[17], where the repetitive controller has prominent high steady-state accuracy for ameliorating the steady-state error of all harmonics. Unfortunately, it is unable to shorten the dynamic response time of the system to a level less than one fundamental period owing to its dynamic response speed is slow. The P controller responds quickly, but it couldn't be adjusted with zero static error in medium and high frequency. Since neither of the schemes alone can effectively address this issue, there is an increasing awareness that the two controllers can be combined for making up for the shortcomings of the repetitive controller and the P controller.

This paper proves that essentially the serial and parallel connection of repetitive controller and proportional controller are essentially the same. It adds voltage feedforward on the original basis and creatively applies the control strategy to the 3P4L SVG. This paper is structured in six main sections, where the working principle of 3P4L SVG has been presented in Section II. Section III proves the connection mode of P controller and repetitive controller, which is equivalent in series or parallel. Section IV proposes the structure and design scheme of compound control step-by-step and introduces the application of grid Voltage feed-forward. The validity and correctness of the proposed scheme are demonstrated by simulation and experiment in Section V.

2. THE STRUCTURE OF 3P4L-SVG

The circuit topology of 3P4L-SVG with LCL filter is depicted in the Figure 1. The fourth arm is added to the traditional three-phase three-leg APF. Here $V_{sa}$, $V_{sb}$ and $V_{sc}$ are the three-phase voltage of the system, $i_{sa}$, $i_{sb}$ and $i_{sc}$ are the power supply current, $i_{sn}$ is the middle line current of the power supply side, $i_{ca1}$, $i_{cb1}$, $i_{cc1}$ and $i_{cn1}$ are the three-phase current of the inverter output without LCL filter, $i_{ca2}$, $i_{cb2}$, $i_{cc2}$ and $i_{cn2}$ are three-phase incoming current pass through LCL filter, $i_{La}$, $i_{Lb}$ and $i_{Lc}$ are nonlinear unbalanced load distortion current, $i_{Ln}$ is load side neutral current.

3. CONNECTION MODE OF REPETITIVE CONTROLLER AND P CONTROLLER

As is portrayed in the Figure 2, the repetitive controller and P-controller are connected in parallel. Here, $G_{1}(z)$ is the transfer function of LCL filter. $G_{3}(z)$ is the transfer function of grid voltage to grid current. $G_{2}(z)$ is the transfer function of P controller. $Q(z)$, $z^{-1}$ and $S(z)$ are three parts of repetitive control. $G_{u}(z)$ is the transfer function of voltage feed-forward. $i_{r}(z)$ is the output current of SVG grid, and $i_{ref}(z)$ is its reference. $z^{-1}$ is an inherent one beat delay factor in digital control. The repetitive controller can output $u_{l}(z)$ at an appropriate time in the next cycle, so that the output $i_{r}$ can track the instruction $i_{ref}(z)$ more accurately to reduce the error $e(z)$.

| Symbol | Description | Value | Symbol | Description | Value |
|--------|-------------|-------|--------|-------------|-------|
| $L_{1}$ | Filter inductance | 1mH | $V_{g}$ | Grid voltage | 220V |
| $C$ | Filter capacitor | 20μF | $V_{d}$ | DC bus voltage | 750V |
| $L$ | Grid Inductance | 0.4mH | $f_g$ | grid voltage frequency | 50Hz |
| $R$ | Resistance | 0.6Ω | $f_s$ | Sampling frequency | 20kHz |
| $P$ | Output Power | 8.8kW |
Figure 1. Circuit topology of 3P4L SVG with LCL

The following equation can be obtained from Figure 2:

\[ u_p(z) = e(z) \left[ G_p(z)z^{-1} + RC \right] \]

In equation (1):

\[ RC = \frac{z^{-N}S(z)}{1 - Q(z)z^{-N}} \]  

First, extracting the common factor \( G_p(z) \) from the repetitive controller and the proportional controller, where \( M(z) = S(z) / G_p(z) \).

At this time, equation (3) can be calculated:

\[ u_p(z) = e(z) \left[ z^{-1} + RC' G_p(z) \right] \]

In equation (3):

\[ RC' = \frac{z^{-M(z)}}{1 - Q(z)z^{-N}} \]  

What’s more, moving forward the comparison point of \( z^{-1} \) link in Figure 2, and Figure 3 can be obtained.

Equation 5 can be obtained from Figure 3:
\[ u_p(z) = v(z) \left( G_p(z)z^{-1} + RC' \right) \]  

(5)

By comparing Figure 2 with Figure 3, it can be observed that the difference between the serial and the parallel of the repetitive controller and the proportional controller lies in the compensator.

Generally speaking, the connection mode of P controller and repetitive controller, which is equivalent in series or parallel, both of which are composed of open-loop proportional control and closed-loop repetitive controller. In this paper, two kinds of controllers are connected in parallel, and each parameter is designed in detail.

In figure 2, \( G_1(z) \) and \( G_2(z) \) are the transfer function of the input voltage \( u_{inv} \) of the LCL filter and the transfer function of the grid voltage \( u_g \) in response to the grid current \( i_g \), respectively. The system parameters of the LCL filter are shown in Table 1.

The traditional LCL filter [18] has a harmonic peak in its bode diagram.

The filter capacitor \( C_f \) series resistance \( R \) can suppress the resonance peak by adding passive damping in the LCL filter. The transfer functions of \( ig(s) \) to \( u_{inv}(s) \) and \( ig(s) \) to \( u_g(s) \) can be obtained from Figure 4.

\[ G_1(s) = \frac{i_g(s)}{u_{inv}(s)} = \frac{RC_s + 1}{L_1L_2C_is^2 + (L_1 + L_2)RC_is^2 + (L_1 + L_2)s} \]  

(6)

\[ G_2(s) = \frac{i_g(s)}{u_g(s)} = \frac{1}{L_1L_2C_is^2 + (L_1 + L_2)RC_is^2 + (L_1 + L_2)s} \]  

(7)

4. DESIGN OF CURRENT COMPOUND CONTROL SCHEME

4.1. The controlled object of the repetitive controller

The digital control has the characteristics of control delay and zero-order hold (ZOH). The equivalent controlled object \( G_{cl}(z) \) of repetitive controller is:

\[ G_{cl}(z) = \frac{G_i(z)}{1 + G_p(z)z^{-1}G_i(z)} \]  

(8)

Figure 5 denotes bode diagram of the equivalent controlled object in the discrete system when the sampling frequency is 20 kHz. As can be seen from a-a' in the Figure 5, the phase crossover frequency is 630 kHz, the amplitude margin is -14.4 dB, and the phase margin is 58 °. Therefore, the control system is stable.

From the b-b' in Figure 5, the resonance peak still exists, but it is only 9.47dB, which can be ignored approximately. But its gain in the middle and low frequency range is -10.8 dB, and there is phase lag which will seriously affect the dynamic performance of harmonic compensation. As the frequency increases, the phase lag becomes larger, which greatly affects the control effect. It is necessary to adopt a repetitive controller to correct \( G_{cl}(z) \) result from SVG requiring the bandwidth of the controller to be large enough for realizing the accurate tracking of high-order harmonics.

4.2. the Design of P controller

The PI controller has a fast dynamic response speed, but it can’t follow the sinusoidal command signal without static difference. There is a steady-state error in the dynamic response difference. It takes the form of \( PI(s) = K_p + K_i/s \), where the integral coefficient \( K_i \), a large value of \( K_i \) is needed to reduce the steady-state error of the system, but it will increase the offset between the output of the system and the given phase. For the purpose of making the phase offset as small as possible, the integral coefficient is often small or even zero[21]. PI can't eliminate static error completely because of bandwidth limitation. In this paper P controller is used to simplify and replace PI. Here P is 4.5.

4.3. Design of repetitive controller

Repetitive controller is a control scheme based on internal model principle. However, the output of the
controller is delayed by one cycle due to the time delay of the internal model of repetitive control, which slows down the regulation of the system transient process and affects the dynamic response speed. The dynamic response of the proportional (P) controller is fast and the error can be corrected immediately. Therefore, the compound control strategy of repetitive controller and proportional controller is often used in practice, which makes the system not only has the advantages of zero static error tracking AC signal and small steady-state error, but also has the fast dynamic response ability.

The tracking error value of the system is very small under steady state, the repetitive controller accumulates the historical error; In the case of disturbance, the P controller will quickly adjust the sudden changes situation. The repetitive controller won’t participate in the adjustment at this time because of one cycle delay; The repetitive controller will adjust the system again after one cycle, so it gradually returns to the stable state.

Figure. 6 reveals block diagram of repetitive controller in discrete domain. Repetitive controller is composed of internal model and compensator of repetitive controller. These links are designed as follows:

1) The design of periodic delay $z^{-N}$

For the purpose of adding error points corresponding to error signals of different periods, $z^{-N}$ delays the feedback amount of the output signal by one cycle and then it calculates with the input signal. $N$ is the ratio of the sampling frequency ($f_s$) to the fundamental frequency ($f_0$), that is, the number of sampling points in each fundamental period. The sampling frequency of the system in this paper is 20 kHz and the fundamental frequency is 50Hz, so $N$ is 400.

2) The design of repetitive controller internal model

$Q(z)$ ameliorates the anti-interference ability of the system in the critical stable state, stabilizing the internal model system, and preventing the ideal repetitive control model from bringing in $N$ critical poles. In the discrete domain, the internal model of the repeating controller is:

$$G_{in^{-N}}(z) = \frac{1}{1 - Q(z)z^{-N}}$$

Equation (9)

$Q(z)$ can be a low-pass filter or a constant of 0.95 to 1. In this paper $Q(z)$ is taken as a constant less than 1. If $Q(z)$ chooses the way of low-pass filter, it will increase the difficulty of design and complicate the system.

It can be seen from Figure. 7 that the bode plot of the repetitive controller has higher gain and zero phase shift characteristics at the fundamental wave and the integer multiples of the fundamental frequency. As the value of $Q(z)$ is larger, the higher the steady-state gain of the system, the better waveform quality and steady-state accuracy of compensation current, which significantly improving the tracking ability of the system with zero static error. By contrast, it reduces the robustness of the system. The value of $Q(z)$ needs to be selected between balancing steady-state error and margin. As shown in Figure 8, the system stability is worse when the value of $Q(e^{j\omega T})$ approaches to 1. When $Q(e^{j\omega T})= 1$, the poles of the system exceed the unit circle, which represents the system is unstable. So the $Q(e^{j\omega T})$ is chosen as 0.95.

3) Design of repetitive control compensator

The design of the compensator plays a crucial role in the performance of the repetitive controller.
The main function of the compensator is to correct the $G_{cl}(z)$. At the middle and low frequency, its amplitude is corrected to 0 dB, its phase is corrected to 0°, and its amplitude at the high frequency is rapidly attenuated to 0, which can be written as

$$ S(z) = F_1(z) K_r z^k $$

In the above equation, $F_1(z)$ is a second-order Butterworth filter, $K_r$ is a repeating controller gain, and $z^k$ is a leading link.

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$F_1(z)$ is used for the attenuation of high frequency harmonics. From Figure 6, it can be seen that the gain of $G_{cl}(z)$ is −18.4 dB in the middle and low frequency, and there is phase lag. In order to improve the attenuation effect of the system on the high-frequency section, the second-order Butterworth filter is added here. The cut-off frequency of the second-order filter is 2.6 kHz, the damping ratio $\xi$ is 0.707, in order to ensure the dynamic compensation performance of the system for harmonics, the transfer function of filter $F_1(z)$ is designed as

$$ F(z) = \frac{0.8(z^2 + 2z + 1)}{z^2 - 0.4562z + 0.2798} $$

$z^k$ is the leading link to compensate the phase lag of controlled object in the middle and low frequency range.

It can be seen from Figure 9 that the phase frequency curves of $F_1(z) G_{cl}(z)$ and $z^4$, $z^5$, $z^6$, $z^7$ are basically similar in the middle and low frequency band, and the system has zero phase shift characteristics after the fourth-order lead link compensation. Therefore, the leading phase of $z^4$ can compensate for the lagging phase of $F_1(z) G_{cl}(z)$ effectively.

$K_r$ is the gain of repetitive controller, which affects system stability and controller accuracy.

The appropriate value can ensure the stability of the system in the middle and high frequency. The smaller the value is, the better the system stability is, but the adjustment time of the system will be longer and the static error will be larger. Therefore, the parameters can be adjusted by experiments, the value of $K_r$ is usually selected between 0 and 2.

Frequency characteristics of the controlled object after compensation is illustrated in Figure 10 where demonstrates that $s(z) G_{cl}(z)$ has high steady-state accuracy, the amplitude basically approaches to 0 dB and the phase is close to 0° in the low frequency; the phase is difficult to be corrected to 0° in the high-frequency band, but its amplitude decays sharply, which has a extraordinary suppression ability for the high-frequency signal. According to Figure 10, we can get the phase lag can be compensated by the fourth-order lead link effectively.

The open-loop transfer function of the repetitive control outer loop is

$$ RC(z) = \frac{z^3 s(z)}{1 - Q(z) z^3} $$

The closed-loop transfer function of the repetitive double loop controller can be obtained:
As illustrated curve a in Figure 11, it shows the frequency characteristic of system with compensation. Curve a is the open-loop characteristic of repetitive controller, Curve b is the closed-loop characteristic of repetitive controller, Curve C is the transfer function characteristic of the controlled object after being compensated.

![Figure 11. Frequency characteristic of system with compensation](image)

It can be inferred from curve a in Figure 11 that the system has a high open-loop gain of 49.9 dB in the range of fundamental frequency and medium and low frequency. From the phase frequency curve of curve c', therefore, it can maintain the characteristics of zero phase shift and unit gain in the middle and low frequency. Compared with the high frequency section, the gain of the composite controller rapidly attenuates below -10dB, while the phase compensation is still around 0, maintaining the stability of the system.

Therefore, zero steady-state error tracking can be realized and grid interference can be suppressed through the correction of repetitive controller and P controller.

Normal operation of the SVG system will be seriously affected by the grid voltage will be distorted and asymmetric when the equivalent controlled object without grid voltage feed-forward. An additional path is introduced at the output of $G_{cl}(z)$ for the purpose of suppressing the influence of the grid voltage fluctuation on the DC side voltage without affecting the output current of the APF. As shown in Figure 12 (a), if the grid voltage is superimposed on the output of the inner loop to act on the controlled object, the interference of the grid voltage to the incoming current will be eliminated. As shown in Figure 12 (b), add a channel after $G_1(z)$ that has the opposite effect to the $G_2(z)$ transfer function to basically eliminate the influence of grid harmonics.

\[ G(z) = \frac{s(z)G_r(z)}{[z - Q(z) + s(z)G_r(z)]} \]  

(13)

![Figure 12. Voltage feed-forward control block diagram](image)

In the above equation,$a_0=-0.000181,a_1=-0.005485,a_2=-0.00063,a_3=-0.0001144,a_4=0.005913,a_5=0.002125;b_0=-0.0006532,b_1=-0.005837,b_2=-0.001322,b_3=-0.009622,b_4=0.005313,b_5=0.003462.

From the system parameters and transfer functions, it can be known from equation (14) that the current output of the feed-forward control loop is not only related to the current grid voltage value, but...
also to the grid voltage values from the last five-beats. This also reflects the participation of the grid voltage in feedback control.

5. SIMULATION ANALYSIS

Under the condition of unbalanced load of uncontrolled rectifier bridge, the LCL filter parameters are shown in Table 1. Under 220V grid voltage, the SVG can only operate normally when the bus voltage is higher than 600V. Therefore, the bus voltage of this article is selected as 750 V. The non-linear load consists of a three-phase uncontrolled rectifier bridge followed by a resistor with a resistance of 80Ω. The inverter bridge in the simulation consists of a three-phase half bridge and a single-phase bridge.

Figure 13(a) is a simulation diagram of the three-phase current and zero-sequence current of the load before compensation. It can be seen that the three-phase load current is seriously unbalanced before compensation. The peak value of phase a current is 8A, which is larger than the current of phase B and phase C (4A). The degree of imbalance is serious, and the peak value of the neutral current is ± 4A. Figure 13(b) is the compensation current waveform diagram of three-phase and neutral current. Figure 13(c) is the waveform diagram of the power supply current and the neutral current after the dual-loop control compensation. It can be seen that the three-phase current waveform is basically sinusoidal after compensation, and the three-phase current is balanced. It can be seen from Figure 13(d) that the DC voltage of the capacitor is stabilized at 750V after PID control.

The THD values of the three-phase grid-side currents in Figure 13(e)–(g) are 2.79%, 2.82%, and 2.93%, respectively.

![Waveform of load current and neutral current](image1)

![Waveform of compensation current of each phase](image2)

![Waveform of power grid current and neutral current after Compound Control compensation](image3)

![Voltage waveform of DC side bus](image4)

![FFT spectrum of phase A current after compensation](image5)

![FFT spectrum of phase B current after compensation](image6)

![FFT spectrum of phase C current after compensation](image7)

Figure 13. The simulation results under the condition of unbalanced load of uncontrolled rectifier bridge.
In the case of unbalanced resistive load, the single-phase uncontrolled bridge load is removed, and a three-phase unbalanced resistive load is added. The A-phase load resistance is 60Ω, and the B and C-phase loads are 150Ω. Figure 14(a) is a simulation diagram of the three-phase current and zero-sequence current of the load before compensation. It can be seen that the three-phase load current is severely unbalanced before compensation. The peak value of the phase A current is 12A, which is greater than the current of the two phases B and C (8A). The peak value of the neutral current is ± 4.5 A. Figure 13(b) is the compensation current waveform diagram of three-phase and neutral current.

It can be seen from Figure 14(c) that under the unbalanced resistance load, The compensation effect of 3P4L SVG on harmonic and unbalanced current is still very outstanding, and the positive and negative peak values of the neutral zero sequence current are still ± 1A. As shown in Figure 14(e)-(g), the THD of the A-phase grid-side current is 3.09%, the THD of the B-phase load current is 2.75%, and the C-phase is 3.01%. It shows that the current distortion of three-phase load under unbalanced resistance load is smaller than that of parallel single-phase uncontrolled bridge. It is proved that the 3P4L SVG can ameliorate the imbalance of the system.

Figure 14. The simulation results under the condition of unbalanced resistive load

(a) Waveform of load current and neutral current under unbalanced resistive load
(b) Waveform of compensation current of each phase
(c) Waveform of load current and neutral current under load imbalance of uncontrolled rectifier bridge
(d) Voltage waveform of DC side bus
(e) FFT spectrum of phase A current after compensation
(f) FFT spectrum of phase B current after compensation
(g) FFT spectrum of phase C current after compensation

In this section, through the analysis of waveforms before and after various forms of compensation, we can see the feasibility and effectiveness of the SVG designed in this paper.
6. CONCLUSION

In this paper, a compound control scheme of repetitive controller and proportional controller is adopted for the 3P4L SVG based on LCL filter. The design scheme of each parameter of the controller and voltage feed-forward is given. The stability and steady-state error performance of the system are analyzed in detail. The simulation results under the condition of load imbalance are obtained on Simulink, respectively. The results show that compared with the traditional method, the proposed scheme has the advantages of simple structure, a high steady-state accuracy, a fast response and low cost, and voltage feed-forward can effectively suppress the harmonic disturbance of power grid.

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