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Application of electric spring in coal mine power supply

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Abstract With the continuous improvement of mine automation, coal mines have higher and higher requirements for the quality of power supply voltage, and voltage fluctuations have become one of the factors that threaten the safe operation of coal mines. In order to solve this problem, this article uses the electric spring (ES) in the coal mine power supply system. First, it analyzes the working principle of the electric spring. Next, aiming at the deficiencies of the resonance control strategy, a compound control strategy in which quasi-proportional resonance control (QPR) and repetitive control are parallel is proposed. The introduction of repetitive control can suppress the periodic disturbance of the power grid, effectively improve the steady-state accuracy, and reduce system harmonics. Then, the design method of repeated controller parameters is studied in detail. Finally, MATLAB/Simulink is used to build a simulation model, and dSPACE is used as the control core to build an ES experiment platform. Simulation and experimental results verify the correctness and effectiveness of the proposed control algorithm, and point out that the electric spring can ensure the voltage stability of key electrical equipment and provide a reliable guarantee for the safe production of the mine.

Keywords electric spring, coal mine safety, voltage stabilization, repetitive control, harmonic compensation

1 Introduction

With the continuous improvement of mine automation, more and more power electronic equipment is applied to coal mine production (Liu 2016). Hoists, ventilators, gas monitoring equipment, etc. play an extremely important role in coal mine production. They are all supplied with electric energy from the underground grid, and the requirements for the quality of the power supply voltage are very strict. However, due to the existence of a large number of impulsive loads, intermittent loads and various short-circuit faults in the power supply system, the system voltage often changes in a short time and quickly, that is, voltage fluctuations [Li 2015]. The voltage fluctuation range of the underground power grid in the coal mine is large, which can cause the operation of the corresponding equipment to malfunction, which will increase the probability of safety accidents. Voltage fluctuations have seriously affected mine production management and the safe operation of the system and should be taken seriously.

To solve this problem, currently underground mines often increase power quality by adding static var generator (SVG). Mine-used SVG is mainly compensated on-site at high-power loads. However, harsh underground conditions, long lines, and many electrical equipment will cause the grid voltage below the compensation point (For example: the supply voltage of critical loads such as control systems) to still be distributed by natural landing, once disturbed, the compensation effect of upstream is limited (Li et al. 2015).

This paper proposes the use of electric spring to stabilize the power supply system for control equipment with strict requirements on voltage quality. When voltage fluctuates,

the voltage (energy) fluctuations of the critical load (CL) (Such as hoist, ventilator, etc.) in the power supply system can be transferred to the non-critical load (NCL) (such as ground auxiliary workshops, repair plants, etc.), thereby Guarantee the quality of critical load voltage, which reduces the cost compared with SVG under the same compensation effect.

At present, the existing control method of power spring is to control the effective value and phase of the critical load voltage respectively, but it is easy to introduce grid harmonics. Yan et al. (2014) proposed the dq0 decoupling control method, which transforming the current variables in the system into dq0 coordinate system, and adopts proportional-integral (PI) controller to control the d and q axis currents respectively. This control method can simultaneously control the power factor angle of SL and the stability of CL voltage, but there is still serious coupling and the actual workload of parameter debugging is large. Mok et al. (2016) proposed the control method of radial - chord decoupling (RCD), and decomposed the voltage phase of ES into the chord component that is only related to the power factor angle of SL and the radial component that is linearly related to the apparent power of SL according to the function, so as to achieve the decoupling of the control objective. This control strategy has strong decoupling ability, but the inverter cannot realize controllable pure reactive power compensation. Parag et al. (2013) based on PI control mode proposed to use multi-resonance controller and second-order generalized integrator to suppress harmonics, and to stabilize CL voltage through double closed-loop control, but the power grid voltage disturbance

is ignored. Cheng et al. (2015) considered the disturbance of power grid voltage, proposed a control strategy combining quasi-proportional resonant (QPR) controller with power grid voltage feed-forward to eliminate harmonic pollution in power grid. However, obtaining controller parameters according to pole placement method requires a large number of formulas and calculations, which increases the amount of calculation. Wang et al. (2015) proposed a phase control method, in which the QPR controller is used to control the critical load voltage as the outer loop, and the proportional (P) controller is used to control the inductance current as the inner loop. This control method simplifies the complex control system, but depends on circuit parameters.

The PI control algorithm is simple and its parameters are easy to design, which is the most widely used control strategy at present (Yi et al. 2016; Yang et al. 2011). However, PI control can't track AC signal without static error, and its dynamic response time and overshoot can't reach the optimal value at the same time. The QPR control can track AC signal without static error by using the high gain at the resonant frequency, but it cannot suppress the periodic disturbance (Zeng et al. 2016; Fan et al. 2016). In order to effectively suppress harmonics of multiple frequencies, a corresponding number of resonance compensators are needed, but this will complicate the structure of the control system. The deadbeat control has good dynamic performance, but it requires high precision of the system mathematical model. When the mathematical model is different from the actual object, it will not only fail to achieve good control, but also deteriorate the output performance and endanger the safe operation of the inverter (Jahanbakhshi et al. 2015). Compared with other control strategies, repetitive control has the following advantages: for periodic interference signals, its repeatability can be used to achieve good harmonic suppression (Yang et al. 2015; Chaves et al. 2016); it has good waveform quality and steady-state performance, and can theoretically realize no static error tracking (Jia et al. 2014). However, its dynamic performance is poor and the effect of aperiodic disturbance suppression is not good.

To solve the above problems, based on the phase control algorithm, a compound control strategy of quasi proportional resonant controller parallel repetitive controller is proposed, which improves the steady-state tracking performance and anti-harmonic interference performance of the system.

2 Electric spring theory

2.1 Operating principle of the ES

Fig. 1 Typical application topology of ES

Fig. 1 shows the typical application topology of ES. The left dotted line box is ES topology, which is composed of single-phase full bridge voltage source inverter and LC low-pass filter. V_{dc} is the DC side voltage source of the inverter; V_i is the inverter output voltage; i_L is the filter inductance current; V_{ES} is the ES output voltage; i_C is ES (filter capacitor) current; Z_3 is non-critical load, whose terminal voltage can fluctuate in a large range; V_o is non-critical load voltage; i_3 is non-critical load current; Z_2 is critical load, whose terminal voltage is only allowed to fluctuate in a very small range; V_s is the critical load voltage; i_2 is the critical load current; Z_1 is the transmission line; i_1 is the transmission line current; V_G is the grid voltage.

The working principle of the ES: when the grid voltage V_G does not fluctuate, the ES output voltage V_{ES} is 0. The grid voltage at this time is defined as the reference value, and the ES works in resistive mode. When V_G is lower than the reference value, by adjusting the ES current i_C , the ES output voltage V_{ES} lags the NCL current i_3 phase by 90° . So that ES can provide capacitive reactive power to improve CL voltage V_s , making it stable near the expected value and working in capacitive mode. When V_G is higher than the reference value, by adjusting i_C , make V_{ES} lead i_3 phase 90° , let ES provide inductive reactive power to reduce V_s to keep it stable, and work in inductive mode.

According to Norton's equivalent principle, the ES system is modeled and the S-domain expression of the CL voltage V_s is obtained:

$$V_s(s) = G_1(s)V_i(s) + G_2(s)V_G(s), \quad (1)$$

where

$$\begin{cases} G_1(s) = \frac{Z_1 Z_2}{(Z_1 + Z_2)(Z_0 L C s^2 + L s + Z_0)} \\ G_2(s) = \frac{Z_2 (Z_3 L C s^2 + L s + Z_3)}{(Z_1 + Z_2)(Z_0 L C s^2 + L s + Z_0)} \end{cases} \quad (2)$$

If there is no controller, the open loop transfer function from reference to output is expressed as:

$$G_o(s) = K_{pwm} \frac{Z_1 Z_2}{(Z_1 + Z_2)(Z_0 L C s^2 + L s + Z_0)}, \quad (3)$$

where K_{pwm} is the ratio of the inverter DC side voltage V_{dc} to the carrier amplitude V_{tri} .

It can be seen from formula (2) that ES system is a dual-input single-output system, which is difficult to control. In actual control, the output voltage V_i of the inverter bridge can be regarded as the control quantity, and the grid voltage V_G can be regarded as the disturbance quantity.

2.2 Existing control strategy of the ES

Double closed loop control is used in the existing control, as shown in Fig. 2

Fig. 2 Existing control of ES

The outer-loop control adopts QPR controller, in which the critical load voltage is controlled to follow a sinusoidal

reference, and the inner-loop control adopts the P controller, which uses the i_L as the feedback variable to modify the output of the voltage controller (Wang et al. 2015).

The transfer function of the QPR controller is:

$$G_{QPR}(s) = k_p + \frac{2k_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (4)$$

where k_p and k_r are the proportional gain and resonant gain, respectively. ω_c is the cutoff frequency for the resonant main bandwidth control. ω_0 is the resonant frequency and $\omega_0=100\pi$ rad/s.

Wang et al. (2015) select controller parameters through experience, and then verify the parameters through Bode diagram. The final controller parameters and circuit parameters are list in Table 1.

Table 1 Parameters of circuit and controllers

Parameter name	Symbols	Value
CL voltage rms reference value (V)	V_S	220
Inverter DC side voltage (V)	V_{dc}	480
Transmission line resistance(Ω)	R_1	0.1
Transmission line inductance(mH)	L_1	2.4
Critical load(Ω)	R_2	43.5
Non-critical load(Ω)	R_3	2.2
Low pass filter inductor(mH)	L	3
Low pass filter capacitor (μF)	C	50
Voltage feedback coefficient	k_{vf}	1
Current feedback coefficient	k_{if}	0.5
Current inner loop proportional coefficient	I_{L_kp}	0.2
QPR controlled proportional coefficient	k_p	0.1
QPR controlled resonant coefficient	k_r	30
QPR controlled cutoff frequency	ω_c	π

The QPR controller can achieve high gain, zero steady-state error tracking and a wide bandwidth near the resonant frequency. However, the discrete process of the QPR controller mostly adopts a bilinear transformation DSP implementation method, and a resonance compensator needs to be introduced to reduce the harmonic pollution of the power grid; with the increase of the harmonic order, the resonant compensator will also increase, which makes the control algorithm more complicated and the system calculation amount increase (Zhang et al. 2016; Zhang et al. 2014; Teng et al. 2013).

3 Proposed control strategy of the ES

Considering the shortcomings of the above-mentioned QPR control harmonic compensation, this paper introduces repetitive control on the basis of double closed-loop control. Repetitive control is used to suppress multiple harmonics, which can simplify the calculation of DSP and improve the control effect of the system.

3.1 Principle of repeat controller

The repetitive controller based on the theory of internal model produces correction signal based on the control error of the last cycle to eliminate the error in the latter cycle. The control block diagram of the outer-loop using QPR in parallel with the repetitive controller is shown in Fig. 3.

Fig. 3 Structure of QPR parallel repetitive controller

In the Fig. 3, $R(z)$, $Y(z)$, $E(z)$, and $D(z)$ represent the reference input, system output, tracking error, and periodic harmonic disturbance respectively. $G_o(z)$ is the open loop transfer function of the control object. The dashed frame is the repeat controller, which is composed of the compensator $C(z)$, the period delay link z^{-N} and the inner membrane of the discrete domain.

The internal model of discrete domain is:

$$M = \frac{1}{1 - Q(z)z^{-N}}, \quad (5)$$

where N is the sampling number in a fundamental period, and the value of $Q(z)$ is closely related to the convergence rate and degree of the system.

3.2 Parameter design of repeat controller

The quality of the repetitive controller depends on $Q(z)$, $C(z)$, and the relationship between various parameters should be considered comprehensively in the design.

1. Establish mathematical model of the electric spring for controlled object $G_o(z)$

When there is no controller and feedback loop, the open-loop transfer function from CL voltage to reference voltage is:

$$G_o(s) = \frac{3.046e^9 s + 1.269e^{11}}{s^3 + 1351.842s^2 + 1.462e^7 s + 6.095e^9} \quad (6)$$

When the sampling frequency is 40 kHz, the zero order holders are used to discretize the above formula, and the z-domain transfer function is obtained as follows:

$$G_o(z) = \frac{0.9409z^2 - 0.009237z - 0.9297}{z^3 - 2.958z^2 + 2.925z - 0.9668} \quad (7)$$

Draw the $G_o(z)$ bode diagram as shown in Fig. 4.

Fig. 4 $G_o(z)$ bode diagram

It can be seen from the Fig. 4 that $G_o(z)$ has a resonant peak at the resonant frequency $f_0=589$ Hz, the peak value reaches 65.9dB, and the phase lags rapidly after the resonant frequency.

2. Design of delay link z^{-N} and parameter internal model $Q(z)$

The function of z^{-N} is to delay the control command for one cycle. In this paper, the sampling frequency is 40 kHz and the fundamental frequency of output voltage is 50Hz, then $N=40000 / 50=800$.

$Q(z)$ should have low-pass characteristics to suppress periodic interference. When $Q(z)=1$, the system can track the input signal without static error and is in a critical stable state. Considering the steady-state margin, $Q(z)$ is usually designed as a constant less than 1. It has been proved in engineering that when $Q(z)$ value is about 0.95, the system stability and harmonic suppression characteristics can be taken into account. In this paper, $Q(z)=0.95$.

3. Design of compensator $C(z)$

Based on the frequency response characteristics of the controlled object, $C(z)$ is divided into phase compensation and amplitude compensation:

$$C(z) = K_r z^k S(z) = K_r z^k S_1(z) S_2(z), \quad (8)$$

where K_r is the repetitive control gain; z^k is the phase compensator; $S(z)$ is the filter function. In this paper, $S(z)$ is composed of notch filter $S_1(z)$ and second-order low-pass filter $S_2(z)$. The reasonable design of $S(z)$ can not only attenuate the resonance peak to the maximum extent, but also does not need phase compensation

- Design of K_r

K_r is the quality factor used to improve the internal model critical stability characteristics of repetitive controller, and the value range is (0-1). Under the premise of ensuring the stability of the system, the value should be as close as possible to 1. In this paper, the $K_r=0.98$.

- Design of $S_1(z)$

The function of $S_1(z)$ is to eliminate the resonance peak of $G_o(z)$ in Fig. 4 by using its zero phase shift characteristic. The expression is as follows:

$$S_1(z) = \frac{z^m + 2 + z^{-m}}{4}. \quad (9)$$

According to the relationship between z-domain and frequency-domain $z = e^{j\omega T} = e^{j\theta}$ (T is the sampling time), it can be concluded that:

$$S_1(z) = \frac{e^{jm\theta} + 2 + e^{-jm\theta}}{4} = \frac{\cos m\theta + 1}{2}, \quad (10)$$

where m determines the notch frequency. Since the first attenuation point of the notch filter has the largest attenuation range, it is designed to cancel with $f_0=589 \approx 600\text{Hz}$, then:

$$m\theta = m\omega_0 T = \pi$$

$$\Rightarrow m = \frac{\pi}{\omega_0 T} = \frac{1}{2f_0 T} = \frac{1}{2 * 600 * 1 / 40000} = 33.33 \approx 33, \quad (11)$$

$$S_1(z) = \frac{z^{33} + 2 + z^{-33}}{4}. \quad (12)$$

Fig. 5 $S_1(z)G_o(z)$ frequency characteristic

Fig.5 shows the frequency characteristics of $S_1(z)$, which can attenuate the resonance peak to the maximum extent, and no phase compensation.

- Design of $S_2(z)$

$S_2(z)$ is used to attenuate the amplitude above the cut-off frequency, so as to eliminate the high-order harmonics. According to the system compensation requirements, 600Hz is taken as the cut-off frequency. In order to prevent oscillation, the damping ratio is taken as $1.2 > 0.707$. $S_2(s)$ is:

$$S_2(s) = \frac{\omega^2}{s^2 + 2\xi\omega s + \omega^2} = \frac{600^2}{s^2 + 1440s + 600^2}. \quad (13)$$

The sampling frequency is 40 kHz, and the zero order holders are discretized as follows:

$$S_2(z) = \frac{0.0001112z + 0.0001098}{z^2 - 1.964z + 0.9646}. \quad (14)$$

The comparison chart before and after correction is shown in Fig. 6. It can be seen that after $S_1(z)$ and $S_2(z)$ are compensated at the same time, the high-frequency gain decreases rapidly and the resonance peak value is attenuated.

Fig. 6 Bode diagram before and after correction

- Design of z^k

It can be seen from Fig. 4 and 6 that $G_o(z)$ and $S_2(z)$ have phase lag, which makes the system unable to track accurately. Therefore, the phase leading function z^k with zero gain amplitude is selected for phase compensation, and the leading step $k=16$. The frequency characteristics of $G_o(z)S_2(z)$ and z^{16} at different frequencies are shown in Fig. 7.

Fig. 7 Frequency characteristics of $G_o(z)S_2(z)$ 、 z^{16}

It can be seen from Fig. 7 that the phase compensation error of $G_o(z)S_2(z)$ and z^{16} in the middle and low frequency band is small, and the leading link can provide phase compensation to make the system tend to zero phase; in the high frequency band, the phase compensation is excessive, but the amplitude attenuation amplitude in the high frequency band is relatively large, and the impact is small, so the phase in the high frequency band is not considered.

4 Simulations and Discussions

To verify the aforementioned analysis, simulations are conducted based on parameters shown in Table 1. The off-line model of single-phase power spring based on quasi proportional resonance and repetitive control is shown in Fig.8.

Fig. 8 Off-line model based on quasi proportional resonance and repetitive control

V_s is the transient voltage of the critical load, V_{sfb} is the feedback voltage sensed from V_s multiplied by a coefficient k_{vf} (e.g., 1). Signal V_{sref} is the predefined sinusoidal reference of which the magnitude is given as needed and phase lags V_G by δ . The voltage error is used to generate reference of current loop via the QPR parallel repetitive controller. The feedback i_{Lfb} is sensed from inductor current i_L , just multiplied by a coefficient k_{if} (e.g., 0.5). The current error is used to generate the modulation signal via the P controller and a limiter. Through the combination of modulation signal and triangular carrier signal, the pulse signal which changes according to the sinusoidal law is generated to control the power switch on and off, and convert DC to AC. After LC filtering, the ES current i_C is output. By adjusting the i_C , the output voltage of ES lags behind the current i_3 of NCL by 90° so that ES can provide capacitive or inductive reactive power and stabilize V_s .

Under the parameter settings in Table 1, it can be calculated that the effective voltage range that ES can realize compensation is $191.3V \leq V_G \leq 267.3V$. When $V_{ES} = 0$, $V_G = 243.7V$, ES works in resistive mode. 192V, 243.7V and 267V are selected as the corresponding grid voltage values of capacitive, resistive and inductive modes respectively for simulation verification.

4.1 Steady state tracking performance

On the basis of the effective value of the grid voltage of 192V, 12% of the 3rd harmonic, 6% of the 5th harmonic and 3% of the 7th harmonic are added to make the grid voltage seriously distorted. Observe the simulation waveforms of critical load voltage (V_s) and voltage tracking error (e_u) when the QPR+P double closed-loop control and the repetitive controller based optimal control are adopted respectively, as shown in Fig. 9.

(a) The QPR+P double closed-loop control

(b) The repetitive controller based optimal control

Fig. 9 Simulation waveforms of V_s and e_u

It can be seen from Fig. 9 that the amplitude of steady-state tracking error e_u under QPR+P double closed-loop control is 30.17V, which is about 9.7% of the reference input; and the e_u amplitude after adding repetitive control is 14.92V, which is about 4.8% of the reference input. Under the two control strategies, the V_s waveform of CL voltage is sine wave, and the effective value is stable around 220V. The results show that the introduction of repetitive control makes the system maintain good CL voltage waveform and higher steady-state accuracy.

4.2 Harmonic suppression performance

In order to further verify the harmonic suppression performance, the effective value of the grid voltage of 192V, Simulation is carried out when 12% third harmonic, 6% 5th harmonic and 3% 7th harmonic are added to make the grid voltage seriously distorted. Observe the simulation waveform of THD content of CL voltage when the double closed-loop control and the repetitive controller based optimal control are adopted respectively, as shown in Fig.10.

(b) The repetitive controller based optimal control

Fig. 10 Total harmonic distortion of CL voltage

It can be seen from Fig. 10 that the grid voltage distortion causes low-frequency harmonics in CL voltage, and the total harmonic distortion rate of CL voltage under double closed-loop control is 10.16%, with high harmonic content; the introduction of repetitive control reduces the harmonic content, and the total harmonic distortion rate is 2.56%, which meets the IEEE std.929-2000 standard. The results show that the proposed control strategy has stronger anti harmonic interference ability.

4.3 Dynamic performance

The initial value of grid voltage is set as 243.7V, which drops to 192V at 0.2s and rises to 267V at 0.4s. Observe the dynamic waveforms when the QPR+P

double closed-loop control and the repetitive controller based optimal control are adopted respectively, as shown in Fig. 11. Each sub graph in Fig. 11 contains four channels, measuring grid voltage V_G , CL voltage V_S , ES voltage V_{ES} and NCL voltage V_0 .

(a) The QPR+P double closed-loop control

(b) The repetitive controller based optimal control

Fig. 11 Dynamic simulation waveforms

From the second channel of Fig. 11(a) and 11(b), it can be seen that even if the power grid suddenly changes, the effective value of the CL voltage can be quickly controlled at the given 220V value.

In Fig. 11, the grid voltage $V_G=243.7V$ during 0.15s-0.2s, at this time, ES voltage is close to 0, NCL voltage effective value tends to CL voltage effective value, indicating that ES works in resistive mode; during the period of 0.2s-0.4s, the grid voltage $V_G=192V$. Comparing the waveforms of channel 3 and channel 4, it can be seen that the ES voltage lags behind NCL voltage by 90° after entering the steady state, indicating that ES is working in the capacitive mode; during the period of 0.4s-0.6s, the grid voltage $V_G=267V$. Comparing the waveforms of channel 3 and channel 4, it can be seen that ES voltage is 90° ahead of NCL voltage after entering steady state, which indicates that ES works in inductive mode. The analysis shows that the steady-state simulation results of the two control strategies are consistent with the theoretical analysis results of the power spring working mode.

Comparing the waveforms of channels 3 and 4 in Fig. 11(a), it can be seen that when $V_G=192V$, ES works in capacitive mode; after switching to $V_G=267V$ at 0.4s, ES gradually stabilizes and enters induction mode after 5-6 cycles. It can be seen from Fig. 11(b) that after adding the repeat controller, the ES enters the induction mode stably after 7-8 cycles.

5 Experiment

In order to verify the method and parameter design based on quasi proportional resonance parallel repetitive control proposed in this paper, a single-phase power spring system

experimental platform is built with dSPACE as the control core and relevant peripheral circuits, as shown in Fig. 12. The main circuit parameters are the same as table 1. Due to the limitation of oscilloscope output amplitude, the amplitude of output waveform is reduced by 31 times.

(a) Driver board

(b) Inverter bridge plate

(c) Experimental setup

Fig. 12 Experimental platform s

5.1 Steady state tracking performance

On the basis of the effective value of the grid voltage of 192V, the experiment is carried out under the condition that 12% of the 3rd harmonic, 6% of the 5th harmonic and 3% of the 7th harmonic are added to make the grid voltage seriously distorted. The results are shown in Fig. 13 and 14.

It can be seen from Fig. 13 that the V_S waveform is a sine wave, and the amplitude is stable near the expected value. In Fig. 14(a): the amplitude of the corresponding steady-state tracking error e_u under QPR + P double closed-loop control is 1000mV. In Fig. 14 (b): the e_u amplitude after adding repetitive control is 500mV. The introduction of repetitive controller can make the system maintain good CL voltage waveform and higher steady-state accuracy.

(a) The QPR+P double closed-loop control

(b) The repetitive controller based optimal control

Fig. 13 Experimental waveforms of V_s

(a) The QPR + P double closed-loop control

(b) The repetitive controller based optimal control

Fig. 14 Experimental waveforms of e_u

5.2 Dynamic performance

When $V_G=192V$, ES works in capacitive state, and $V_G=267V$, ES works in inductive state. Therefore, the dynamic switching process of capacitive and inductive modes is observed by switching between the two input voltages.

(a) V_G switches from 192V to 267V

(b) V_G switches from 267V to 192V

Fig. 15 Dynamic experimental waveform under QPR+P control

(a) V_G switches from 192V to 267V

(b) V_G switches from 267V to 192V

Fig. 16 Dynamic experimental waveform under repetitive controller

It can be seen from Fig.15 and 16 that the experimental results are similar to the simulation results. When $V_G = 192V$, the ES voltage of channel 3 lags behind the NCL voltage of channel 4 by 90° and ES works in capacitive mode; when $V_G = 267V$, ES voltage is 90° ahead of NCL voltage, and ES works in inductive mode; the results are consistent with the theoretical analysis results of the power spring working mode. When the grid voltage suddenly rises and drops, the CL voltage can be stabilized at the expected value after 4-5 cycles by using QPR+P control strategy. With the proposed control strategy, the CL voltage can be stabilized at the desired value after 8-9 cycles.

6 Conclusions

In view of the shortcomings of QPR control harmonic compensation, this paper studies ES and its related technologies, and proposes an improved scheme of repetitive control based on double closed-loop control. On the basis of simulation, an experimental platform based on dSPACE is constructed and verified by experiments:

(1) The controller designed in this paper can protect the voltage stability of important equipment with strict requirements for voltage quality, transfer the fluctuation of the grid voltage to non-critical loads, so as to ensure the safety of the mine, ensure the safe progress of production, and play an important role in the long-term stability of the mine. In addition, as the grid voltage changes, ES can automatically work in capacitance, resistance and inductance modes.

(2) Repetitive control has strong suppression effect on harmonic and periodic disturbance of power spring system. The introduction of repetitive controller can not only ensure good dynamic performance, but also effectively improve the steady-state accuracy of the system and reduce the total harmonic distortion rate of the critical load voltage.

(3) ES has a wide application prospect, but the related research is still in its infancy, and many problems need to be further studied.

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Figures

Figure 1

Typical application topology of ES

Figure 2

Existing control of ES

Figure 3

Structure of QPR parallel repetitive controller

Figure 4

Go(z) bode diagram

Figure 5

S1(z)Go(z) frequency characteristic

Figure 6

Bode diagram before and after correction

Figure 7

Frequency characteristics of $G_o(z)S_2(z) \square z^{16}$

Off-line model based on quasi proportional resonance and repetitive control

(a) The QPR+P double closed-loop control

(b) The repetitive controller based optimal control

Figure 9

Simulation waveforms of V_s and e_u

(a) The QPR+P double closed-loop control

(b) The repetitive controller based optimal control

Figure 10

Total harmonic distortion of CL voltage

(a) The QPR+P double closed-loop control

(b) The repetitive controller based optimal control

Figure 11

Dynamic simulation waveforms

(a) Driver board

(b) Inverter bridge plate

(c) Experimental setup

Figure 12

Experimental platform s

(a) The QPR-P double closed-loop control

(b) The repetitive controller based optimal control

Figure 13

Experimental waveforms of VS

(a) The QPR + P double closed-loop control

(b) The repetitive controller based optimal control

Figure 14

Experimental waveforms of eu

(a) V_c switches from 192V to 267V

(b) V_c switches from 267V to 192V

Figure 15

Dynamic experimental waveform under QPR+P control

(a) V_o switches from 192V to 267V

(b) V_o switches from 267V to 192V

Figure 16

Dynamic experimental waveform under repetitive controller