

# Control method of Three-phase Four-leg converter based on repetitive control

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**Abstract.** The research chose the magnetic levitation force of wind power generation system as the object. In order to improve the power quality problem caused by unbalanced load in power supply system, we combined the characteristics and repetitive control principle of magnetic levitation wind power generation system, and then an independent control strategy for three-phase four-leg converter was proposed. In this paper, based on the symmetric component method, the second order generalized integrator was used to generate the positive and negative sequence of signals, and the decoupling control was carried out under the synchronous rotating reference frame, in which the positive and negative sequence voltage is PI double closed loop, and a PI regulator with repetitive control was introduced to eliminate the static error regarding the fundamental frequency fluctuation characteristic of zero sequence component. The simulation results based on Matlab/Simulink show that the proposed control project can effectively suppress the disturbance caused by unbalanced loads and maintain the load voltage balance. The project is easy to be achieved and remarkably improves the quality of the independent power supply system.

## 1. Introduction

Maglev wind power generator is often used in Wind-photovoltaic Hybrid street lamps, garden lighting, landscape lighting, traffic lights and other small off-grid power supply system and the large wind farm because of its advantages such as breeze starting, efficient power generation and stable operation, and it also plays an important role in the researches of power transport, use and control of large magnetic levitation wind power system.

Three-phase Four-leg inverter provides access for nonlinear and unbalanced load with zero sequence current by adding the fourth bridge arm, making sure that the inverter can still provide a balanced three-phase sinusoidal voltage to load end under various severe load conditions. [1] Due to the addition of a bridge arm, the switch condition changes from the original 8 to 16, so the modulation mode becomes more complex comparing the traditional Three-leg inverter. At present, there are many strategies aiming at four-leg inverter such as pulse width modulation, space vector modulation technology and saddle pulse width modulation and so on[2-5]. SAPWM modulation is equivalent to common SVPWM modulation wave, which substantially both mean injecting 3 harmonics in a sinusoidal modulated signal. In order to realize independent control of three-phase voltage, different decoupling control strategies have been developed in different coordinate systems by scholars both at home and abroad. PIR-P dual-loop control in dq0 rotating coordinate system was proposed [6], which can suppress unbalanced loads through the reasonable resonant controller. A study suggests [7-8] that the load voltage is controlled by the PI regulator under the synchronous rotating coordinate of positive and negative sequence, and because the positive and negative sequence

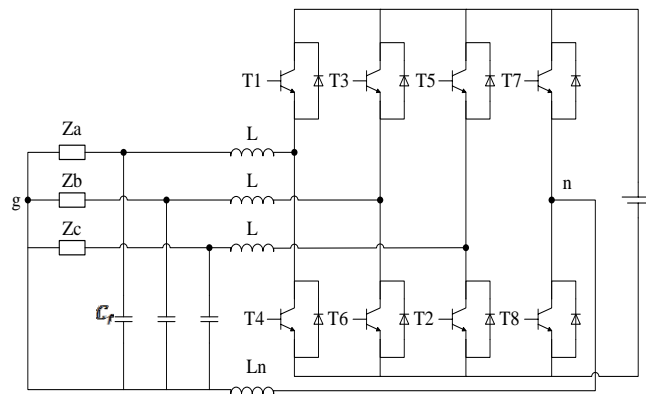


separation are not carried out, so the PI regulator is unable to track the resulting two octave voltage component without static difference. Therefore, based on positive and negative sequence separation, a closed-loop control algorithm in double synchronous rotating coordinate system is proposed [9], and the zero sequence voltage component is controlled by proportional resonant controller. On this foundation [9], an improved derated generalized integrator for fast sorting was introduced [10]. The study [11] suggests that Repetitive control is introduced under two coordinate systems to achieve stable output voltage with unbalanced loads.

Based on the above literature, this paper presents an improved positive sequence, negative sequence and zero sequence separation control strategy: the load voltage is divided by Second-order generalized integrator in order to increase the separation speed of positive and negative sequence, and the positive and negative sequence voltage components are respectively controlled in the positive and negative sequence synchronous coordinate system. Then, zero axis control is simplified, combining with repetitive control dual-closed loop of PI regulator, and the effectiveness of the control scheme has been proved by simulation.

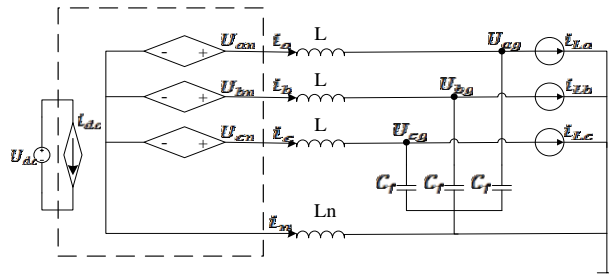
## 2. VSC - HVDC transmission system structure

Fig. 1. It shows the topology of the three-phase four-leg inverter with load operation. The fourth leg is consist of switch tube  $T7$  and  $T8$ , in which the point  $n$  is connected with the load common point  $g$  through the inductance  $L_n$ . The output of the switch tube S1-S6 is connected with the load by the LC filter.



**Figure 1.** Topology of four-leg inverter

Since the DC side of inverter is supplied by a DC voltage source, so the voltage is constant and the switching frequency is 12.8 KHZ which is much higher than the fundamental frequency of the output voltage (50Hz), and therefore the converter average switching model can be used to simplify the analysis.



**Figure 2.** Average switching model of four-leg inverter

$$u_{xn} = U_{dc} * d_{xn} \quad (1)$$

$$L p i_x = u_{xn} - u_{xg} + L_n p i_n \quad (2)$$

$$i_a + i_b + i_c + i_n = 0 \quad (3)$$

$$C_f p u_{xg} = i_x - i_{Lx} \quad (4)$$

In the above formula,  $x=a, b, c$ ;  $u_{xg}$  is the load voltage,  $u_{xn}$  is the output voltage of the inverter,  $d_{xn}$  is the duty cycle of the phase voltage,  $p$  is the differential operator  $d/dt$ . In order to decouple the traffic flow control, the average switching model is transformed to the  $d-q$  synchronous rotating coordinate system by using the transform matrix  $T_{abc/dq0}$  just as shown in formula (5). In a synchronous rotating coordinate system, the formula (2) - (4) can change to formula (5) and formula (6). Among them,  $\omega$  inverter output fundamental angular frequency. Subscript  $dq0$  represent the corresponding  $dq0$  component of the physical quantity respectively.

$$T_{abc/dq0} = \frac{2}{3} \begin{bmatrix} \cos \omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin \omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (5)$$

**Figure 3.**The inverter switch model under rotating coordinate system

$$\begin{cases} L p i_d = d_u U_{dc} + \omega L i_q - u_d \\ L p i_q = d_q U_{dc} - \omega L i_d - u_q \\ (L + 3L_n) p i_0 = d_0 U_{dc} - u_0 \end{cases} \quad (6)$$

$$\begin{cases} C_f p u_d = \omega C_f u_q + i_d - i_{Ld} \\ C_f p u_q = -\omega C_f u_d + i_q - i_{Lq} \\ C_f p u_0 = i_0 - i_{L0} \end{cases} \quad (7)$$

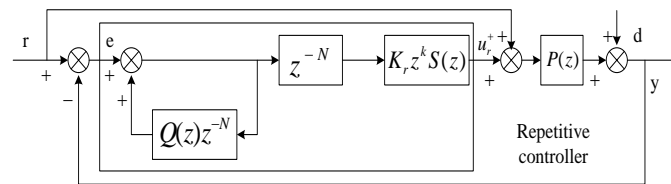
### 3. The controller design

#### 3.1. Repetitive controller

Based on internal model principle, a repetitive controller makes an internal model  $1/(1-e^{-ts})$  which contains all the fundamental harmonic sub internal mode, inserting it into the controller, so that the system can realize the static tracking of the periodic AC signals [12]. It can be seen from its equation, the eigenvalues of roots  $0$ ,  $\omega$  and  $2\omega$  are all distributed on the imaginary axis, and the gain of system at these characteristic frequency points is infinitely large. Therefore, the closed-loop feedback system can realize perfect tracking of AC signals. The sampling points of each cycle are  $N$ , and their internal modes are represented in the  $Z$  domain as follows:

$$G_R(z) = \frac{1}{1 - z^{-N}} \quad (8)$$

From the Z domain structure of internal model, the repetitive controller is a positive feedback loop with periodic delay. Its function is accumulating the input signal periodically, similar to the integral link. When the given and feedback are inconsistent, the output of controller will continue to increase until the error is eliminated. However, the controller has  $N$  poles located on the unit circle, which makes the system be in critical undefined state. Therefore, the low pass filter  $Q(z)$  is introduced to obtain the improved repetitive controller, as shown in Fig. 4. Meanwhile, taking a constant less than 1, usually 0.95. Because the repetitive controller has a slow dynamic response, a repetitive controller combine with PI control is adopted.



**Figure 4.** The improved repetitive controller

The repetitive controller is composed of a delayed positive feedback link and a compensator. The output error of inverter is accumulated by the fundamental period according to the delayed positive feedback. The function of compensator is to realize medium low frequency cancellation and high frequency attenuation with the inverter object, so that the compensation signal given by the internal model can correct the amplitude and phase correctly against to the disturbance, so as to realize the difference of the implicit waveform.  $S(z)$  is designed to eliminate the peak value of the amplitude frequency characteristic curve of  $P(z)$  and attenuate the high frequency, and we take the value of  $S(z)$  as a cut-off frequency, and we also take  $S(z)$  as a first order filter approximating to  $P(z)$  in order to achieve high frequency attenuation and lead to phase compensation realized by leading link.

### 3.2 Symmetrical components method

According to the symmetrical component theory<sup>[13]</sup>, the three-phase unbalanced vector system can be decomposed into three symmetrical vector systems. The symmetric vectors in each system are called positive sequence components, negative sequence components and zero sequence components in turn. Therefore, under unbalanced load, the three-phase load voltage and inductance current can be expressed as:

$$u_{xg} = u_{xg+} + u_{xg-} + u_0 \quad (9)$$

$$i_x = i_{x+} + i_{x-} + i_0 \quad (10)$$

$$u_{xn} = u_{xn+} + u_{xn-} + u_{xn0} \quad (11)$$

$$\begin{cases} u_{xn+} = Lp i_{x+} + u_{xg+} \\ u_{xn-} = Lp i_{x-} + u_{xg-} \\ u_{xn0} = (L + 3L_n) p i_0 + u_0 \end{cases} \quad (12)$$

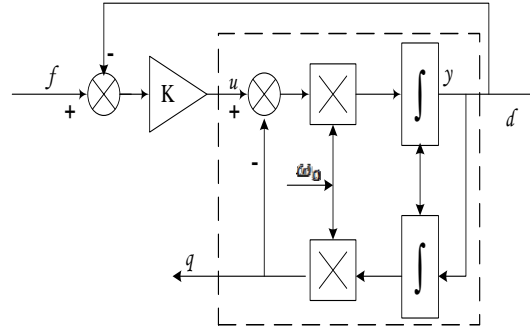
Through the coordinate transformation, the physical quantity in the abc coordinate system is transformed into the ab0 coordinate system.

$$T_{abc/\alpha\beta 0} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (13)$$

In this coordinate system, the positive and negative sequence components have nothing to do with the zero sequence component, and  $f_0^+$ ,  $f_0^-$  is 0. The phase shift operator composed of second order generalized integrator SOGI is  $S = e^{-j90^\circ}$ .

$$\begin{cases} f_{\alpha\beta}^+ = \frac{1}{2} \begin{bmatrix} 1 & -S \\ S & 1 \end{bmatrix} f_{\alpha\beta} \\ f_{\alpha\beta}^- = \frac{1}{2} \begin{bmatrix} 1 & S \\ -S & 1 \end{bmatrix} f_{\alpha\beta} \end{cases} \quad (14)$$

The following is a SOGI shifted circuit diagram.



**Figure 5.** The phase shift operator is composed of second order generalized integrator

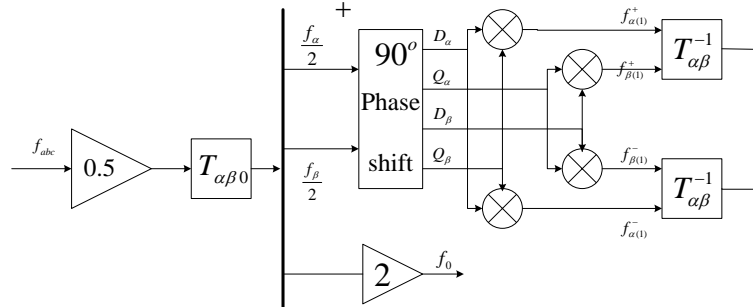
The transfer function of SOGI:

$$G_s = \frac{y(s)}{u(s)} = \frac{s\omega_0}{s^2 + \omega_0^2} \quad (15)$$

According to the above Fig.5, we can see:

$$\begin{cases} u_{\alpha\beta+} = \frac{k\omega_0 s}{s^2 + k\omega_0 s + \omega_0^2} u_{\alpha\beta} \\ u_{\alpha\beta-} = \frac{k\omega_0^2}{s^2 + k\omega_0 s + \omega_0^2} u_{\alpha\beta} \end{cases} \quad (16)$$

Based on SOGI phase-shift circuit of positive and negative sequence component, the extraction implementation flow chart is just as shown in Fig.6

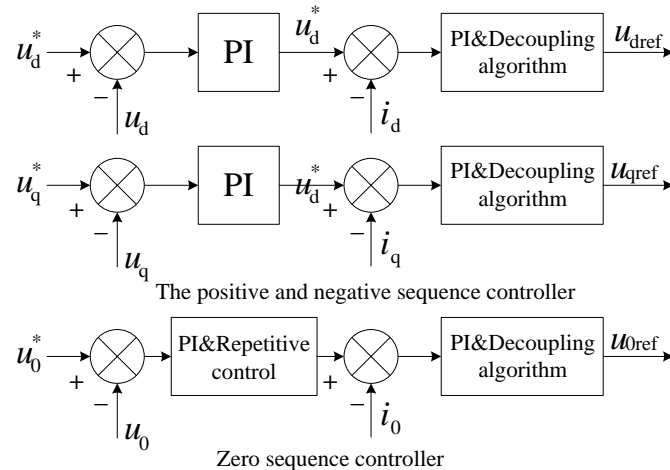


**Figure 6.** The fundamental principle

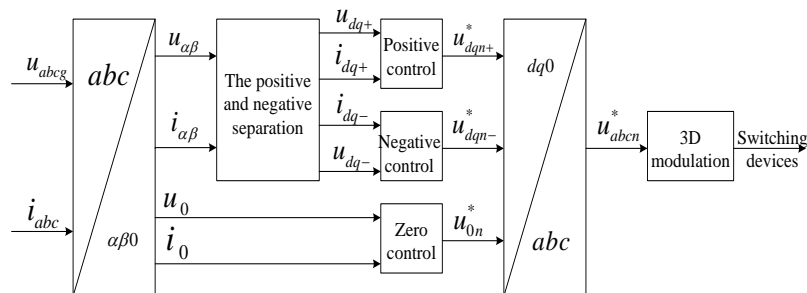
### 3.3 Dividing-sequence control

In order to achieve the voltage balance control, the control objectives should be set as that positive sequence component for a given value, negative sequence and zero sequence voltage components are zero. In the forward rotating coordinate system, the positive sequence  $d-q$  component is the direct flow, and in the negative rotation coordinate system, the negative sequence  $d-q$  component is also the direct

flow. Therefore, the *PI* controller can achieve the control effect. When the load is unbalanced, the zero sequence component is a set of alternating currents with equal amplitude and phase, and the traditional *PI* controller is difficult to achieve good control effect, so the *PI* controller with repetitive control is used to track the zero sequence voltage current component. The repetitive controller is used to eliminate static error, *PI* controller is used to adjust the system dynamic performance. The system control diagram is as shown. There is no coupling between zero line and d-q axis, so the zero sequence component exists only on the zero axis and can be independently controlled.



**Figure 7.** Dividing-sequence controller structure



**Figure 8.** System control block diagram

#### 4. The simulation and conclusion

In order to verify the effectiveness of control strategy proposed in this paper, a simulation model is built on the Matlab/Simulink platform as shown in Fig. 1. The component parameters are shown in Table 1, and first the three-phase unbalanced load experiment is carried out, in which the three-phase load of ABC is 10, 10, 30, and the capacitance voltage and inductance current are measured just as shown in Figure.

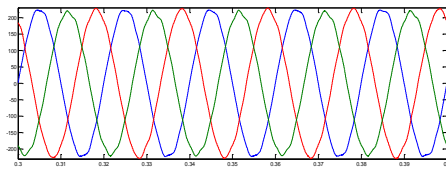
Then, the single-phase load experiment is carried out, in which the A load is 10 and the B C both no-load. The capacitance voltage and inductance current output are measured in the experiment just as shown in Figure.

**Table 1.** The simulation parameters

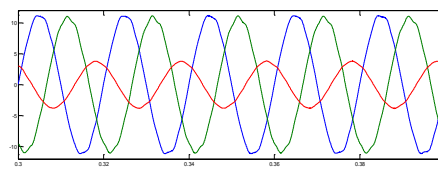
parameters	parameters
DC voltage /V	600
Filtering inductance /L	5
Filter capacitor /uf	30
The midline inductor /mH	2
Switching frequency /kHz	12.8
Output voltage instruction value /V	220

## The output voltage frequency/Hz

50

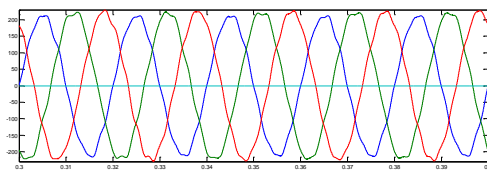


A. Improved points sequence control output voltage waveform

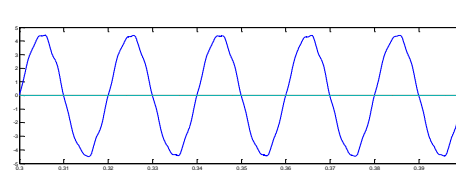


B. Improved points sequence control output current waveform

The Figure shows under the improved points sequence control strategy, the three-phase output voltage is 223.1V, 218.7V, 223.4V, the harmonic content is 1.72%, 1.46%, 1.56%, and the maximum voltage imbalance is 1.54%. The calculation shows that the current negative sequence imbalance is 0.8%, and the zero sequence imbalance is 0.7%.



A. Improved points sequence control output voltage waveform



B. Improved points sequence control output current waveform

The Figure shows under the improvement points sequence control strategy, The three-phase output voltage is 213.8V, 223.3V, 224.1V, the harmonic content is 2.79%, 3.17%, 2.76%, and the maximum voltage imbalance is 2.81%. The calculation shows that the current negative sequence imbalance is 0.7%, and the zero sequence imbalance is 1.4%.

## 5. Conclusion

The simulation results show that the improved sequence control strategy can suppress unbalanced loads effectively and has a good effect on improving the power quality of the maglev wind power grid-connected system.

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