A SHUNT ACTIVE POWER FILTER CONTROL FOR UNBALANCED CONDITIONS

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ABSTRACT

This paper first presents a simple control technique for active filters to compensate current harmonics and reactive power of nonlinear loads. This method is usable for both single –phase and three –phase systems. Then a new method for load balancing and reactive power compensation for unbalanced sinusoidal load currents is presented. Finally by combination of two methods an active filter control method for eliminating load current harmonics and reactive power compensation is achieved. Simulation results demonstrate the feasibility of proposed methods. Suggested method is expected to be used in future for active filter designs produced for load compensation.

I. INTRODUCTION

Modern power-electronic devices have been widely used in power system applications. Devices such as rectifiers, inverters and cycloconverters lead to non-linear current wave forms. These nonlinear loads degrade electric power quality, the quality degradation leads to low power factor, low efficiency, overheating of transformers and so on. The active power filter appears to be a proper solution for reactive power compensation, load balancing as well as for eliminating current harmonics. The concept of using active power filters proposed more than two decades ago, since then, the theories and applications of active power filters have become more popular and have attracted a great attention. In recent years different methods for active power filter control is presented which each of them have their special applications.

In this paper a useful method is proposed for reactive and harmonic current compensation and load balancing. The control method have two separately sections, one for harmonic current compensation and another for load balancing and reactive current compensation. Simulation results for each of control methods are presented. Both single-phase and three-phase systems are simulated. Simulation has been carried on to show active filter performance under highly polluting load operation.

II. HARMONIC COMPENSATION CONTROL METHOD

Fig.1 shows basic compensation principle of shunt active power filter.

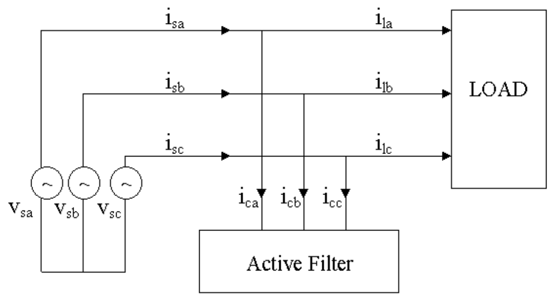

Figure 1. System configuration.

In first control method it is desired that ac mains feed only fundamental active power to the nonlinear load while the active filter supplies the harmonics of the load. Therefore, desired three-phase supply currents must be close to sinusoidal and be in phase with the supply voltages. Now, if desired currents substracted from load currents active filter's reference currents are easily obtained [1]. The system is considered three-phase, three-wire system. Then, the three-phase distorted load currents can respectively be represented by [2]

$$i_{La} = \sum_{m=1}^{\infty} I_m Sin(m\omega t + \phi_m) \quad (1)$$

$$i_{Lb} = \sum_{m=1}^{\infty} I_m Sin\left[m(\omega t - \frac{2\pi}{3}) + \phi_m \right] \quad (2)$$

$$i_{Lc} = \sum_{m=1}^{\infty} I_m Sin\left[m(\omega t + \frac{2\pi}{3}) + \phi_m \right] \quad (3)$$

By multiplication of i_{La} respectively by $\sin(\omega t)$ and $\cos(\omega t)$ and by using trigonometric equations the following equations are obtained:

$$i_{La}\sin\omega t = \frac{I_1}{2}\cos\phi_1 + [-\frac{I_1}{2}\cos(2\omega t+\phi_1) + \frac{I_2}{2}\cos(\omega t+\phi_2) - \frac{I_2}{2}\cos(3\omega t+\phi_2) + ...] \quad (4)$$

$$i_{La}Cos\omega t = \frac{I_1}{2}Sin\phi_1 + [\frac{I_1}{2}Sin(2\omega t+\phi_1) + \frac{I_2}{2}Sin(\omega t+\phi_2) + \frac{I_2}{2}Sin(3\omega t+\phi_2) + ...] \quad (5)$$

The DC Components of above equations can be obtained by low pass filter, and then I_1 can be obtained from the following equation:

$$\frac{I_1^{\,2}}{2}Cos\phi_1^{\,2} + \frac{I_1^{\,2}}{2}Sin\phi_1^{\,2} = \frac{I_1^2}{2} \quad (6)$$

Where I_1 is the amplitude of fundamental load current. For second step, the three-phase source voltage unit vectors are computed. Multiplication of unit vectors of three-phase source voltage (u_{sa},u_{sb},u_{sc}) with amplitude of the reference supply current I_1 results in three-phase desired supply currents $(i^*_{sa}, i^*_{sb}, i^*_{sc})$.

The amplitude of supply voltages is computed from three-phase supply voltages (v_{sa}, v_{sb}, v_{sc}) as [3]:

$$v_m = \left[\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)\right]^{\frac{1}{2}} \quad (7)$$

The unit vectors of three-phase source voltages are computed as:

$$u_{sa} = \frac{v_{sa}}{v_m},\; u_{sb} = \frac{v_{sb}}{v_m},\; u_{sc} = \frac{v_{sc}}{v_m} \quad (8)$$

Finally $i^*{}_{sa}, i^*{}_{sb}, i^*{}_{sc}$ can be obtained using:

$$i_{Sa}{}^* = I_1 u_{sa},\; i^*_{Sb} = I_1 u_{sb},\; i^*_{sc} = I_1 u_{sc} \quad (9)$$

The reference currents of active filter are computed as

$$\begin{aligned} i^*_{ca} &= i^*_{sa} - i_{La} \\ i^*_{cb} &= i^*_{sb} - i_{Lb} \\ i^*_{cc} &= i^*_{sc} - i_{Lc} \end{aligned} \quad (10)$$

III. THE LOAD BALANCING AND REACTIVE POWER COMPENSATION CONTROL METHOD

For three-phase voltages, the instantaneous α, β, and 0 transformation is as (11):

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (11)$$

Also, in three-phase unbalanced source supplies, the relation between voltage phasors (v_a, v_b, v_c) and symmetrical components for those phasors in steady – state condition are given by (12):

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} v_0 \\ v_+ \\ v_- \end{bmatrix} \quad (12)$$

Where $a = e^{j\frac{2\pi}{3}}$, and 0, +, - represent zero, positive and negative sequence respectively. Using Eq. (11) and (12), the following equations are obtained [4]

$$\begin{aligned} v_\alpha &= \sqrt{3}V_+ Sin(\omega t+\phi_+) + \sqrt{3}V_- Sin(\omega t+\phi_-) \\ v_\beta &= -\sqrt{3}V_+ Cos(\omega t+\phi_+) + \sqrt{3}V_- Cos(\omega t+\phi_-) \\ v_o &= -\sqrt{6}V_0 Sin(\omega t+\phi_o) \end{aligned} \quad (13)$$

In the balanced three-phase three-wire case, it can be seen that the voltage has just a positive sequence component and the trajectory in the $\alpha\beta$ plane is a circle (negative and zero sequences are zero).

$$\begin{aligned} v_\alpha &= \sqrt{3}V_+ Sin(\omega t+\phi_+) \\ v_\beta &= -\sqrt{3}V_+ Cos(\omega t+\phi_+) \end{aligned} \quad (14)$$

Using above equations it is possible getting Eq. (15) as

$$v_\alpha^2 + v_\beta^2 = 3V_+^2 \quad (15)$$

If load currents is forced to follow a circular path, namely

$$i_{s\alpha}^2 + i_{s\beta}^2 = 3I_+^2 \quad (16)$$

Then there will be no negative or zero sequence currents. The I_+ stands for rms value of the load current's positive sequence component. The method of calculation of i_+ is presented by [2]. By assumption:

$$\begin{aligned} i_+ &= \sqrt{2}\, I_+ Sin\omega t \\ i_+^2 &= 2I_+^2 Sin^2\omega t = 2I_+^2(\frac{1-Cos2\omega t}{2}) \end{aligned} \quad (17)$$

then by using of a LPF I_+^2 is achieved and I_+ can be calculated easily. On the other hand for unit power factor, source current must be in phase with source voltage, in other words, the vector slope of v_s and i_s must be equal:

$$\frac{v_\alpha}{v_\beta} = \frac{i_{s\alpha}}{i_{s\beta}} \quad (18)$$

Equations (16) and (18) can be rewritten as follows:

$$(i_{L\alpha} + i_{c\alpha})^2 + (i_{L\beta} + i_{c\beta})^2 = 3I_+^2 \quad (19)$$

$$\frac{i_{L\alpha} + i_{c\alpha}}{i_{L\beta} + i_{c\beta}} = \frac{v_\alpha}{v_\beta} \quad (20)$$

From (19) and (20) $i_{c\alpha}, i_{c\beta}$ can be obtained as:

$$i_{c\alpha} = \sqrt{\frac{3v_\alpha^2}{v_\alpha^2 + v_\beta^2}} I_+ - i_{L\alpha}$$
$$i_{c\beta} = \sqrt{\frac{3v_\beta^2}{v_\alpha^2 + v_\beta^2}} I_+ - i_{L\beta} \quad (21)$$

i_{ca}, i_{cb}, i_{cc} can be obtained from reverse transformation.
By combination of this control method by control method presented in section 2 final control method is achieved. This control method has two steps. Since in control method presented in section 2 the load current's fundamental component of each phase can be calculated separately, for unbalanced nonlinear loads, in first step with the harmonic compensation method current's fundamental component of each phase calculated separately, which results in the three unbalanced sinusoidal currents. In second step by applying the load balancing and reactive power compensation control method to this unbalanced sinusoidal currents three balanced sinusoidal currents are obtained. The total active filter's reference current is computed as the sum of reference currents of two control methods.

IV. SIMULATION RESULTS

The operation of an active filter using proposed control method is simulated using Matlab Simulink Software. Fig 1 shows the power circuit of simulated system. The source consist of a three-phase 220V (rms), 50 Hz utility. The active power filter comprises of three-phase voltage source inverter bridge isolated with unity turns ratio transformers from utility. A hysteresis rule based carrierless PWM current controller is used to derive gating signals.

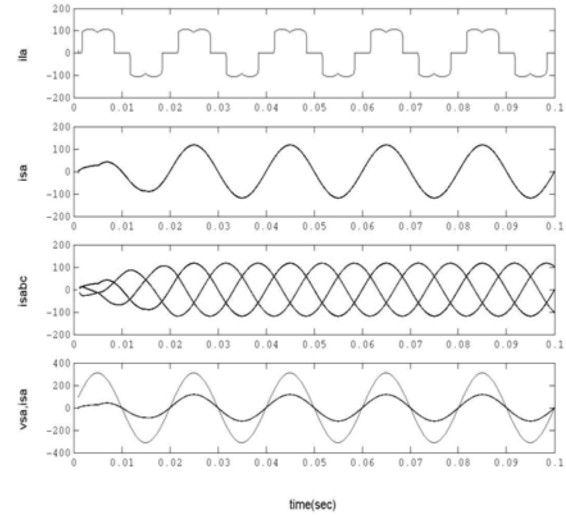

Figure 2. (a) Load current, (b) Source current, (c) Three-phase source current, (d) Source current and voltage.

For first control method the load consist of a three-phase rectifier with R-L load (R=5 Ω, L=5mH). Fig. (2) shows the simulation results. For single-phase case a single-phase rectifier with R-L load considered (R=3 Ω, L=5mH). Simulation results are shown in Fig. (3). As shown in above figures load current harmonics are eliminated and source currents are sinusoidal and in-phase with utility voltages.

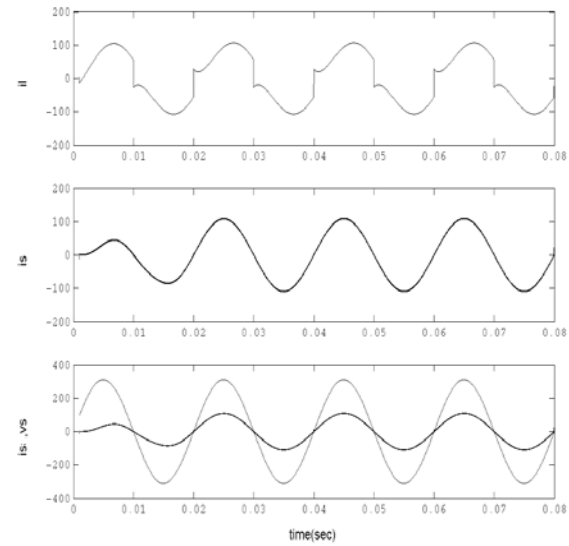

Figure 3. (a) Load current, (b) Source current, (c) Source current and voltage.

For simulation of control method represented in section 3, a three-phase unbalanced R-L load is considered.
In this simulation we have: R_a=10 Ω , L_a = .02 mH, R_b =18 Ω, L_b=.05 mH, R_c = 15 Ω, L_c=.1 mH.
The simulation results are shown in Fig. (4). By this control method source side currents are balanced and in phase with source voltages. In Fig.4(c), (d) i_{la} and i_{sa} are multiplied by 12 for better comparing with v_{sa}.

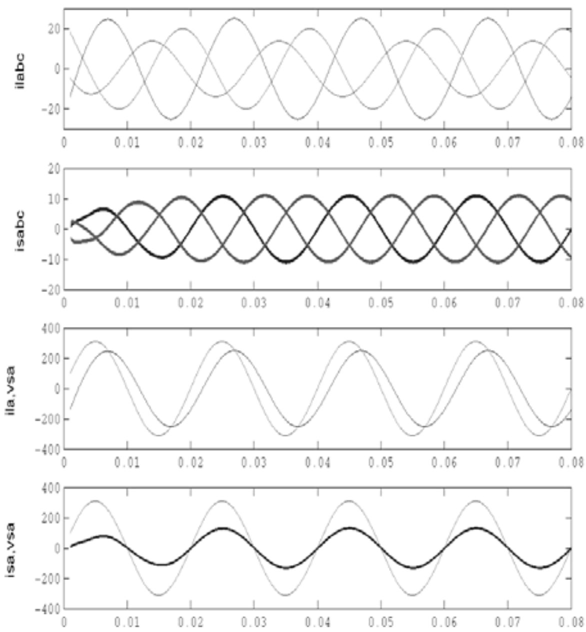

Figure 4. (a) Three-phase load currents,
(b) Three-phase source currents,
(c) load current and source voltage,
(d) source current and voltage.

For final control method a three-phase rectifier in parallel with a three-phase unbalanced R-L load is considered (R=20 Ω , L=2mH) , (R_a=50 Ω , L_a = 12mH , R_b=20 Ω , L_b=2.5mH , R_c=100 Ω , L_c=27mH). Simulation results are shown in Fig. (5), (6). In Fig.5(c) i_{sa} is multiplied by 2.5 for better comparing with v_{sa}. As shown in above figures, simulation results verify correct operation of proposed control method.

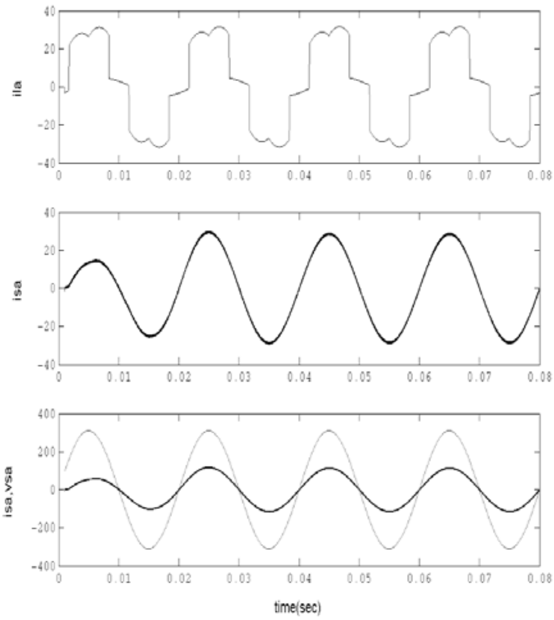

Figure 5. (a) Load current, (b) Source current,
(c) Source current and voltage.

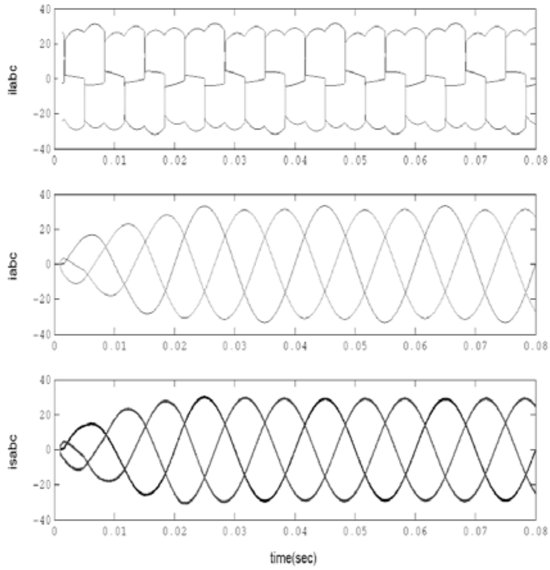

Figure 6. (a) Three-phase load currents,
(b) Three-phase sinusoidal unbalanced currents,
(c) Three-phase source currents.

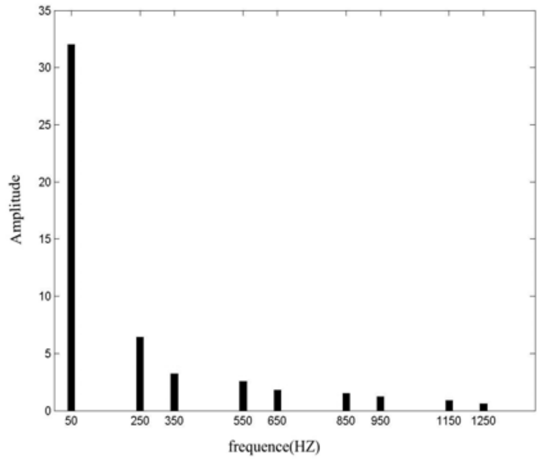

Figure 7. Harmonic spectrums of phase a load current.

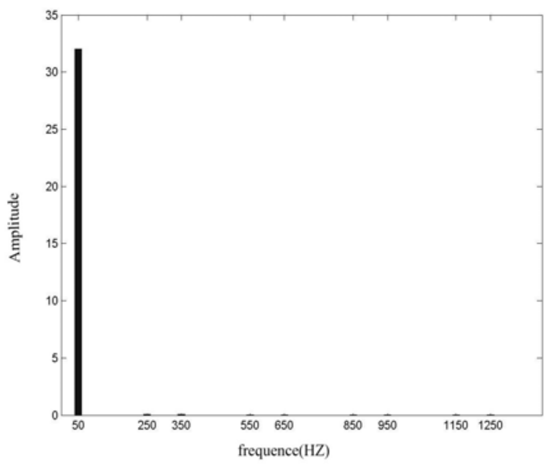

Figure 8. Harmonic spectrums of phase a source current.

V. CONCLUSIONS

In this paper a control method for active filter in order to harmonic elimination, reactive power compensation and load balancing is presented. This method is suitable for both single-phase and three-phase systems. This control method is combination of two methods first method is used for harmonic elimination and second method is used for reactive power compensation and load balancing. Each of control methods can operate separately. Simulation results for each of control methods and combinational method are presented which verify the correct operation and effectiveness of proposed method. It is envisaged that the proposed control method will be useful to industries because of its easy implementation for both single-phase and three-phase systems.

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