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Shunt Active Power Filter Using Average Power and RLS Self-adaptive Algorithms

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Abstract

Design a Shunt Active Power Filter (SAPF) based on Average Power Algorithm (APA) and Recursive Least Squares (RLS) Self-adaptive Algorithms. Its reference active current is a balanced three-phase current which has the same phase with voltage of power system source. Two components is included in the reference active current. One is the instantaneous active current that should be sent from power system to loads based on APA. The other part, calculated mainly by a filter based on RLS Algorithm, is the instantaneous active current that should be sent to SAPF to maintain the DC-link voltage invariable. Combine these two parts to get the final instantaneous reference active current value. Controlled by the PWM pulse which get by comparing between the reference compensating current and real generating current through current hysteresis regulator, the inverter compensates the reactive power and restrain the harmonics to make there is only fundamental active current in the power system. The results of simulation comparing between RLS and PI control demonstrate the availability, well performance and real-time characteristics of this SAPF.

Keywords – Average power algorithm, Recursive Least Squares(RLS), self-adaptive algorithm, Shunt Active Power Filter(SAPF)

1. INTRODUCTION

Due to more and more nonlinear loading used in the power system, harmonic problems have been serious in industrial and utility power system. Generally, Static Var Compensator (SVC) is used to restrain the harmonics and compensate the reactive current, but recently research on Active Power Filter (APF) has received a good deal of

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attention. As a result, the SAPF, showed in Fig.1, is widely used. APF can raise the power factor as well as improve the quality of power system. One key point of APF's control is to calculate the compensating current reference value from the nonlinear load current [1].

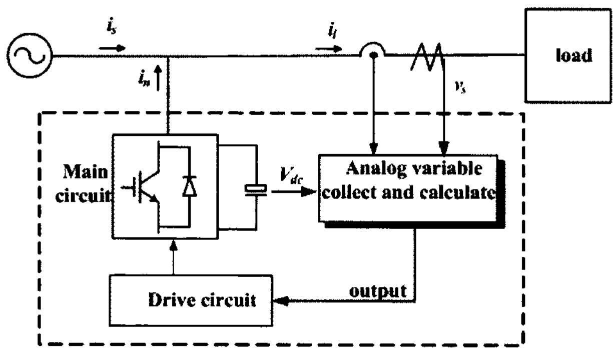


Figure 1. Schematic diagram of SAPF

However, normally the capacity of APF cannot be made very large due to limitations of power electronics devices. Therefore, APF is often used with SVC so as to restrain harmonics and compensate reactive currents better; as Fig.2 and Fig.3 shows.

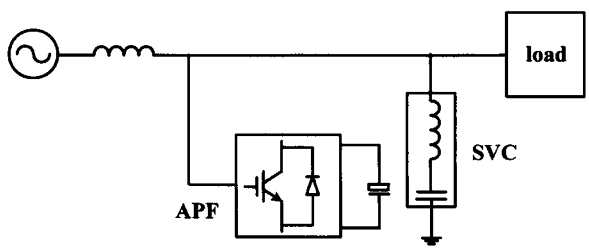


Figure 2. Schematic diagram of PAPF working with SVC

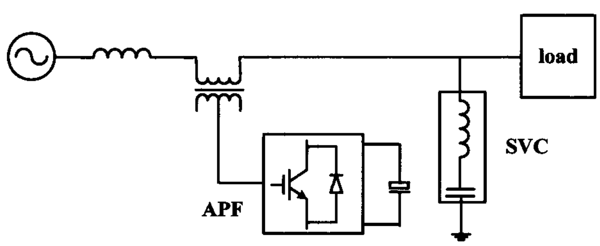


Figure 3. Schematic diagram of SAPF working with SVC

This paper proposes an SAPF model based on APA and RLS Self-adaptive Algorithm. Compared with SAPFs based on Instantaneous Reactive Power Theory and Fourier Transform[2][3], this model needs less calculation and has a good dynamic response.

When system is in steady state or system has a three-phase unbalanced load current, the APA assures calculation of active current reference value. The RLS filter figures out active parameter A_{dc}, which is used to get instantaneous active current reference value to maintain the DC-link voltage. The parameters of PI control are normally sensitive and very difficult to get [4], which leads to more ripples appearing in the system current after compensation. By using A_{dc}, SAPF can overcome these two problems.

When system is in transient state, the DC-link voltage will fluctuate greatly. However, parameter A_{dc}, which is based on good convergence property of RLS filter, can also change rapidly, so this SAPF has a good real-time characteristic.

2. PRIINCIPLE OF THIS SAPF

2.1. Average Power Algorithm using in SAPF

Decompose each phase current into fundamental active current, fundamental reactive current and total distorted current [5], as shown in Fig.4.

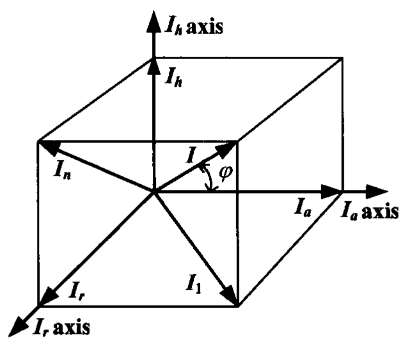


Figure 4. Current coordinate

The following formulas describe their relationship

$$I^2 = I_a^2 + I_r^2 + I_h^2 \tag{1}$$

$$I_n^2 = I_r^2 + I_h^2 \tag{2}$$

$$I^2 = I_a^2 + I_n^2 \tag{3}$$

$$I^2 = I_1^2 + I_h^2 \tag{4}$$

$$I_1^2 = I_a^2 + I_r^2 \tag{5}$$

Where I — the RMS of system current;

I_a — the RMS of fundamental active current;

I_r — the effective value of a reactive current;

I_h — the RMS of distorted current;

I_n — the RMS of compensating current;

I_1 — the RMS of fundamental current.

In one power system cycle time T, each phase voltage RMS V_x, current RMS I_x, active power RMS P_x and apparent output S can be calculated by using instantaneous voltage value $v_x(t)$ and current value $i_x(t)$.

$$V_x = \sqrt{\frac{1}{T}\int_0^T v_x(t)v_x(t)\mathrm{d}t} \tag{6}$$

$$I_x = \sqrt{\frac{1}{T}\int_0^T i_x(t)i_x(t)\mathrm{d}t} \tag{7}$$

$$P_x = \frac{1}{T}\int_0^T v_x(t)i_x(t)\mathrm{d}t \tag{8}$$

$$S = V_x I_x \tag{9}$$

Subscript x denotes phase A, B or C of system.

Considering unbalanced three-phase load, define the fundamental active parameter A_{ax} based on APA as following

$$A_{ax} = P_A + P_B + P_C / 3V_x^2 = P_{aver} / V_x^2 \tag{10}$$

So the RMS of each phase fundamental active current can be calculated by

$$I_{ax} = A_{ax} V_x \tag{11}$$

2.2. RLS Algorithm using in SAPF

According to the features that species can make various bio-effective ways to meet the strong vitality of the living environment, people summarize the concept of self-adaptive characteristics. In 1960s, Hoff and B.Windrow in United States started the development of adaptive filter and for the first time they using self-adaptive algorithms in a signal-processing filter. The self-adaptive filter uses the parameters that have been obtained a moment ago to adjust automatically filter parameters in a pattern of real-time. The filter can consequently get rid of the unknown signal and noise characteristics of the statistical changes over time, and finally achieves optimal filtering.

Filters with fixed parameters use its own transmission characteristics to suppress the interference signal and its effect would be largely restricted. However, it is not necessary for the self-adaptive filter to know in advance the function of signal and noise correlation in the filtering process; the self-adaptive filter automatically adapts to adjust even if the function changes slowly over time.

The self-adaptive filter developed rapidly soon after it was proposed. Due to its good performance and simple design, self- adaptive active filter has been a hot topic of digital filter.

The self-adaptive filter includes a recursive-least-square (RLS) filter, a minimum mean-square (LMS) filter and an infinite impulse response (IIR) filter. RLS adaptive filter is simple and good performance.

Assume that data $x(1)$ ..., $x(i)$, ..., $x(n)$ have been known, and the signal $y(1)$ ..., $y(i)$, ..., $y(n)$ which needed(del) can be got by m rank RLS filter. The principle diagram of m rank RLS filter is shown in Fig.5.

RLS algorithm in self-adaptive algorithm recently gets more and more application because of its simplicity and fast convergence. With RLS algorithm, it is very easy to filter noise, adjust parameters automatically and finally get the signal needed.

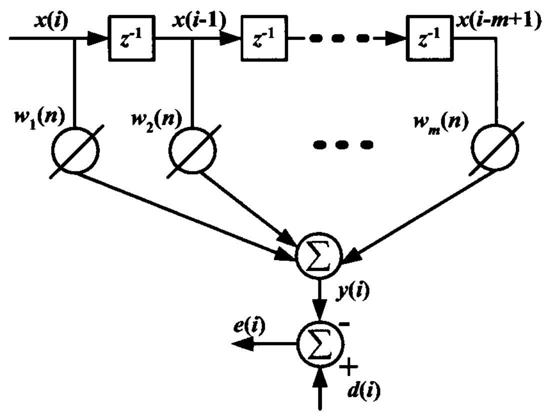


Figure 5. Principle diagram of m rank RLS filter

When system is in steady state, the active power offered by power system is equal to active power needed by load, so there is no active current flowing through the SAPF. DC-link voltage is fixed and its waveform has six ripples in one cycle under this case. If transient state happens in power system because of the load variation, capacitor in the DC-link will offer the active power difference between power system gives and load needs. This case will lead to fluctuation of DC-link voltage [6].

To keep DC-link voltage constant and weaken the ripples in the waveform, SAPF uses RLS filter to get the DC-link active current parameter A_{dcx} for each phase.

Through the parameter A_{dcx}, the SAPF obtains the instantaneous active current value, which can compensate the power loss of inverter itself and active power difference between power system gives and load needed. The working flow chart of RLS filter is shown in Fig. 6 [7, 8]. In Fig. 6 V_{ref} is reference value of DC-link voltage, $V_{dc}(i)$ is instantaneous sampling value of DC-link voltage.

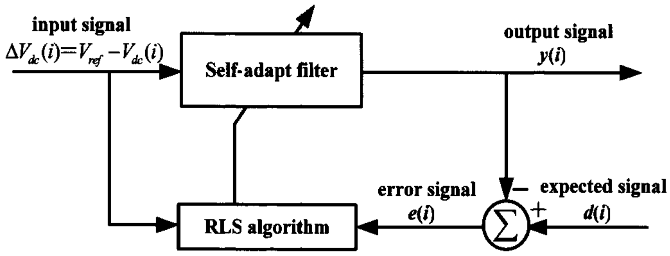


Figure 6. Flow chart of RLS filter

To weaken the sixth ripples of DC-link voltage, define the expecting signal $d(i)$ as

$$d(i) = \pm\sqrt{\frac{3}{T}\int_0^{\frac{T}{3}} \Delta V_{dc}(i)\Delta V_{dc}(i)\mathrm{d}i} \tag{12}$$

If the mean value of $\Delta V_{dc}(i)$ is negative during T/3, $d(i)$ will be negative. The target formula of RLS is

$$\underset{\omega_m(n)}{\mathrm{Min}}\left\{\xi(n) = \sum_{i=1}^{n} \lambda^{n-i} e^2(i)\right\} \tag{13}$$

Where λ in (9) is forgetting factor and λ=0.98. RLS filter needs to calculate the matrix value of $\omega_m(n)$ to assure $\xi(n)$ has the minimum value. The exponent number of RLS filter is m=3.

Define output signal $y(i)$ as

$$y(i) = \sum_{k=1}^{m} w_k(n)\Delta V_{dc}(i-k+1) \tag{14}$$

Where $w_k(n)$ is weight value of input signal.

The error signal $e(i)$ is defined as

$$e(i) = d(i) - y(i) = d(i) - \Delta V_{dcm}^{T}(i) w_m(n) \tag{15}$$

Where

$$w_m(n) = [w_1(n), w_2(n)\ \cdots,\ w_m(n)]^T$$

$$\Delta V_{dcm}(i) = [\Delta V_{dc}(i),\ \cdots,\ \Delta V_{dc}(i-m+1)]^T$$

The function help to refresh $w_m(n)$ is

$$\boldsymbol{w}_m(n) = \boldsymbol{w}_m(n-1) + \boldsymbol{g}_m(n)\boldsymbol{e}^*(n) \tag{16}$$

Where

$$\boldsymbol{e}^*(n) = \boldsymbol{d}(n) - \Delta\boldsymbol{V}_{dcm}^T(n)\boldsymbol{w}_m(n-1) \tag{17}$$

$$\boldsymbol{g}_m(n) = \boldsymbol{C}_m(n-1)\Delta\boldsymbol{V}_{dcm}(n)/(\lambda + \boldsymbol{\mu}(n)) \tag{18}$$

$$\boldsymbol{\mu}(n) = \Delta\boldsymbol{V}_{dcm}^T(n)\boldsymbol{C}_m(n-1)\Delta\boldsymbol{V}_{dcm}(n) \tag{19}$$

$$\boldsymbol{C}_m(n) = \lambda^{-1}\left[\boldsymbol{C}_m(n-1) - \boldsymbol{g}_m(n)\Delta\boldsymbol{V}_{dcm}^T(n)\boldsymbol{C}_m(n-1)\right] \tag{20}$$

Where $\boldsymbol{g}_m(n)$ is the weight refresh matrix by using equations (19) and (20) to get. $\boldsymbol{e}^*(n)$ is the pre-estimate value to $\boldsymbol{d}(n)$ according to known $\boldsymbol{w}_m(n\text{-}1)$ and input value $\Delta\boldsymbol{V}_{dcm}^T(n)$. Set $\boldsymbol{w}_m(0)$=0 and $\boldsymbol{C}_m(0)$=1000 as the initial value.

To maintain the DC-link voltage, instantaneous active power needed by capacitor is

$$P_{dc}(i) = [(V_{ref} + y(i))^2 - V_{ref}^{\ 2}] * C / 2 \tag{21}$$

Where C is the value of DC-link capacitor.

So define A_{dcx} as

$$A_{dcx} = P_{dc}(i) / V_x^2 \tag{22}$$

2.3. Calculate the compensating current

Using equations (10) and (22), finally define the total active parameter A_x as

$$A_x = A_{ax} + A_{dcx} \tag{23}$$

According to equations (1), (2) and (3), the relationship between instantaneous current of each phase can be denoted as

$$i_x(t) = i_{ax}(t) + i_{nx}(t) \tag{24}$$

$$i_{nx}(t) = i_{rx}(t) + i_{hx}(t) \tag{25}$$

In power system, generally think there is no harmonics in source voltage, so instantaneous voltage can be expressed as

$$v_x(t) = v_{ax}(t) \tag{26}$$

According to equations (11), (23) and (26), get instantaneous reference fundamental active current for each phase as

$$i_{ax}(t) = A_x v_x(t) \tag{27}$$

Finally the instantaneous compensating current value reference is

$$i_{nx}(t) = i_x(t) - i_{ax}(t) \tag{28}$$

3. CONSTRUCTION AND SIMULATION OF SAPF SYSTEM

DSP TMS320F2812 is used as the processor of this SAPF. The control system of SAPF is shown in Fig. 7.

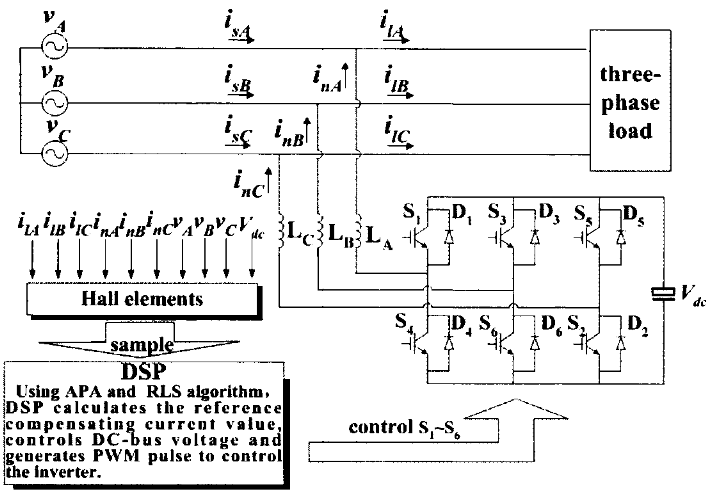


Figure 7. Control system of SAPF

According to its high speed (about 150MIPS), DSP can control the SAPF in real-time mode. IGBT is used as the power devices for the inverter. RLS filter can be built in the software very easy basing on the good filtering characters of DSP. PWM pulses that output by DSP directly drive the SAPF to finish the active power filtering.

The system is simulated by the well known software Simulink[9-11]. Chart of simulation system is shown in Fig. 8. There are four important modules in this simulation system, measure module, calculating module, compensating current generating module and load module. The "Average Power and RLS Algorithm" module is just the calculating module in Fig. 8. Fig. 9 is the detail chart of calculating module. In this core module, SAPF calculates parameters P_x, V_x, A_{ax}, A_{dcx}, A_x and finally gets the instantaneous reference fundamental active current value. Compensating current generating module produces PWM pulse to drive the inverter by comparing the compensating current reference with real generating current through current hysteresis regulator. Fig. 10 is the Detail chart of current hysteresis regulator.

Table 1 gives the Parameters of simulation system [12][13].

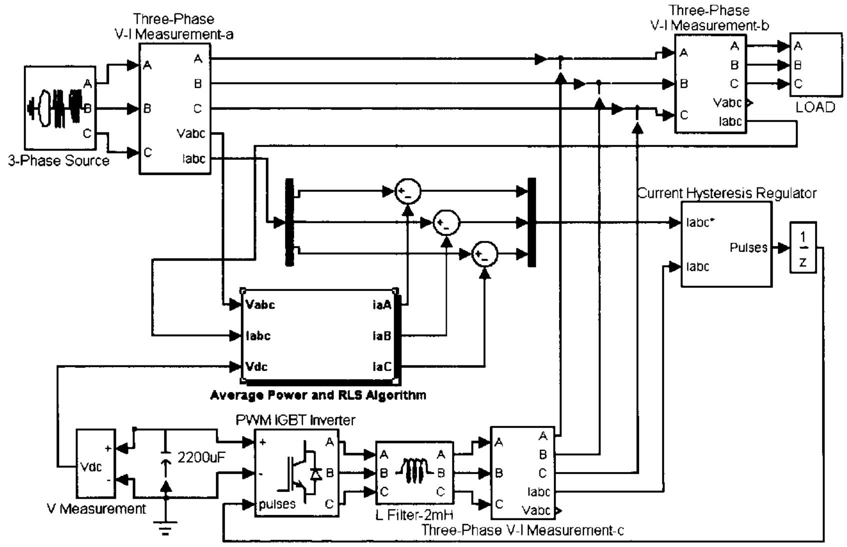


Figure 8. Simulation system made by Simulink

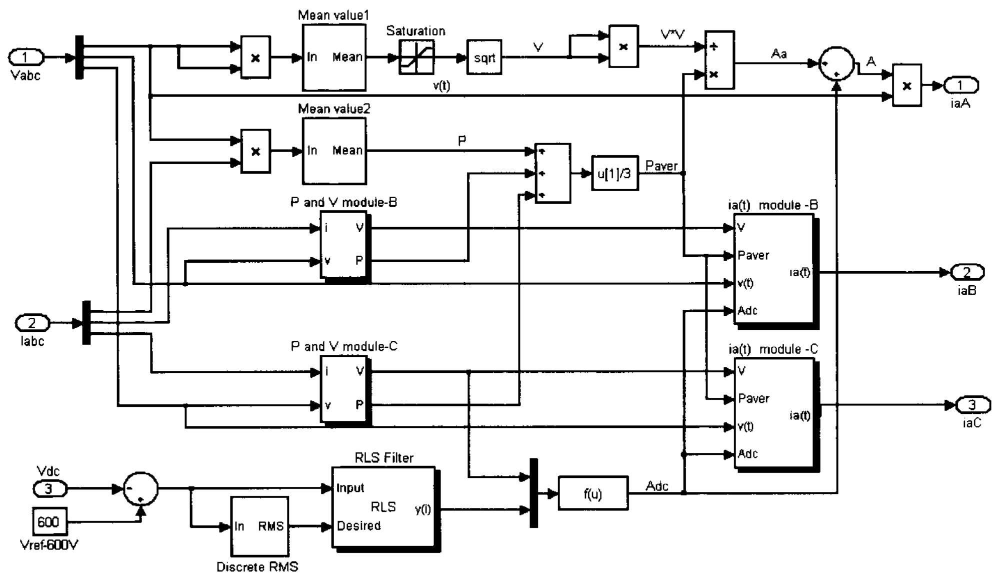


Figure 9. Detail chart of calculating module

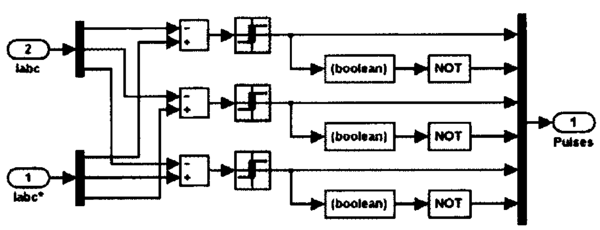


Figure 10. Detail chart of current hysteresis regulator

Table 1. Parameters of simulation system

Phase voltage (RMS) V /V	220
Power source Frequency f /Hz	50
DC capacitor C/ μF	2200
Reference value of DC-link voltage V_{ref} /V	600
AC inductor L /mH	2
IGBT switching frequency f_c /kHz	10

4. RESULT AND ANALYSIS OF SIMULATION

To demonstrate the availability of this SAPF system, this system is tested in three case of load [14, 15].

In the first two cases, the results of simulation using PI regulator to control the DC-link voltage are also given in this paper. Compared with PI control, the RLS has a better performance and real-time characteristics.

4.1. Simulating under balanced three-phase load current

Amplitude of power source voltage of each phase is equal and the nonlinear load is a three-phase diode rectification circuit with resistance and inductor. Fig.11 is the diagram of balanced three-phase load.

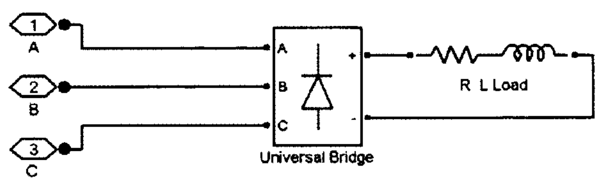
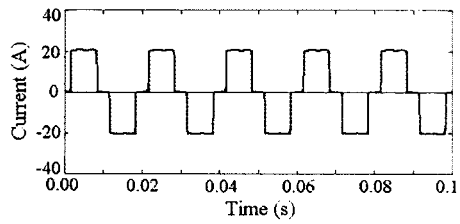
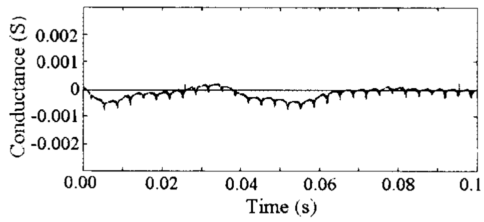


Figure 11. Diagram of balanced three-phase load

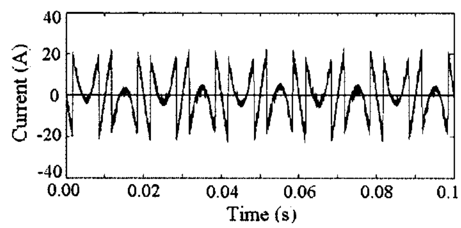
Fig. 12(a), (b), (c), (d) and (e) show the waveforms referred to phase A, DC-link voltage and A_{dcA} under APA and RLS filter control; (f) and (g) show the waveforms referred to phase A, DC-link voltage under APA and PI control. Notice that the line current of phase A in (c) is nearly sinusoidal after compensation from Fig. 12. The SAPF has been able to suppress all the load current harmonics. When system is in steady state, the DC-link voltage is approximately maintained constant with visible weak sixth ripples and A_{dcA} is nearly equal to zero in (d). Comparing APA with RLS filter control, there are more harmonics in (f) after compensation and in DC-link voltage fluctuates more greatly in PI control. So this SAPF exhibits better performance for filtering harmonics and reactive current (g).



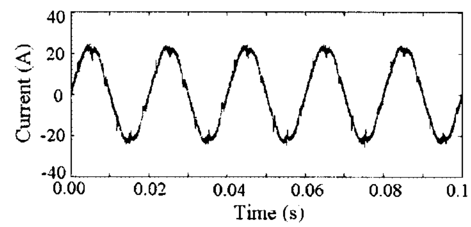
(a) Load current i_{lA}



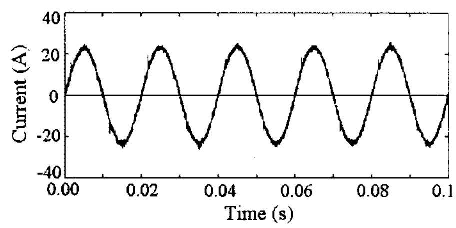
(e) DC-link active parameter A_{dcA}



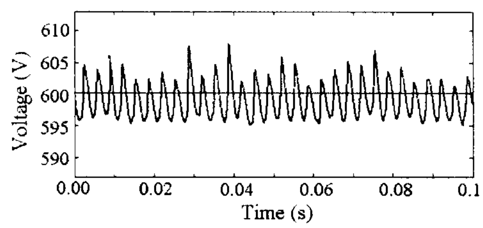
(b) Compensating current i_{nA}



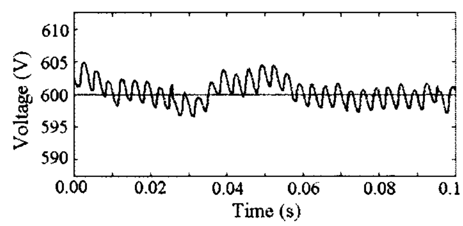
(f) Line current i_{sA} after compensation under PI control



(c) Line current i_{sA} after compensation



(g) DC-link voltage V_{dc} under PI control



(d) DC-link voltage V_{dc}

Figure 12. Waveforms under balanced nonlinear load

4.2. Simulating under balanced variable three-phase load current

Amplitude of power source voltage and nonlinear load are same to the case 1. A sudden load variation occurs at 0.04s. Fig. 13 is the diagram of balanced three-phase load.

Fig. 14 (a), (b), (c), (d) and (e) show the performance waveforms referred to phase A, DC-link voltage and A_{dcA} under APA and RLS filter control; (e) and (f) show the waveforms referred to phase A, DC-link voltage under APA and PI control. From Fig. 14

notice that the line current of phase A is nearly sinusoidal after compensating and when a sudden variation in the load occurs at 0.04s, A_{dcA} can track with V_{dc} very quickly based on the good convergence property of algorithm. Thus SAPF can recover V_{dc} to the reference value in very short time. SAPF exhibits good dynamic response within a half period of the fundamental frequency (10 ms).

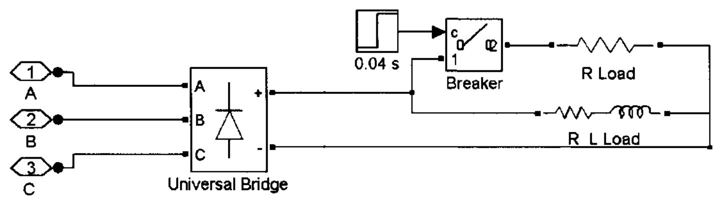
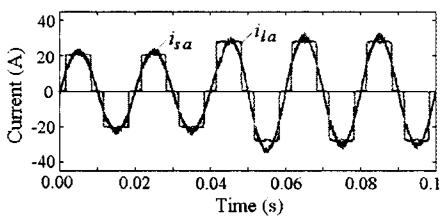
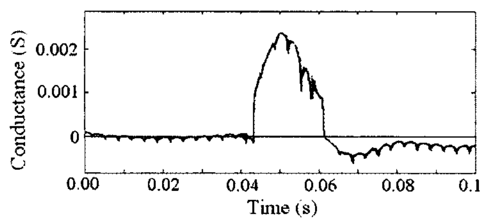


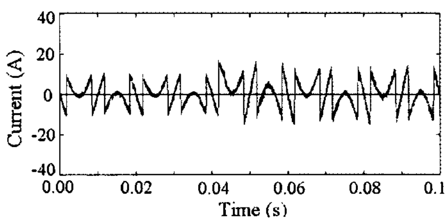
Figure 13. Diagram of balanced variational three-phase load



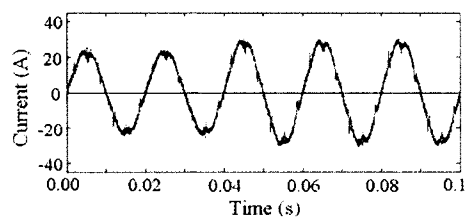
(a) Line Current i_{sA} after compensation and load i_{lA}



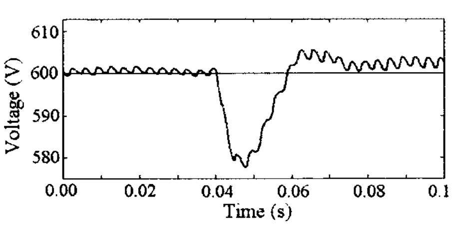
(d) DC-link active parameter A_{dcA}



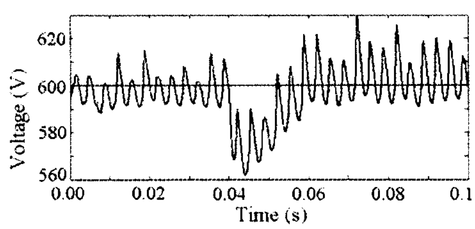
(b) Compensating Current i_{nA}



(e) Line Current i_{sA} after compensation under PI control



(c) DC-link voltage V_{dc}



(f) DC-link voltage V_{dc} under PI control

Figure 14. Waveforms under balanced variational nonlinear load

Comparing APA with RLS filter control, there are more harmonics in (f) after compensation and in (g) DC-link voltage fluctuates more greatly in PI control.

4.3. Simulating under unbalanced three-phase load current

Amplitude of power source voltage of each phase is equal to each other. Fig. 15 is the diagram of unbalanced three-phase load.

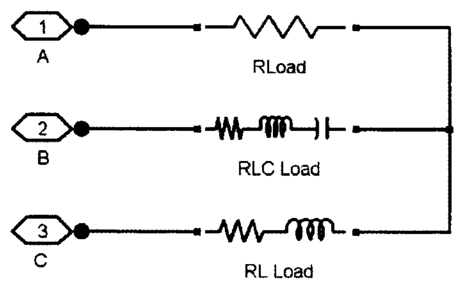
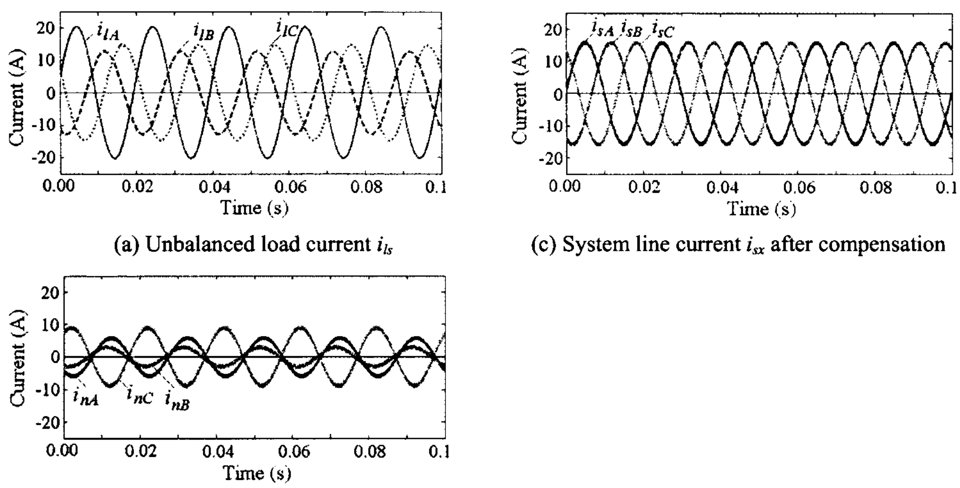


Figure 15. Diagram of unbalanced three-phase load

The waveforms of three-phase currents under this condition are shown in Fig. 16. Three-phase loads connect as Y shape and the neutral point does not connect to the ground. Load of phase A is resistance; loads of phase B and C are both resistance and inductor. Due to the unbalanced load of three- phase, line current of each phase has large difference both in amplitude and phase degree. But by using the APA, considering the total balance of energy, SAPF makes three-phase line current balanced again finally with a good performance. The waveforms of V_{dc} and A_{dcx} are elided because they are almost same to the waveform in steady state in Fig. 16.



(a) Unbalanced load current i_{ls}

(c) System line current i_{sx} after compensation

(b) Compensating current i_{nx}

Figure 16. Waveforms under unbalanced nonlinear load

5. CONCLUSIONS

SAPF based on Average Power and RLS Algorithms has been proposed, analysed and simulated in this paper. Its function is to compensate for harmonics, reactive power and unbalanced current of nonlinear three-phase loads.

Normally SAPF is designed base on PI control, but its parameters are too sensitive so that it is very difficult to erase voltage ripple in the DC-link. By using A_{dcx} to control DC-link voltage, SAPF based on the RLS algorithm maintain a constant DC-link voltage. When system is in steady state, DC-link voltage is maintained to a fixed value with very little sixth ripples of voltage waveform. When transient state happens in power system because of the load variation, capacitor in the DC-link will offer active power difference between power system gives and loads needed caused by rapid feedback to the calculation of direct current. Through the parameter A_{dcx}, the SAPF obtains the instantaneous active current value that can compensate the power loss of inverter itself and active power difference between power system gives and load needed. Although this SAPF has a work cycle delay, its algorithms are easier and its construction is simpler.

MATLAB/Simulink software builds a simulation model of the entire system. Simulation results show that the method is feasible and real-time. The superior performance and the good dynamic response of this SAPF have been assured by simulation results, but to realize this SAPF there is still a lot of experimental research to do in the future.

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