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Research on Reactive Power Compensation and Harmonic Suppression of Shield Machine Based on APF

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***Abstract*—In the Grid system connected with shield machine, harmonic pollution and low power factor are the two power quality problems that need to be solved. Reactive power compensation and harmonic suppression are two different aspects of the problem, but their common characteristics provide the possibility for a comprehensive study of the two. By detecting harmonics and reactive currents in power system and then using Power Filter Active to dynamically track and compensate the power grid system can solve the problem of harmonic pollution and low power factor. The simulation experiment was carried out to prove the compensation system can improve the power quality of the power grid effectively.**

Keywords-shield machine; harmonic suppression; reactive power compensation; active power filter

I. INTRODUCTION

Shield machine is a special construction machine which uses the steel components of the cylinder to push the soil along the axis of the tunnel. In recent years, the shield machine for its high degree of automation, high construction speed, not affected by climate, reduce the impact of buildings on the ground and excavation under water does not affect the ground traffic characteristics get more and more application in tunnel construction. There are a lot of inductive loads in the shield machine, which will consume a large amount of reactive power, the increase of reactive power will increase the loss of power supply equipment and line; The nonlinear load of the shield machine produces a large amount of harmonic current. The existence of harmonics may cause the local resonance of the public power grid; The over voltage and over current caused by harmonics will make the transformer, capacitor and other serious overheating affect the normal operation of the equipment[1,2].

In order to reduce the access of the shield machine to the power grid power quality problems, using power electronic devices to reduce the impact of the harmonic current generated by reactive power and harmonic is an effective measure to solve the harmonic pollution and low power factor. At the same time, the power factor of the power network is improved, the loss of the transformer and the circuit is reduced, the efficiency of the equipment is improved, and the purpose of energy saving is achieved.

II. WORKING PRINCIPLE OF ACTIVE POWER FILTER

According to the different connection with the power grid, APF can be divided into parallel type, series type, mixed type and series parallel type [3]. Parallel APF can compensate harmonic and reactive power at the same time, so the parallel APF is used in this paper to carry out the harmonic suppression and reactive power compensation of the shield machine system. The system schematic is shown in figure I. Among them, u_S is the grid voltage, i_S and i_L respectively is the grid current and load current, reactive power and harmonic compensation current, command current. i_c , i^*_c respectively reactive power and harmonic compensation current, command current.

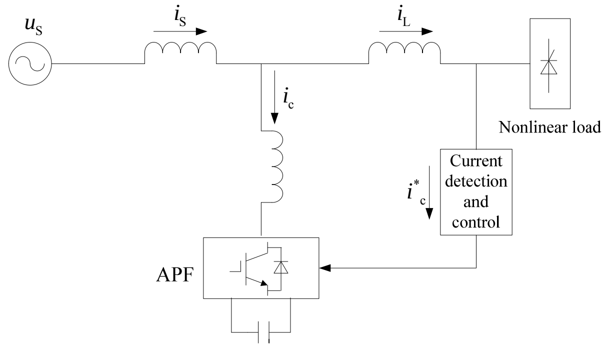

FIGURE I. SCHEMATIC DIAGRAM OF PARALLEL APF SYSTEM

The harmonic current component i_{Lh} and the reactive current component i_{Lfq} in the load current are detected by the current detection part in Figure 1. Compensating current i_c is generated by i_{Lh} and i_{Lfq} as an instruction signal i^*_c , injecting i_c into the grid to offset the harmonic current component and reactive current component of the load current, so as to realize the harmonic current suppression and reactive power compensation of the shield machine system. The working principle of APF can be expressed as follows:

$$i_L = i_{Lf} + i_{Lfq} + i_{Lh} \tag{1}$$

Among them, i_L is the load current, and i_{Lf} is the fundamental current component.

$$i^*_c = i_{Lfq} + i_{Lh} \tag{2}$$

Make the compensating current:

$$i_c = -i^*_c$$

$$i_c = -(i_{Lfq} + i_{Lh}) \tag{3}$$

III. DETECTION AND CONTROL OF CURRENT IN SHIELD MACHINE

A. Harmonic and Reactive Current Detection

In order to compensate the harmonic and reactive current in the shield system, it is necessary to detect the harmonic current and reactive current in the load current. In this paper, the detection method based on instantaneous reactive power theory[4].

The instantaneous value of three-phase voltage and current respectly is e_a, e_b, e_c and i_a, i_b, i_c.

$$\begin{cases} e_a = E_m \sin \omega t \\ e_b = E_m \sin(\omega t - 2\pi/3) \\ e_c = E_m \sin(\omega t + 2\pi/3) \end{cases} \tag{4}$$

Among them, E_m is the voltage amplitude. The instantaneous value of three-phase voltage and current is transformed into a two - phase orthogonal static coordinate system $\alpha - \beta$:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ i_c \end{bmatrix} = C_{32} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{6}$$

Bring the formula 4 into the formula 5:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{3/2} E_m \begin{bmatrix} \sin \omega t \\ -\cos \omega t \end{bmatrix} \tag{7}$$

Based on instantaneous reactive power theory, three phase instantaneous active power p and instantaneous reactive power q can be expressed as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ e_\beta & -e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{pq} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8}$$

Bring the formula 7 into the formula 8:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \sqrt{3/2} E_m \sin \omega t & -\sqrt{3/2} E_m \cos \omega t \\ -\sqrt{3/2} E_m \cos \omega t & -\sqrt{3/2} E_m \sin \omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{9}$$

Because $\vec{e}_\alpha$ and $\vec{e}_\beta$ mutually orthogonal, and because $\vec{e} = \vec{e}_\alpha + \vec{e}_\beta$, so the modulus value of $\vec{e}$ is $\sqrt{3/2} E_m$,By formula 9:

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \begin{bmatrix} \sin \omega t & -\cos \omega t \\ -\cos \omega t & -\sin \omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{10}$$

Based on $i_p - i_q$ harmonic reactive current detection principle shown in Figure II, In this method, the sine and cosine signals with the same phase of the grid voltage are obtained by the phase locked loop circuit. avoiding the calculation error caused by voltage distortion. The load current i_{sa}, i_{sb}, i_{sc} are transformed into i_p, i_q the p-q coordinate system, Using low pass filter (LFP) to filter the harmonic component of i_p, i_q, output the DC component in the i_p, i_q.The DC component is transformed into the A-B-C coordinate system to obtain the fundamental current i_{af} , i_{bf} , i_{cf} of the load. The harmonic current and reactive current are obtained by subtracting the fundamental current from the load current.

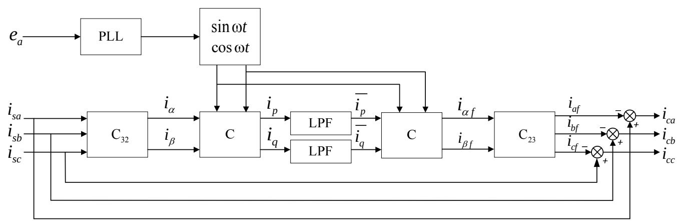

FIGURE II. $i_p - i_q$ PRINCIPLE OF HARMONIC REACTIVE CURRENT DETECTION

It's needed to have Harmonic current and reactive current compensation at the same time, making i_q=0 to remove the i_q channel of Low pass filter (shown as figure 2). Obtain the load fundamental active current by carries on the Coordinate transformation of active current. Subtracting the fundamental active current with the actual load current, then we obtain the fundamental reactive current and harmonic current. The current is used as command current as reactive harmonic compensation, The reactive harmonic compensation can be realized simultaneously.

B. Control Method for Compensation Current

The structure diagram of three-phase active power filter connected in parallel with the grid is shown in Figure III, Shield machine is connected to the load side, the main circuit of APF is consisted of reactance L, converter and the DC side capacitor C. The whole system consists of two parts: command current operation circuit and compensation current generating circuit. The harmonic and the reactive current component of the load current (i_{sa} , i_{sb} , i_{sc}) can be detected by the command current operation circuit, and the command current (i_{ca} , i_{cb} , i_{cc}) of the inverter can be generated by compensation current according to harmonic and reactive current detected. Then the command current is compared with the feedback current (i_{fa} , i_{fb} , i_{fc})of the inverter and the command signal of pulse width modulation is obtained, It controls the conduction of insulated gate bipolar transistor V1~V6 in the inverter, and the compensating current which can reduce harmonic and reactive current is generated.

The control method used in this paper is shown in Figure Ⅳ, where K is the transformation ratio of coupling transformer, Comparing the feedback current (i_{fa} , i_{fb} , i_{fc}) of the inverter with the command current (i_{ca} , i_{cb} , i_{cc}) of the inverter which generated by harmonic current and reactive current, its result can become a modulated signal after a proportional component P, and then the triangular wave signal is used as the carrier to obtain the PWM command signal ,which is used to control the IGBT.

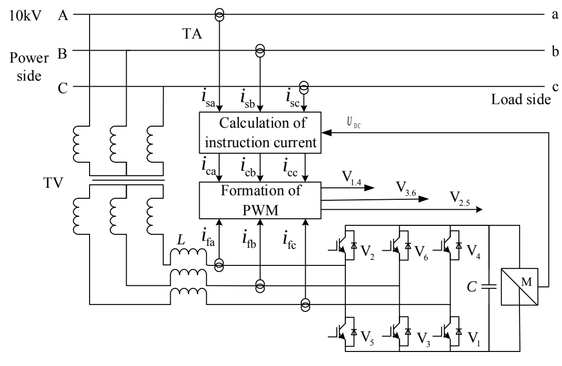

FIGURE III. TRUCTURE OF 10KV THREE PHASE HIGH POWER ACTIVE POWER FILTER

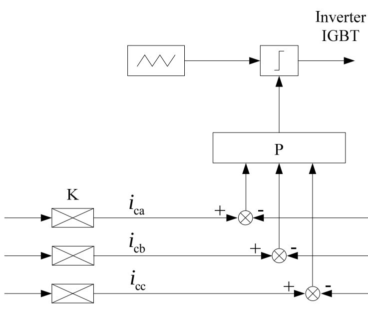

FIGURE IV. THE BLOCK DIAGRAM OF APF CONTROL METHOD

IV. SIMULATION AND ANALYSIS

A. Selection of Main Circuit Device Parameter

Due to the shunt Active Power Filter and the shield machine system are connected in parallel to the power grid, the voltage of APF is almost equal to that of the shield machine. Therefore, the capacity of APF mainly depends on the compensation current. In three-phase circuit, the effective value of AC side harmonic current component is about 25% of the total effective value of current. When compensating harmonic and reactive currents simultaneously, the compensation current i_c can be expressed as

$$I_c = \sqrt{I^2_{Lh} + I^2_{Lfq}} = \sqrt{0.25^2 + (1-\cos\alpha_{max})^2 I_L} \quad (11)$$

where the meaning of I_L , I_{Lh} and I_{Lfq} are the same as Formula 1, $\cos\alpha_{max}$ is the maximum trigger delay angle when the converter operates in the rectifier state. In this paper, the capacity of APF is selected as 10 kVA in this paper, and the line voltage of the shield machine is 380V.Therefore, the compensation current is 15.1A, the peak value of the AC side voltage of the converter can be calculated as:

$$U_m = \sqrt{2}U = \sqrt{2} \times 220 = 311.1\text{V}$$

Consider the 1.5~2 margin, the voltage can be taken as 600V.

In the APF, the magnitude of the voltage U_{DC} on the DC side capacitor C has a direct impact on the tracking ability of the device to the compensation current. The higher the voltage across the capacitor C, the better the tracking performance of the compensation current. However, taking into account capacity and pressure requirements of capacitance, U_{DC} can be calculated as follows:

$$U_{DC} \geq 3U_m \quad (12)$$

The main function of the AC side inductor in APF is to make the compensation current change continuously. Therefore, in order to make the compensation current track the reactive power and harmonic current immediately, smaller inductance should be selected, but taking into account the requirements of the system for ripple of compensating current, the inductance value of L can be calculated as follows[5]:

$$L = \frac{4U_{dc}t_c}{9\lambda i^*_{c\max}} \quad (13)$$

where $i^*_{c\max}$ represents the maximum value of reactive and harmonic command current, which generally takes 70% of the load current. t_c is sampling interval, λ is the coefficient obtained by simulation, when it takes 0.3~0.4, the compensation effect is best. By the formula 11, if the maximum delay angle is 30°, $I_c = 0.28I_L = 15.1\text{A}$, that is $I_L = 53.9\text{A}$, then:

$$i^*_{c\max} = 0.7 \times 53.9 = 37.7\text{A} \quad (14)$$

When the sampling frequency is 12.8kHz, the sampling period is 78.1μs . Can be derived from formula 12 that $U_{dc} \geq 933.4\text{V}$

Take $M = 1000V$, $\lambda = 0.35$, the value of L is calculated as $2.63mH$. Thus the inductor is selected as $2\,mH$.

In APF, the capacitor C on the DC side plays a role in buffering the energy stored in the AC side inductance and the energy fluctuation caused by the higher harmonics. Therefore, in the choice of parameters, it is necessary to consider the fluctuation of capacitance voltage caused by harmonics, According to the literature [5]. The value of C can be calculated as follows:

$$C = \frac{3U_m I_m^-}{2\varepsilon\omega U_{DC}^2} \tag{15}$$

where, I_m^- indicates the peak of negative sequence current component in i_c, Its value is generally 60% of i_c. ε indicates the voltage fluctuation rate in DC side, it takes 0.01 generally. ω indicates fundamental angular frequency of power grid. Based on the above analysis, The value of C can be calculated as $1346\mu F$. Therefore the capacity of the capacitor C is selected as $1000\ \mu F$.

B. System Simulation

In this paper, the situation of harmonic and reactive power compensated at the same time is simulated in the MATLAB environment of Simulink. In the simulation process, the harmonic source uses a three-phase half controlled bridge rectifier with resistor-inductance load and set the trigger angle of 30°.The simulation results are shown in Figure V, and each section is A, B, C three-phase waveform from top to bottom

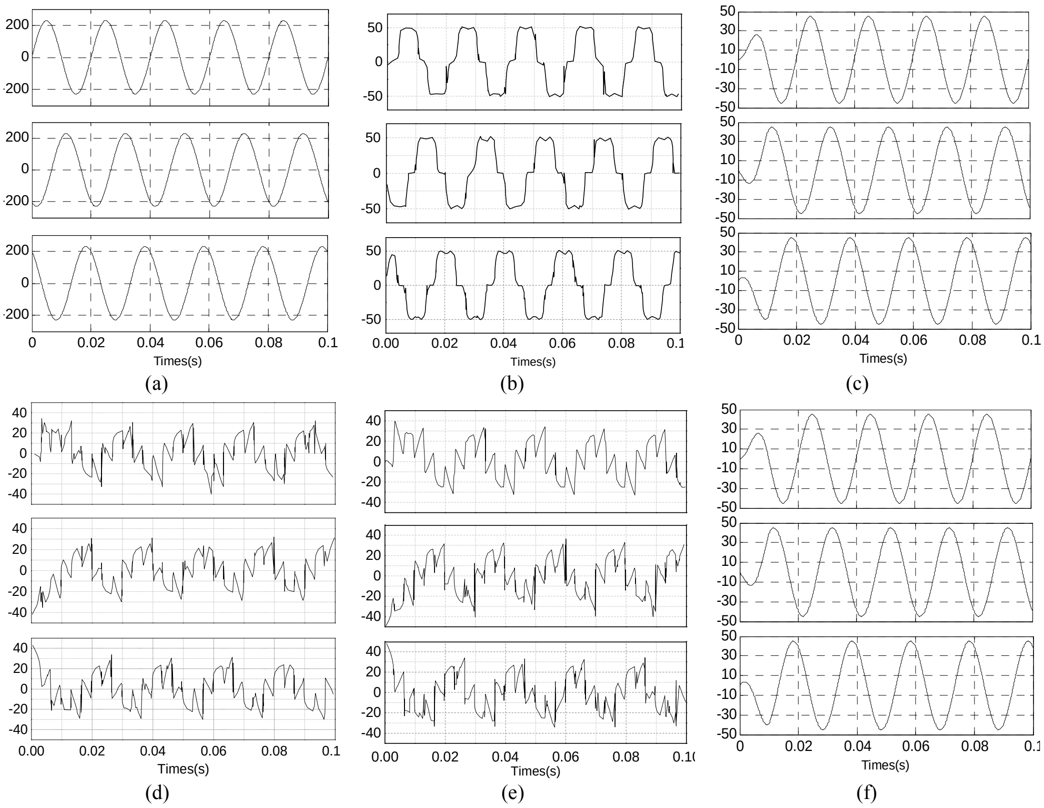

FIGURE V. THE SIMULATION RESULTS OF METHOD PRESENTED: (A) THREE-PHASE GRID VOLTAGE. (B) THREE-PHASE LOAD CURRENT. (C)FUNDAMENTAL CURRENT WHEN COMPENSATED SIMULTANEOUSLY. (D)COMMAND CURRENT WHEN COMPENSATED SIMULTANEOUSLY. (E)COMPENSATING CURRENT WHEN COMPENSATED SIMULTANEOUSLY. (F)COMPENSATED CURRENT WHEN COMPENSATED SIMULTANEOUSLY

The simulation results show that the method presented can effectively separate the harmonic and reactive currents from the load current of the shield machine. The compensation current waveform is sine wave and there is no phase difference with voltage of grid, it can basically meet the compensation requirements.

V. CONCLUSION

This paper proposes the scheme of reactive power compensation and harmonic suppression based on APF. Firstly, reactive and harmonic current component in the load current are detected based on the instantaneous reactive power theory. Then according to the harmonic and reactive current detected, command current is generated, which controls the inverter in the main circuit of APF to generate the compensating current and timely compensates the reactive and harmonic current in the working process of the shield machine. The simulation results show that the scheme can effectively improve the power quality problems caused by the harmonic pollution and low power factor when the shield machine connected to the power grid. At the same time, it can save energy and improve economic benefits.

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