# Sinusoidal Current Control based Shunt Active Power Filter for Current Harmonics Reduction

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Abstract: Most of the power quality issues in power system are due to non-linear loads. The nonlinear load draws non-sinusoidal current from the AC mains which causes load harmonics and increases reactive power leading to pollution in power system. Shunt Active Power Filter (APF) has proven to be effective in improving power quality of distribution network. It compensates load current harmonics and reactive power simultaneously. The working of APF depends on its control strategy which includes generation of compensating reference current and generation of proper gating signal to make APF inject this reference current. This paper presents Sinusoidal current control (SCC) strategy for controlling the operation of shunt APF under balanced and unbalanced source voltage condition. This control strategy is based on instantaneous Reactive Power Theory (IRPT) and contains a positive sequence detector for detecting fundamental positive sequence component of input signal. The shunt APF contains a PWM current controlled voltage source inverter which is connected at the point of Common Coupling (PCC). The gating signal of VSI is derived from hysteresis band current controller (HBCC) and capacitor voltage is kept constant using a PI controller.

**Keywords:** Shunt Active Power Filter (APF), Sinusoidal Current Control (SCC), Instantaneous Reactive Power Theory (IRPT), Hysteresis Band Current Controller (HBCC), Point of Common Coupling (PCC).

## 1. Introduction

Power quality problems due to nonlinear load have been drawing lot of attention these years. The nonlinear load draws non-sinusoidal current from the AC mains leading to harmonics. These harmonics increases losses, causes overheating of equipment and reduces power factor as well. Hence, it is necessary to improve the power quality of the system. Filters are generally used for this purpose. Passive filters due to its tuning and resonance problems are not much used. APF contains power electronic switch and therefore does not have tuning problem. Among different topologies of APF, Shunt APF [1] is widely used for improving the power quality because of its ability to compensate current harmonics and reactive power simultaneously.

### 2. Shunt APF

The shunt APF reduces load current harmonics by injecting equal but opposite harmonic compensating current. Figure 1 shows the circuit diagram of three phase three wire shunt APF. The currents  $i_a$ ,  $i_b$ ,  $i_c$  are the source currents of phase A, B, C respectively. The point of common coupling (PCC) is the point at which the APF is connected in parallel to the load.  $i_{fa}$ ,  $i_{fb}$ ,  $i_{fc}$  are the filter currents which are generated by the VSI using HBCC.  $i_{ca}$ ,  $i_{cb}$ ,  $i_{cc}$  are the compensating currents found using SCC algorithm.  $L_f$  is the filter inductance which is used for commutation purpose.



Figure 1: Three phase three wire shunt APF

The VSI is a three leg VSI having six IGBTs and a capacitor on the DC side. This capacitor is used as energy storage device to maintain voltage  $V_{dc}$  at dc side of VSI. Control block represents the control algorithm for generating required gating pulses for VSI. Nonlinear load consist of a three phase diode bridge rectifier whose input is connected to three phase supply and output is connected to RL load.

#### 3. Control Strategy of Shunt APF

The performance of the APF strongly depends on the control strategy. The control strategy involves generation of compensating reference currents and then generating proper gating signals to three phase VSI. For the purpose of generating compensating currents SCC technique [4] is used.

#### 3.1. Sinusoidal Current Control Strategy

This strategy is based on IRPT also known as pq theory [4]. It involves clarke's transformation which transforms source voltage and load current from a-b-c coordinate to  $0-\alpha-\beta$ coordinate. The SCC strategy makes APF to compensate the current of non-linear load by forcing the compensated source current to become sinusoidal. In order to do so, the shunt APF compensates all harmonic components as well as the fundamental component that differs from the fundamental positive sequence current and to get the fundamental positive sequence component this control uses a positive sequence detector. Thus even if the voltage at the PCC is nonsinusoidal or unbalanced, it will not affect the system. The fundamental positive sequence voltage is then transformed to  $\alpha$ - $\beta$  coordinate using clarke transform, which is used for power calculation. A low pass 5<sup>th</sup> order butterworth filter of cut off frequency equal to 50Hz is used to extract the dc component of power which is then subtracted from total power to get the oscillating power. These powers are used to get the compensating current in  $\alpha$ - $\beta$  coordinate which is converted to a-b-c coordinate using inverse clarke transform. The voltages v'a, v'b, v'c are the fundamental positive sequence voltage of each phase obtained from positive sequence detector.

$$\begin{pmatrix} v'\alpha\\v'\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1-\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v'a\\v'b\\v'c \end{pmatrix}$$
$$\begin{pmatrix} i\alpha\\i\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1-\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} ila\\ilb\\ilc \end{pmatrix}$$

These voltage and current can be used to find the real and reactive power in  $\alpha$ - $\beta$  coordinate.

$$\binom{p}{q} = \binom{\nu'\alpha \quad \nu'\beta}{\nu'\beta \quad -\nu'\alpha} \binom{i\alpha}{i\beta}$$

where, p is the real power and represents the total energy flow per time in the three-wire three-phase system, in terms of  $\alpha\beta$  components; q is the imaginary power and gives the measure of the quantity of power that flows in each phase without transporting energy at any instant. The real and imaginary power can be divided into its average and oscillating components.

$$P = \frac{\overline{p}}{\overline{q}} + \frac{\widetilde{p}}{\overline{q}}$$
$$q = \overline{q} + \frac{\widetilde{q}}{\overline{q}}$$

The oscillating powers  $\tilde{p}$  and  $\tilde{q}$  are the undesirable power due to harmonic component in the load current. Using filter the compensating power  $p_c$  and  $q_c$  can be extracted which is used to find the compensating reference current ( $i_{ca}$ ,  $i_{cb}$ ,  $i_{cc}$ ) using inverse Clarke transform. In order to make sure that only constant real power flows between source and the load, the power components which are needed to be compensated are  $\tilde{p}$ ,  $\bar{q}$  and  $\tilde{q}$ .

$$\begin{pmatrix} i\alpha\\ i\beta \end{pmatrix} = 1/v\alpha\beta^2 \begin{pmatrix} v\alpha & v\beta\\ v\beta & -v\alpha \end{pmatrix} \begin{pmatrix} pc\\ qc \end{pmatrix}$$

Where,  $v_{\alpha\beta}^2 = v_{\alpha}^2 + v_{\beta}^2$ 

$$\begin{pmatrix} ica\\ icb\\ icb\\ icc \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0\\ -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} - \frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i\alpha\\ i\beta \end{pmatrix}$$

Where  $i_{ca}$ ,  $i_{cb}$ ,  $i_{cc}$  are the required compensating currents.



Figure 2: Block diagram of reference current extraction using SCC algorithm

Figure 2 represents the complete block diagram of SCC algorithm.  $p_{loss}$  represents the active power difference between source and load when the load changes. In order to compensate this difference capacitor is used. The peak value of the reference current must be adjusted proportionally to change the active power drawn from the source. This active power charged / discharged by the capacitor compensates the active power consumed by the load. PI controller is used to keep the capacitor voltage  $V_{dc}$  constant and equal to reference voltage  $V_{ref}$ .

Figure 3 shows the block diagram of positive sequence detector which contains a PLL block. PLL block determines the auxillary currents  $i'_{\alpha}$  and  $i'_{\beta}$  in  $\alpha$ - $\beta$  coordinate at fundamental frequency by continuously tracking the fundamental frequency of measured voltage. The source voltages are first transformed to  $\alpha$ - $\beta$  coordinates using Clarke transform. The V<sub>a</sub> and V<sub>β</sub> components and auxiliary currents  $i'_{\alpha}$  and  $i'_{\beta}$  (produced from the PLL-synchronizing circuit) are used to calculate the auxiliary powers p' and q'. The auxiliary real and reactive power is computed as follows

$$p' = V_{\alpha} i'_{\alpha} + V_{\beta} i'_{\beta}$$
$$q' = V_{\beta} i'_{\alpha} - V_{\alpha} i'_{\beta}$$

The auxiliary powers p' and q' are passed through fifth order Butterworth low pass filter with cut off frequency equal to 50 Hz for eliminating the higher frequency components. The average auxillary power obtained is used to find the fundamental positive sequence voltage as shown in fig.3

## International Journal of Science and Research (IJSR) ISSN (Online): 2319-7064 Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438



Figure 3: Positive Sequence Detector block diagram

#### **3.2 Generation of Gate Pulses**

Once the compensating reference currents are obtained the next step is to give proper pulses to the VSI so that the filter injects the compensating reference current which is nothing but the load harmonic current. HBCC generate pulses using Hysteresis band PWM technique. It is an instantaneous feedback current control method of PWM where the actual current continually tracks the reference current within a specified hysteresis band.



Figure 4: Hysteresis Band Current Control

The hysteresis current controller gives output pulses to the inverter according to following rule

If  $i_{ref} - i_{act} < \Delta i$  than keep the output pulse at the same state If  $i_{ref} - i_{act} > \Delta i$  than the output pulse goes at the high state If  $i_{ref} - i_{act} < -\Delta i$  than the output pulse goes at the low state

Where  $\Delta i$  is hysteresis band limit,  $i_{ref}$  is the reference current and  $i_{act}$  is the actual filter current. Thus if the difference between the reference and the actual current is within the hysteresis band the pulse is in same state and if it goes beyond Hysteresis band then the pulse state changes forcing the current to be within hysteresis limit.

# 4. Simulation Results

The Shunt APF model is simulated in MATLAB/SIMULINK under balanced and unbalanced source voltage condition. The System parameters used are: Line to line source voltage Vs is 200 V (rms); System frequency (f) is 50 Hz; Source impedance of R<sub>s</sub>, L<sub>s</sub> is 0.1  $\Omega$ ; 0.1 mH respectively; Filter inductance Lc is 6.5 mH; Diode rectifier R<sub>L</sub>, L<sub>L</sub> load: 10  $\Omega$ ; 14 mH respectively; Unbalanced source voltages for phase A, B, C are: Va = 200  $\Omega$ , Vb = 180  $\Omega$ , Vc= 210  $\Omega$  respectively; DC side capacitance (C<sub>DC</sub>) is 3 mF; Reference voltage (V<sub>dc, ref</sub>) is 400V.

A. System without Shunt APF under balanced source voltage condition



Figure 5: Souce voltage waveform



Figure 6: Souce current waveform



Figure 7: FFT Analysis of Souce Current (THD=18.85%)

B. System with Shunt APF under Balanced source voltage condition



Figure 8: Souce voltage waveform

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Figure 9: Souce current waveform



Figure 10: Filter Current waveform



Figure 11: FFT Analysis of Souce Current (THD=3.65%)

When the filter is not being used, the source current is highly distorted with THD equal to 18.85% (figure 6). As seen from the FFT analysis (figure 7), the source current contains a high percentage of  $5^{\text{th}}$  and  $7^{\text{th}}$  harmonic.

By using filter the THD is reduced from 18.85% to 3.65% (figure 11). Figure 10 shows the current injected by the filter which is nothing but the harmonic current. Since this harmonic current is injected by filter, the source current is almost sinusoidal.

C. System without Shunt APF under Unbalanced Source Voltage Condition



Figure 13: Souce current waveform



Figure 14: FFT Analysis of Souce Current (THD= 18.45%)

D. System with Shunt APF under Unbalanced Source Voltage Condition



Figure 15: Souce Voltage waveform



Figure 16: Souce current waveform



Figure 17: Filter current waveform

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Figure 18: FFT Analysis of Souce Current (THD= 4.92%)

When the source voltage is unbalanced the distortion increases, but since the shunt APF contains positive sequence detector the THD is reduced to 4.92% (figure 18). The simulation results obtained are summarized through table 1 and table 2. As shown in table 1 and 2 the power factor is also improved and is very close to unity due to reduction in harmonics.

**Table 1:** Simulation Result for Balanced Voltage Condition

Parameter	Values without Shunt APF	Values with Shunt APF
Is(THD)	18.85%	3.65%
P.f	0.7	0.98

 Table 2: Simulation Result for Unbalanced Voltage

 Condition

Parameter	Values without Shunt APF	Values with Shunt APF
Is(THD)	18.45%, 20.8%, 17.6%	4.92%
P.f	0.67	0.9

# 5. Conclusion

This paper presented shunt APF based on SCC algorithm for reducing current harmonics injected by nonlinear RL load under balanced and unbalanced source voltage condition. Shunt APF allows compensation of current harmonics and unbalance along with correction of power factor. SCC algorithm guarantees sinusoidal source current even if the source voltage is unbalance because of the presence of positive sequence detector which extracts the fundamental positive sequence component of input voltage. Therefore even if the voltage at PCC is unbalanced, it will not affect system's performance.

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