Passivity-Based Control of the Shunt Active Power Filters

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Abstract

This paper applies the passivity-based control into the active power filters. After simplifying the circuit of the APF, we build the model of it. The voltage of load and the current of supply are considered as the state variables of the system. We take the compensating current as the control variable. Then the control law is performed by passivity theory. Though the theory is complex, the application of the control law obtained by the passivity is very simple. We do simulation with the capacitive load, inductive load and various loads, and the results indicate the very good stability and robustness of the PBC.

I. Introduction

The nonlinear and active loads are used wider and wider, such as motor driver, arc furnace and UPS and so on. These instruments improve the capacity of the control of power energy, but, at the same time, they also produce power pollution. The harmonics and reactive power component of current and unbalance in three-phase system reduce the efficiency of the power system, and they can interfere the communication network nearby. Traditionally, the passive filters, composed of resistors, inductors and capacitors, are used to eliminate the harmonics. As it is known, the passive filters have many disadvantages, for example, the big sizes, fixing frequency and resonance [1]. With the development of power electronics, active power filters are introduced to reduce harmonics current and compensate the reactive component. The main topologies of APF are voltage-source inverters programmed by PWM. The large power solid-state devices as IGBT and GTO are used in active power filter, APF, to improve the power handling of the equipment. Compared with the passive filters and static var compensator, SVC, the APF can be controlled more easily and with better performance [2]. Commonly, the shunt active power filters are considered as a controllable current source which is connected in parallel with the mains. The harmonics and reactive components of the load current is drawn by the APF, so the supply current is sinusoidal with unity power factor, that is, the phases of both supply current and voltage are the same. The control object is to make the output current of APF equal to the harmonics and reactive power component of the load current.

As it is known, energy is a basic concept in both science and engineering. One complex dynamic system could be taken as an energy transformer, so it is able to be divided into many subsystems, which is simpler. The total energy of the subsystems decides the dynamics of the whole system. The passivity approach is a method using the idea of energy. It includes two steps: *energy shaping* and *damping injection*. Energy shaping is to regulate the energy flow of the system as what is desired. The second step is to reform the dynamics of the system. Passivity-based control (PBC) makes the system more robust and simplifies the realization of the controller [3]. Recently, PBC was applied into DC-DC converters [4], UPS [5] and hybrid generators [6] and so on.

When the parameters of the line and load in APF are uncertainty or unknown, the system may be unstable. The conventional compensation method, either load current dictated method, supply current detection method or both, are demonstrated to be able to lead to instability. As a result, the research of the stability of APF system could be important for its wider application. Passivity approach starts from the energy storage in the system. It designs a desired energy storage function with minimum on the desired equilibrium of the system. Thereby if the system is passive, the system will be stable on the equilibrium. Added to this, the robustness of the system is also improved. This paper is based on the load voltage and supply current detection. This paper gives the control law with passivity approach. The results of simulation confirm the theoretical analysis and illustrate advantages of the proposed methodology.

This paper has five parts. The first part is to introduce the theory of passivity briefly; the second one gives the model of APF used in the paper; then the control strategy is analyzed; the simulation results are shown in fourth part; finally, the final part concludes the paper.

II. Brief of passivity

Consider a nonlinear system $G: u(t) \to y(t)$

$$G:\begin{cases} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{cases} \tag{1}$$

The definitions as follows are given.

Definition 2.1 (*Dissipative systems*): The system is said to be *dissipative* with respect to the *supply rate* $s(u,y)$ if there exists a function $V(x) \geq 0$, called the *storage function*, such that the inequality stands for all shapes of the input function *u*:

$$\dot{V} \leq s(u,y)\,, \quad \forall t \geq 0 \tag{2}$$

It expresses the fact that the 'storage energy' $V(x(t))$ of the system G at any future time t is at most equal to the sum of the storage energy $V(x(0))$ at the start time and the total externally supplied energy $\int_0^t s(u,y)dt$ during the time interval $[0,t]$. Hence there can be no internal 'creation of energy' and only internal dissipation of energy is possible. So the inequality of dissipative energy can be written as follow:

$$V(x(t)) \leq V(x(0)) + \int_0^t s(u,y)dt \tag{3}$$

If the supply rate is defined as $s(u,y) = u^{\mathrm{T}} y$, the definitions of passivity and strictly passivity are given.

Definition 2.2 (*Passive systems*): suppose that the system G in (1) is dissipative with supply rate $s(u,y) = u^{\mathrm{T}} y$ and the storage function V with $V(0) = 0$, i.e. for all $t \geq 0$:

$$\dot{V} \leq u^{\mathrm{T}} y \tag{4}$$

Then the system is passive.

Definition 2.3 (*Strictly passive systems*): A system G is said to be strictly passive if it is passive and there exists a positive definition function $Q(x)$ such that for all $t \geq 0$:

$$\dot{V} + Q(x) \leq u^{\mathrm{T}} y \tag{5}$$

III. Formulation of Problem

The generic diagram of the active power filter discussed in the paper is shown as Fig.1. The shunt active power filter is considered as an ideal controllable current source connected in parallel with the main. And the load is represented as a Norton equivalent circuit. So the equivalent circuit of SAPF is shown as Fig.2. The v_s is the supply voltage; Z_s is the impedance of the line, i_s, i_L, i_c is the supply current, load current and compensation current respectively. The current generator i_0 is the purely distorting load of the Norton circuit and the Z_L models the passive parts of load.

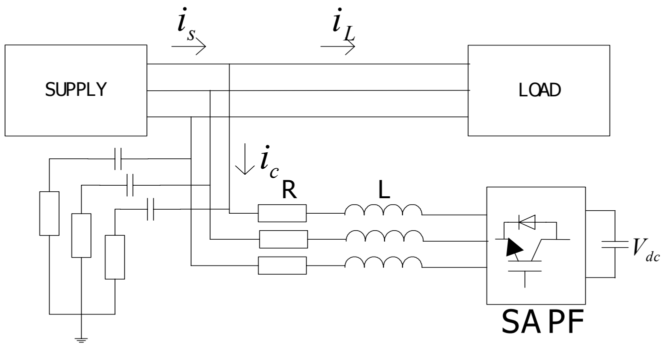


Fig. 1: The principle diagram of SAPF

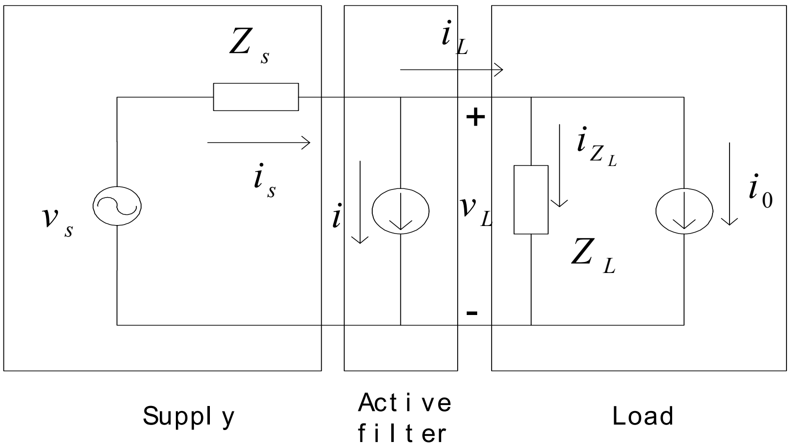


Fig. 2: The equivalent circuit of SAPF

The voltage source inverter is assumed to be driven by a high performance current control, that is, the compensation current i_c can track the reference signal i_c^*, so we only put the focus on how to generate the current references for the active filter current loop. In other words, we concentrate on the compensation strategies.

According to Fig.2, assumed that the impedance is composed of inductor L_s and resistance R_s, the model of the APF is built:

$$\begin{aligned} L_s \frac{d}{dt} i_s &= -R_s i_s - v_L + v_s \\ v_L &= Z_L (i_s - i_c - i_0) \end{aligned} \quad (6)$$

IV. PBC strategy

For the capacitive load, we can rewrite the model of the system:

$$\begin{aligned} L_s \frac{d}{dt} i_s &= -R_s i_s - v_L + v_s \\ C_L \frac{d}{dt} v_L &= -\frac{v_L}{R_L} + i_s - i_c - i_0 \end{aligned} \quad (7)$$

where the C_L and R_L is the equivalent capacitor and resistance of the load respectively. On *d-q* coordinates, the model is:

$$\begin{bmatrix} L_s & 0 & 0 & 0 \\ 0 & L_s & 0 & 0 \\ 0 & 0 & C_L & 0 \\ 0 & 0 & 0 & C_L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{Ld} \\ v_{Ld} \end{bmatrix} = \begin{bmatrix} -R_s & -\varpi L_s & -1 & 0 \\ \varpi L_s & -R_s & 0 & -1 \\ 1 & 0 & -\frac{1}{R_L} & -\varpi C_L \\ 0 & 1 & \varpi C_L & -\frac{1}{R_L} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{Ld} \\ v_{Ld} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} \tag{8}$$

$$+ \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{0d} \\ i_{0q} \end{bmatrix}$$

let $x = \begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{Ld} \\ v_{Ld} \end{bmatrix}, u = \begin{bmatrix} -i_{cd} \\ -i_{cq} \end{bmatrix}, y = \begin{bmatrix} v_{Ld} \\ v_{Lq} \end{bmatrix}$, then

$$\begin{cases} D\dot{x} = (J-R)x + Bu + Ew \\ y = Cx \end{cases} \tag{9}$$

where

$$J = \begin{bmatrix} 0 & -\varpi L_s & -1 & 0 \\ \varpi L_s & 0 & 0 & -1 \\ 1 & 0 & 0 & -\varpi C_L \\ 0 & 1 & \varpi C_L & 0 \end{bmatrix} = -J^{\mathrm{T}} \qquad R = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & \frac{1}{R_L} & 0 \\ 0 & 0 & 0 & \frac{1}{R_L} \end{bmatrix} \qquad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$C^{\mathrm{T}} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} D = \begin{bmatrix} L_s & 0 & 0 & 0 \\ 0 & L_s & 0 & 0 \\ 0 & 0 & C_L & 0 \\ 0 & 0 & 0 & C_L \end{bmatrix} E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} w = \begin{bmatrix} v_{sd} \\ v_{sq} \\ i_{0d} \\ i_{0q} \end{bmatrix}$$

The storage function is defined as

$$V(x) = \frac{1}{2} x^{\mathrm{T}} D x = \frac{1}{2} L_s i_s^{\,2} + \frac{1}{2} C_L v_L^{\,2} \tag{10}$$

Then the passivity of the system can be proved,

$$\dot{V} = -i_s^{\,2} R_s + u^{\mathrm{T}} y + v_s i_s - i_0 v_L - \frac{v_L^{\,2}}{R_L} \tag{11}$$

so the passivity inequality stands:

$$\dot{V} < u^{\mathrm{T}} y \tag{12}$$

The external energy $v_s i_s$ only supplies the energy dissipated in the load. So the system of APF is passive. In accordance with the passivity approach, the control law can be designed. Let $\tilde{i}_s = i_s - i_s^*$, $\tilde{v}_L = v_L - v_L^*$ and i_s^*, v_L^* are the reference signals of the supply current and load voltage respectively. The model of the error is shown as follow:

$$D\dot{\tilde{x}} = (J-R)\tilde{x} + Bu + Ew - (D\dot{x}^* - (J-R)x^*) = (J-R)\tilde{x} + \psi \tag{13}$$

where $\tilde{x} = \begin{bmatrix} \tilde{i}_{sd} \\ \tilde{i}_{sq} \\ \tilde{v}_{Ld} \\ \tilde{v}_{Lq} \end{bmatrix}, x^* = \begin{bmatrix} i^*{}_{sd} \\ i^*{}_{sq} \\ v^*{}_{Ld} \\ v^*{}_{Lq} \end{bmatrix}$,

$\psi = Bu + Ew - (D\dot{x}^* - (J-R)x^*)$. For the error model, the storage function is defined as:

$$V_1(x) = \frac{1}{2}\tilde{x}^{\mathrm{T}} D\tilde{x} = \frac{1}{2}L_s \tilde{i}_s^2 + \frac{1}{2}C_L \tilde{v}_L^2 \quad (14)$$

then

$$\dot{V}_1 = -\tilde{x}^{\mathrm{T}} R\tilde{x} + \psi^{\mathrm{T}}\tilde{x} \quad (15)$$

R, as we know, is positive definite, then if let ψ be the generalized control of the error system, the error system of APF is strictly passive. V_1 taking place of the original storage function V is called energy shaping. From the other side, V_1 can be looked as the Lyaponov function of the system. As a consequence, if we design the control law properly to make $\dot{V}_1 \le 0$, the system is stable asymptotically, that is, $\lim_{t\to\infty} \tilde{x} = 0$. Then we do the damping injection. Let $\psi = K\tilde{x}$, where K is a negative definite matrix. The model of the error system is:

$$D\dot{\tilde{x}} = (J - R + K)\tilde{x} \quad (16)$$

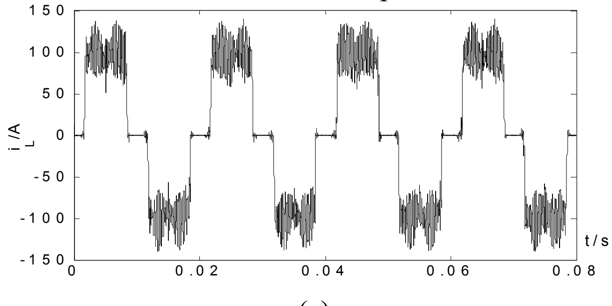
The desire equilibrium point in this control system is the complete elimination of the line current harmonics. Hence the references of the line current are $i_{sd}^* = I_d$, $i_{sq}^* = 0$. We take $I_d = \frac{P}{V_{sd}}$ as the RMS of the supply current, where P is the nominal power of the load. As a result, the active component of current remains and the phase of the supply current is the same as the voltage. Through giving the reference current, we get the reference voltage as $v_{Ld}^* = v_{sd} - I_d R_s$ $v_{Lq}^* = v_{sq} - \varpi L_s I_d$. The desired equilibrium of the system is $\begin{bmatrix} I_d & 0 & v_{Ld}^* & v_{Lq}^* \end{bmatrix}$.

Let $K = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -k & 0 \\ 0 & 0 & 0 & -k \end{bmatrix}$, where k>0, the control law is given as:

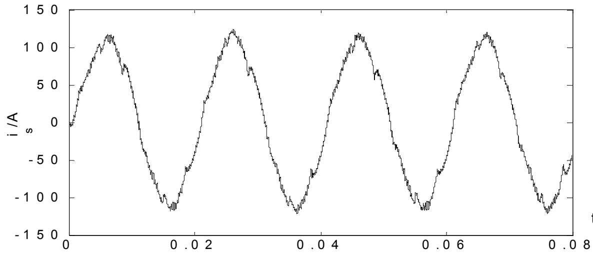
$$\begin{aligned} i_{cd} &= -C_L \dot{v}_{sd} - (\frac{1}{R_L} - k)v_{sd} - \varpi C_L v_{sq} + (\varpi^2 C_L L_s + \frac{R_s}{R_L} + kR_s)I_d - i_{0d} - kv_{Ld} \\ i_{cq} &= -C_L \dot{v}_{sq} - (\frac{1}{R_L} - k)v_{sd} + \varpi C_L v_{sd} + (-\varpi C_L R_s + \frac{\varpi L_s}{R_L} + k\varpi L_s)I_d - i_{0q} - kv_{Lq} \end{aligned} \quad (17)$$

V. Simulation results

The simulations were conducted on SIMULINK of MATLAB. The three loads were tested: capacitive load, inductive load and changeable load, which a capacitive load was added to at 0.04s and cut off at 0.06s. The parameters of the simulation system were chosen as: the impedance of the main is R_s=0.19Ω, L_s=0.22mH; the impedance on the line of active power filter is R_c=0.2Ω, L_c=0.5mH; the DC voltage is 800V; the solid-state devices were used IGBT with 15kHz switch frequency. When the load is capacitive, the power of the load is 15kW. The results of the simulation are shown as Fig. 3. The controller can provide the line current harmonics reduction and stable operation.



(a)



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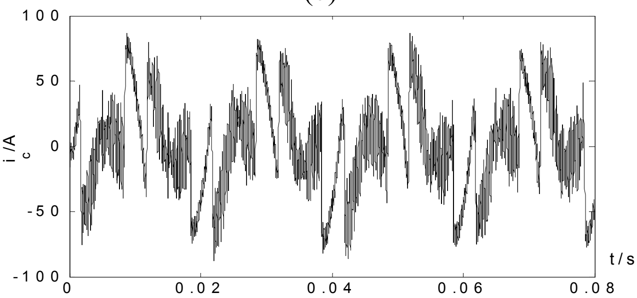
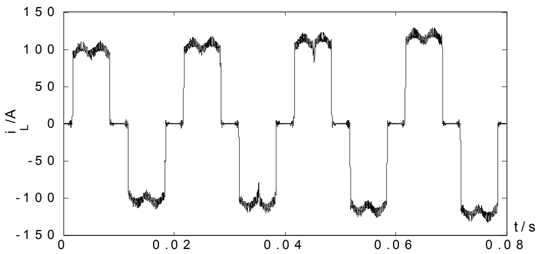
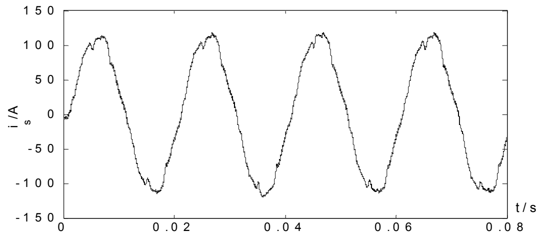


(c)

Fig. 3 The result of simulation of capacitive load (a) The load current (b) the supply current (c) the compensation current



(a)



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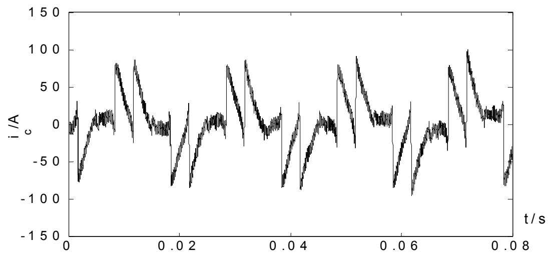
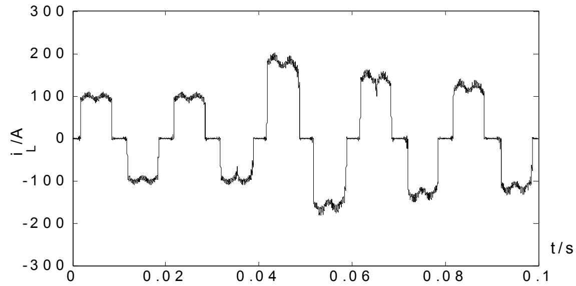


(c)

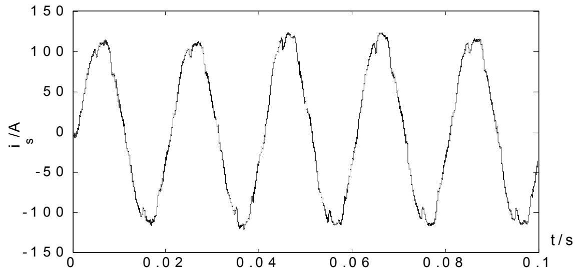
Fig. 4 The result of simulation of inductive load (a) The load current (b) the supply current (c) the compensation current

In order to test the stability, robustness, the load was changed to be inductive in the same power. The parameters of the controller were not revised. The simulation results are shown as Fig.4. In spite of the variation of the load, the steady stability can be guaranteed. It also attests the robustness of the strategy.

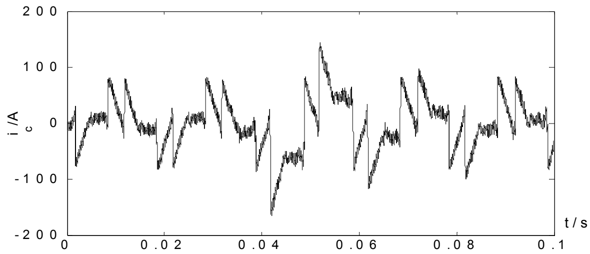
For the sake of testing the dynamic properties, the capacitive load was inserted at 0.04s and separated at 0.06s. The simulation results are presented in Fig. 5.



(a)



(b)



(c)

Fig.5 the result of simulation of various load's (a) The load current (b) the supply current (c) the compensation current

VI. Conclusion

This paper has investigated a passivity-base control for the APF systems. The proposed strategy is intended to eliminate the harmonics and reactive components of the supply current with various loads and uncertain parameters. For simplification, Norton equivalent circuit takes the place of the load .The approach is based the model on *d-q* coordinates. The passivity of the system is stated at the beginning of our design. Compared with the conventional compensation methods, the control by the passivity approach ensures the globe asymptotical stability regardless of the load parameters variations. The robustness and easy realization of the controller is also shown in the results of simulation.

The APF system with passivity approach can compensate the harmonics and reactive parts of various nonlinear loads with good stability and robustness. It represents a positive application of APF.

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