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A New Control Scheme for Hybrid Active Power Filter

Liu Yongqiang and Cao Haitang

***Abstract*-- That correcting power factors and eliminating harmonics current of network sides in supply systems is important, and it is always concerned by electric power users and electric power companies. In this paper, an advanced control techniques are advanced to realize the unified compensation of reactive power and harmonics. The new ideal advanced in this paper is to turn harmonics eliminations to harmonics suppressions, and it conduce stronger robustness of the controller to the disturbances caused by variation of load, parameter perturbations and unmodelled dynamics. The new control scheme can simplify the detection of harmonic current greatly. The method of suppression harmonics presented in the paper has strictly mathematical fundaments. In this paper a simulation example is given and the simulation results show the validity and the performance of the unified compensative method.**

***Index Terms*—passive filter, active power filter, harmonic, harmonics suppressions**

I. Introduction

WITH the development of power electronic technologies, more and more power electronic appliances are widely used to industry, and which result inevitably in serious harmonic pollutions and passive power wastage. Then the problem of how to suppress harmonic current and compensate reactive power is concerned by both power users and electric power companies. Now there are two types of devices to suppress harmonic, i.e., passive power filter (PPF) and active power filter (APF) [1-4]. Industrial users commonly use PPF to deal with harmonic pollutions and passive currents. But PPF has some disadvantages that are not to be overcome, such as the design of PPF depending on network parameters, having larger size and bringing resonance for some harmonic, etc. Now APF becomes an important method to solve harmonics pollutions, and many researchers have obtained many progresses in this area. But some opinions from power users and electric power companies indicated that APF is too expensive. APF needs a large-capacity power inverter that bears the voltage of network-side and goes through all the harmonic currents and passive currents for counteracting harmonics and reactive power. Combining APF with PPF to decrease the capacity of inverter for reducing the cost of APF has been presented by some researches [5-10].

In this paper, the topological structure of hybrid active power filter (HAPF) [11], which combines passive power filter with active power filter, is adopted to realize compensation of passive power and harmonic suppression. In this paper, PPF play an important role in harmonic suppression and reactive power compensation, in which entire fifth harmonic current and the majority of passive current flow, hence the capacity of inverter is decreased obviously. And a new control strategy of unified compensation is advanced, which has stronger robustness and applicability for various power loads in the paper. The new unified control scheme presented in this paper translates eliminating harmonics to suppressing harmonics, i.e., change eliminating harmonics to tracing sinusoidal signal with given phase. Therefore, the detection of harmonics of load side does not needed, and the harmonics and reactive power compensations can be realized uniformly. As a result, some important contributions to this subject have been achieved, which are presented in the following:

The model of the unified compensating circuit is build, in which the currents of the inductor and network side and the voltage of capacitor are treated as the state variables, the harmonic currents of load and the harmonics of network side voltage as the disturbances, the output voltage of inverter as the control, the current of network side as the output of the system. So the problem of eliminating harmonics can be changed to the disturbances suppressed problem, and the control of reactive power compensation becomes very easy after modeling.

A new harmonics suppression method is presented. In this paper the control signal is divided into two parts, one is for correcting power factor and other for suppressing harmonics, and the load current and network side current are also divided into two components, basic frequency and harmonic. After above translating the problem of solving control signal for suppressing harmonics is changed to the robust control problem of linear system, moreover the power factor correcting can be realized by simple control method. The results of simulation show the validity of the unified compensation method presented in this paper.

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II. MODELING FOR HAPF

HAPF topology construction is shown in Fig.1, where PPF consist of capacitance C_1 and inductance L_2, which is designed according to the reactive power of normal load. The APF consist of the voltage-inverter and inductor L_3, which can regulate reactive power and eliminate harmonics. In fact, APF's more important duty is to restrain the resonance between network impedance and PPF. In this paper we regard 5^{th} harmonic current as the maxim harmonic current of load, and C_1, L_2 and L_3 make up of 5^{th} resonance filter to decrease the APF capacity. Hence the parameters C_1, L_2 and L_3 can be determined by the following:

$$\begin{cases} Q_0 = \dfrac{U_{Sb}^2}{\dfrac{1}{\omega_1 C_1} - \omega_1 L_2} \\ \dfrac{1}{5\omega_1 C_1} = 5\omega_1 L_{eq} = \dfrac{5\omega_1 L_2 L_3}{L_2 + L_3} \Rightarrow \dfrac{L_2 + L_3}{L_2 L_3 C_1} = 25\omega_1^2 \end{cases} \tag{1}$$

where L_{eq} is the equivalent shunt inductance of L_2 and L_3, $\omega_1 = 2\pi f_1$, Q_0 is the reactive power corresponding to normal load.

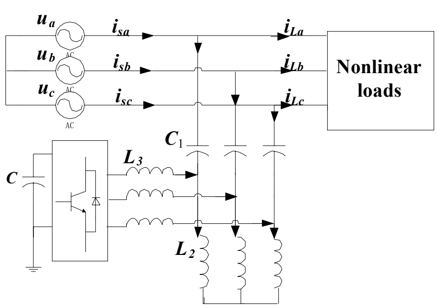

Fig.1. System configuration of HAPF

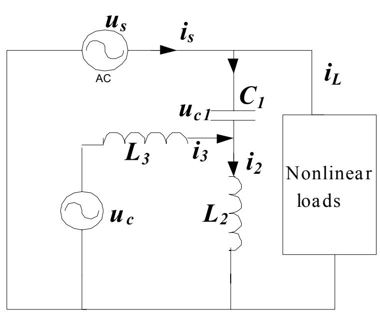

Fig.2. The equivalent circuit of HAF

The single-phase equivalent circuit of HAPF is given in Fig.2, in which u_s is the source voltage, i_s the current in net-side, i_L, the current in load side, u_{c1} the voltage of capacitor C_1, i_2 the current of reactor L_2, i_3 the current of the inverter, and u_c the AC voltage of the inverter.

So we can derive the system state model from Fig.2 as follows:

$$\frac{d^2 i_s}{dt^2} = -\frac{L_2 + L_3}{L_2 L_3 C_1} i_s + \frac{L_2 + L_3}{L_2 L_3 C_1} i_L + \frac{d^2 i_L}{dt^2} + \frac{L_2 + L_3}{L_2 L_3}\frac{du_s}{dt} - \frac{1}{L_3} u \tag{2}$$

where $u = \dfrac{du_c}{dt}$ is treated as the control signal. Obviously, (2) can be regarded as an input-output second order model. So the AC voltage of inverter u_c is governed effectively that means we can successfully compensate passive current and suppress the harmonic currents. We take note of the system (2) is a linear system hence it satisfies superposition principle. So we can take different control strategy to treat passive current and harmonic currents.

$$\begin{cases} u_s = u_{sb} + u_{sh} \\ i_s = i_{sb} + i_{sh} \\ i_L = i_{Lb} + i_{Lh} \\ u = u_1 + u_2 \end{cases} \tag{3}$$

where u_{sb} is the fundamental frequency component of voltage in net-side, i_{sb} the fundamental frequency component of current in net-side, i_{Lb} fundamental frequency component of current in load-side, u_{sh} the harmonic component of source voltage, i_{sh} the harmonic component of current in net-side, i_{Lh} the harmonic component of current in load-side. u_1 denotes the control signal for compensating phase of the fundamental frequency component of current in net-side, and u_2 the control signal for suppressing the harmonics currents in net-side.

The system model is obtained as follows:

$$\frac{d^2 i_{sb}}{dt^2} = -\frac{L_2 + L_3}{L_2 L_3 C_1} i_{sb} + \frac{L_2 + L_3}{L_2 L_3 C_1} i_{Lb} + \frac{d^2 i_{Lb}}{dt^2} + \frac{L_2 + L_3}{L_2 L_3}\frac{du_{sb}}{dt} - \frac{1}{L_3} u_1 \tag{4}$$

$$\frac{d^2 i_{sh}}{dt^2} = -\frac{L_2 + L_3}{L_2 L_3 C_1} i_{sh} + \frac{L_2 + L_3}{L_2 L_3 C_1} i_{Lh} + \frac{d^2 i_{Lh}}{dt^2} + \frac{L_2 + L_3}{L_2 L_3}\frac{du_{sh}}{dt} - \frac{1}{L_3} u_2 \tag{5}$$

where $u_1 = \dfrac{d\tilde{u}_{c1}}{dt}$, $u_2 = \dfrac{d\tilde{u}_{c2}}{dt}$, $u_c = \tilde{u}_{c1} + \tilde{u}_{c2}$

III. CONTROL STRATEGY

The control system is composed of the feedback loop controlled by current. In this paper we adopt different control scheme to treat passive current and harmonics respectively. And APF can be governed through controlling the AC-side voltage of inverter, which can be modulated through regulating pulse width, i.e., pulse width modulation PWM. The structure of control system is shown in Fig.3.

For obtaining the control strategy we have to give the reference current in net-side, and which is to regard as the fundamental frequency real power component of load current. The idea is to adjust i_{sb} to trace i_s^*, where i_s^* is reference current that has the same phase as the fundamental frequency component of source voltage u_{Sb}, that means total compensation are realized.

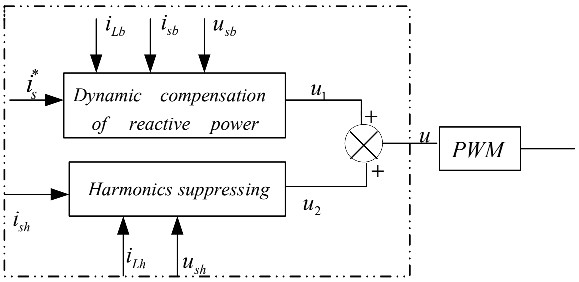

Fig. 3 The structure of the control

It's hard to eliminate harmonics entirely due to inexact measuring technique presently. Therefore we change the problem of eliminating harmonics into suppressing the harmonics in this paper.

A. Dynamic compensation of reactive power

The load current can be divided into three parts, i.e.,

$$i_L = i_{Lbp} + i_{Lbq} + i_{Lh} \tag{6}$$

where i_{Lbp} denotes the fundamental frequency component of active current, i_{Lbq} denotes the fundamental frequency component of passive current. If i_{sb} in (4) traces i_{Lbp}, then it means the total compensation is realized, i.e. using controller u_1 we can compensate reactive current to zero. Obviously, i_{Lbp} is the reference current in net-side which has the same phase as fundamental frequency component of the source voltage, we denote it by i_s^*. Then (4) becomes as follows:

$$\frac{d^2(i_s^* - i_{sb})}{dt^2} = -\frac{L_2 + L_3}{L_2 L_3 C_1}(i_s^* - i_{sb}) + \frac{L_2 + L_3}{L_2 L_3 C_1}(i_s^* - i_{Lb}) + \frac{d^2(i_s^* - i_{Lb})}{dt^2} - \frac{L_2 + L_3}{L_2 L_3}\frac{du_{sb}}{dt} + \frac{1}{L_3}u_1 \tag{7}$$

Let $x = i_s^* - i_{sb}$ and regard x as the state variable, then （7）becomes as follows:

$$\frac{d^2 x}{dt^2} = -\frac{L_2 + L_3}{L_2 L_3 C_1}x + \frac{L_2 + L_3}{L_2 L_3 C_1}(i_s^* - i_{Lb}) + \frac{d^2(i_s^* - i_{Lb})}{dt^2} - \frac{L_2 + L_3}{L_2 L_3}\frac{du_{sb}}{dt} + \frac{1}{L_3}u_1 \tag{8}$$

We assume that u_1 is controlled as follows:

$$u_1 = -\frac{L_2 + L_3}{L_2 C_1}(i_s^* - i_{Lb}) - L_3\frac{d^2(i_s^* - i_{Lb})}{dt^2} + \frac{L_2 + L_3}{L_2}\frac{du_{sb}}{dt} - L_3 k_1 \frac{dx}{dt} \tag{9}$$

where $k_1 > 0$.

Thus (8) is rewritten as:

$$\frac{d^2 x}{dt^2} = -\frac{L_2 + L_3}{L_2 L_3 C_1}x - k_1\frac{dx}{dt} \tag{10}$$

Obviously, the solution of (10) will be quickly attracted to zero if k_1 is proper. It is to say i_{sb} traces i_s^* and the passive currents are compensated.

B. Harmonic currents suppressing

For treating the problem of harmonics suppressing a necessary mathematical theorem is given firstly. Consider following ordinary differential equation:

$$\ddot{x} = -b_1 x + w(t) - u \tag{11}$$

where $b_1 > 0$， $|w(t)| < w_0$， $w(t)$ is disturbance, and u is input.

Theorem 1： Let $u = b_2 x + a\dot{x}$ ， b_2, a are positive constant, $\varepsilon = \min[\frac{a}{4}, \frac{b}{2a}]$， $b = b_1 + b_2$. The solution of (10) satisfies inequality:

$$x^2 \le (\frac{y_0^2}{b - \varepsilon(a-\varepsilon)} + x_0^2)e^{-2\varepsilon t} + \frac{w_0^2}{4\varepsilon(a-2\varepsilon)[b-\varepsilon(a-\varepsilon)]} \tag{12}$$

where $y_0 = \dot{x}_0 + \varepsilon x_0$， $x_0 = x(0), \dot{x}_0 = \frac{dx}{dt}|_{t=0}$.

Proof:

Let $u = b_2 x + a\dot{x}$, and $y = \dot{x} + \varepsilon x$, then (11) can be written as:

$$\dot{y} + (a-\varepsilon)y + Dx = w(t) \tag{13}$$

where $D = b - \varepsilon(a-\varepsilon)$. From the interval of ε, we know that $D > 0$. If the both sides of (13) multiply y, then:

$$\frac{1}{2}\frac{dy^2}{dt} + (a-\varepsilon)y^2 + \frac{D}{2}\frac{dx^2}{dt} + \varepsilon D x^2 = w(t)y \tag{14}$$

where $w(t)y \le (a-2\varepsilon)y^2 + \frac{w_0^2}{4(a-2\varepsilon)}$， $a - 2\varepsilon > 0$， then:

$$\frac{d}{dt}(y^2 + Dx^2) + 2\varepsilon(y^2 + Dx^2) \le \frac{w_0^2}{2(a-2\varepsilon)} \tag{15}$$

The both sides of (15) multiply $e^{2\varepsilon t}$, and then make an integral transform, then:

$$\int_0^t \frac{d}{d\tau}\{e^{2\varepsilon\tau}(y^2 + Dx^2)\}d\tau \le \int_0^t \left\{\frac{w_0^2}{2(a-2\varepsilon)}e^{2\varepsilon\tau}\right\}d\tau \tag{16}$$

Hence we have:

$$e^{2\varepsilon t}(y^2 + Dx^2) - (y_0^2 + Dx_0^2) \le \frac{w_0^2}{4\varepsilon(a-2\varepsilon)}(e^{2\varepsilon t} - 1) \tag{17}$$

The both sides of (17) multiply $e^{-2\varepsilon t}$, and let $D = b - \varepsilon(a-\varepsilon)$， then (12）is obtained. (End of the proof)

From above theorem it is easy to see that when a, b_2 and ε are sufficiently large, x will be attracted to a very small domain i.e., limit the despondence of disturbance $w(t)$.

Remark 1: For system (11), let $u = b_2 x + a\dot{x}$ and the disturbance $w(t)$ is bounded then $x(t)$ would be easily suppressed to a very small domain when a, b_2 and ε are sufficiently large. And above result shows that although $w(t)$ is unknown, if $w(t)$ is bounded then the filter control will guarantee $x(t)$ is enough small. Obviously, the suppression harmonics has strong robustness to various kinds of disturbances.

Now we employed *Theorem 1* to design the controller of APF. For (5), let

$$w(t)=\frac{L_2+L_3}{L_2L_3C_1}i_{Lh}+\frac{d^2i_{Lh}}{dt^2}+\frac{L_2+L_3}{L_2L_3}\frac{du_{sh}}{dt}$$

$$u_2=L_3Gi_{sh}+L_3k_2\frac{di_{sk}}{dt} \tag{18}$$

where $G,\ k_2\geq 0$, then (5) is rewritten as:

$$\frac{d^2i_{sh}}{dt^2}=-(G+\frac{L_2+L_3}{L_2L_3C_1})i_{sh}-k_2\frac{di_{sh}}{dt}+w(t) \tag{19}$$

No matter harmonics current or harmonics voltage, their first derivative and their derivatives are bounded functions hence we assume $w(t)$ is bounded, i.e., $|w(t)|<w_0$. From *theorem 1* we know that if k_2 and ($G+(L_2+L_3)/(L_2L_3C_1)$) are selected properly then the i_{sh} will be attracted to a small domain. We take note of $(L_2+L_3)/(L_2L_3C_1)$ being a larger constant from (1) hence we set $G=0$. So the control signal u_2 can be simplified as $u_2=L_3k_2\dfrac{di_{sk}}{dt}$.

C. Control signal u and the AC voltage of inverter u_c

From (9) and (18), the general control signal u is obtained:

$$u=u_1+u_2=-\frac{L_2+L_3}{L_2C_1}(i_s^*-i_{Lb})-L_3\frac{d^2(i_s^*-i_{Lb})}{dt^2}+\frac{L_2+L_3}{L_2}\frac{du_s}{dt}$$
$$-L_3k_1\frac{d(i_s^*-i_{sb})}{dt}+L_3k_2\frac{di_{sh}}{dt} \tag{20}$$

Take note of u being the derivation of u_c, so u_c is the integration of u as follows:

$$u_c=-(L_3-\frac{L_2+L_3}{\omega_1^2L_2C_1})\frac{d(i_s^*-i_{Lb})}{dt}+\frac{L_2+L_3}{L_2}u_{sb}$$
$$-L_3k_1(i_s^*-i_{sb})+L_3k_2i_{sh} \tag{21}$$

Remark 2: Since ($i_s^*-i_{Lb}$) is sine wave hence its derivative is cosine wave, once ($i_s^*-i_{Lb}$) is obtained then its derivation can be derived easily.

IV. Simulation Study

In this work, the MATLAB software is used as the simulation software to test the validity of the proposed control scheme. We assume that the magnitude and initial phase of voltage are invariable, and source voltage is shown as Fig. 4 (a). A typical three-phase rectifier is adopted as the nonlinear load, whose current is shown as Fig. 4 (b).

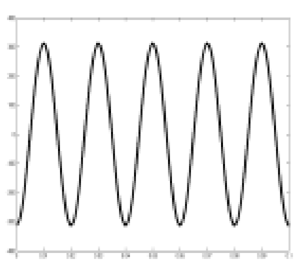

Fig. 4 (a) The source voltage

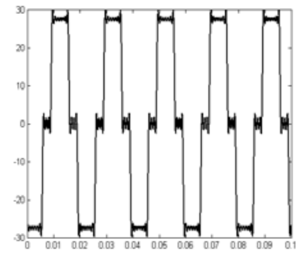

Fig. 4 (b) The current of load

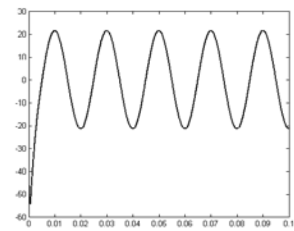

Fig.4 (c) The current in net-side

Parameters of the passive filter and control scheme are selected as $L_2=46.2mH, C_1=110uF,\ L_3=4mH,\ k_1=400$ and $k_2=10000$. The capacity of rectifier load is 15KVA. Two different cases are simulated for typical loads. The typical load is three-phase rectifier parallel with linear inductance. We consider two cases, one is to simulate under common operation condition, and other is to simulate the robustness under changed load abruptly. Fig.4 (c) shows the source current under case 1, which shows the validity of the control scheme. Fig.5 shows the simulation results under case 2. For case 2 Fig. 5(a) shows the current of load, and the source current is shown by Fig. 5(b), which shows the strong robustness of the control scheme.

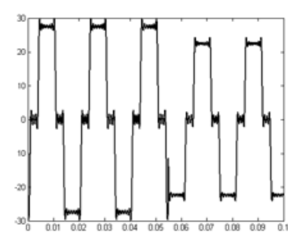

Fig.5 (a) The current of load

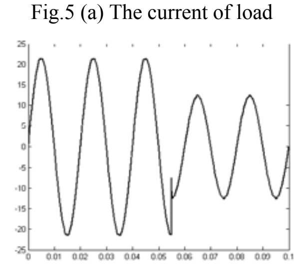

Fig.5 (b) The current in net-side

V. Conclusion

In this work, the second order system state model due to HAPF is built. It is a linear system hence it satisfies superposition principle. So we take different control strategy to treat passive current and harmonic currents. In this paper suppressing harmonics is changed to the robust control problem of linear system. We present a new harmonics suppression method and apply it to HAPF. It possesses strict mathematical foundation and has strong robustness to the disturbances caused by variation of load, parameter perturbations and unmodelled dynamics. The harmonic currents of load and the harmonics of network side voltage are treated as disturbances and needn't be measured, which can simplify the detection of harmonic of signal. We make simulations under common operation condition and abruptly changed load condition. Results show the validity and the performance of the unified compensative method.

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VII. BIOGRAPHIES

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