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# A Simplified Control Algorithm for Series Hybrid Active Power Filter

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**Abstract:** Series Hybrid Active Power Filters (SHAPF) have been the main topic of interest for researchers working in the area of power quality, as it combines best features of active power filters (APF) and passive filters. Moreover it is proved to be a cost-effective solution as compared to standalone active and passive filters. Control strategy is a key part of any APF system which decides the compensating characteristics of the filter. For SHAPF many control algorithms have been proposed, they are mainly based on either detecting source current harmonics or load voltage harmonics. Both these methods require decomposition of voltage or current vectors in active and reactive components corresponding to these harmonics. This paper proposes a simplified method of calculating reference for SHAPF. In proposed method the component of voltage vectors corresponding to different parts of active power are only used for deriving reference voltage. This helps avoiding the reactive power calculation and simplifies the control system to a greater extent. Simulation study of SHAPF is done with proposed method and performance of filter is tested in terms of its current harmonic compensation characteristics.

**Keywords:** active power filters, hybrid active power filter, passive filter, THD.

## I. INTRODUCTION

The harmonic propagation in power distribution system becomes a serious problem in recent years because of the wide application of power electronic equipments and nonlinear loads. If not mitigated, harmonics badly influence the power quality of electric network, such as deterioration of voltage available at point of common coupling (PCC), overheating of conductors and equipments connected, poor power factor etc.

In order to suppress harmonics, many methods have been proposed. Conventionally, stand alone passive or active filters are used for harmonic mitigation [1],[2],[3]. But they suffer from several practical limitations.

Practical limitations of passive filters are:

(1) Low value of the source impedance, which is also not accurately known and varies with the system configuration, makes the filtering characteristics of the shunt passive filter poor.

(2) Parallel resonance between a source and passive filter causes amplification of harmonic voltages on the source side at specific frequencies.

(3)The shunt passive filter may fall in series resonance with the source impedance and acts as a current sink to the harmonic current from the source.

Practical limitations of active power filters are:

(1) Initial and running costs are high.

(2) It is difficult to construct a large rated converter with rapid current response.

To overcome the problems of both passive and active power filters, hybrid active power filters (HAPF) have been evolved and extensively used in practice as a cost effective solution for the compensation of nonlinear loads. HAPF combines the best features of both passive and active power filters. Many combinations of HAPF configurations have been proposed in literature [4],[5],[6],[7]. The passive filter suppresses the harmonic currents produced by the nonlinear load and active power filter improves the performance of passive filter.

Control strategy plays an important role in performance of HAPF. Many control algorithms have been proposed in literatures. All control algorithms are based on calculation of instantaneous active and reactive powers. Main theme involves decomposition of voltages or currents in to active and reactive components related to active and reactive powers to be compensated respectively. Effectiveness of the control strategy also depends on the time taken for the calculation of voltage or current components required for the compensation based on whether series or shunt active filters are used.

In this paper, HAPF combining series active power filter (SAPF), connected in series with the source, and passive filter, connected in parallel with the nonlinear load, is analyzed [8], [9].

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This paper proposes new simplified control strategy for SAPF. This control strategy eliminates calculation of instantaneous reactive power. Active power is used to calculate the voltage corresponding to reactive power which simplifies the derivation of compensation voltage and also saves the calculation time.

Analysis of selected SHAPF topology based proposed simplified control algorithm is verified by simulation. Simulation is performed in PSIM software [10]. Parameters to be analysed are source current THD, load voltage THD, power factor and VA rating of the inverter. Transient performance of the SHAPF is also verified by simulation.

## II. MAIN CIRCUIT CONFIGURATION OF SERIES HYBRID ACTIVE POWER FILTER

Fig-1 shows the main circuit configuration of SHAPF. The SAPF is connected in series with the source branch and passive filters, tuned at 5th and 7th harmonics as well as high pass filter, are connected parallel to the nonlinear load.

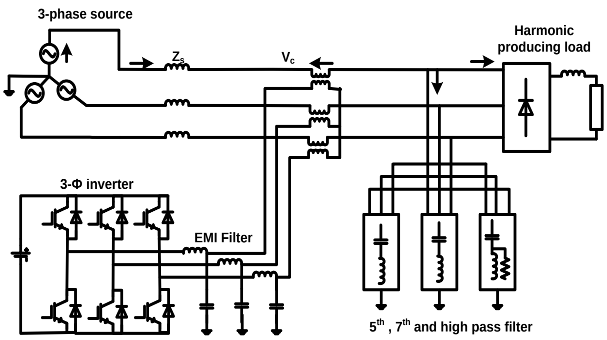

Figure 1 Series Hybrid Active Power Filter configuration

### A. Operating principle

Only passive filters cannot completely remove the harmonics from the source current because of its practical limitations as discussed earlier. So SAPF is connected in series with the source branch to improve the performance of the passive filters.

The SAPF increases the resistance of the source branch for the load harmonics and opposes its entrance in the source current.

Fig-2 shows the harmonic equivalent circuit of the SHAPF topology.

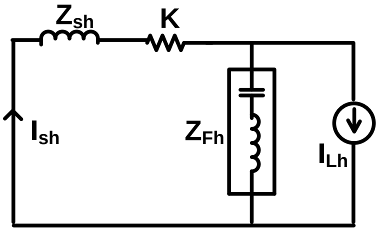

Figure 2 Harmonic equivalent circuit of SHAPF

***'Distribution factor'*** is ratio of source current harmonics $I_{sh}$ to load current harmonics $I_{Lh}$ and it indicates the presence of harmonic contents in source branch. It should have as low value as possible for having less source harmonics. Equation-1 shows the value of distribution factor. Equation-2 shows the load voltage harmonics.

$$\frac{I_{sh}}{I_{Lh}} = \frac{Z_{Fh}}{Z_{Fh} + Z_{sh} + K} \tag{1}$$

$$V_{Lh} = -\frac{Z_{sh} + K}{Z_{sh} + Z_{Fh} + K} Z_{Fh} I_{Lh} \tag{2}$$

Equation-1 indicates that distribution factor depends on harmonic impedance of source branch $Z_{sh}$ , harmonic impedance of passive filter branch $Z_{Fh}$ and resistance offered to the load current harmonics in source branch K. Control algorithm takes care of not providing resistance to fundamental components.

As the values of $Z_{sh}$ and $Z_{Fh}$ are constant, K is only the variable which can control the value of distribution factor. K is the gain of control circuit. As the value of K increases, distribution factor decreases consequently, harmonic injection in source current decreases.

There is always one optimized value of K which gives minimum harmonic injection in source branch and is very difficult to decide the precise value.

### B. Main parts of SAPF

SAPF is one of the important parts of the main circuit configuration of SHAPF. Main parts of SAPF include control circuit, three phase inverter, high frequency LC filter, three phase coupling transformer etc. Three phase inverter and LC filter are discussed here under.

#### 1) Three phase full bridge inverter

The inverter used in the SAPF is voltage source PWM inverter. Six power IGBTs are its switching devices. Gate pulses obtained by comparing the reference voltages with high frequency carrier are used to control the PWM inverter and make it produce the required reference voltage.


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Control circuit continuously detects the source voltages and currents and derives the reference voltage for the inverter and tracks any change that occurs in the power circuit.
The value of the dc side voltage of the inverter directly influences on the compensation effects of the SAPF. If it is too low, the SAPF cannot produce the required compensation voltage to cancel the source harmonics. On the other hand, if it is too high, the voltage stress on both the switching devices and the dc side capacitor will subsequently increase. The maximum voltage produced by the inverter is 2/3 times the dc side voltage. This must be taken in to account when deciding the gain of the control circuit.

*2) High frequency LC filter*

The high frequency LC filter is used to remove the high switching ripples from the output of the inverter. For good dynamic response, the values of filter inductor $L_r$ and capacitor $C_r$ must be chosen suitably.

Being too small, they cannot successfully suppress the switching ripples. Too large values of $L_r$ and $C_r$ will increase the physical size of the whole equipment and response of the system will also be slow down. This will result in the poor compensation characteristics of SHAPF. So the values of filter inductor $L_r$ and capacitor $C_r$ must be chosen through suitable compromise between the speed of the response and the smoothing effects.

## III. REALIZATION OF SIMPLIFIED CONTROL STRATEGY

This paper presents simplified control strategy for derivation of reference voltage for SAPF. New control strategy eliminates instantaneous reactive power calculation which reduces the complication and time consumption for control circuit and thus simplifies the calculation.

Fig-3 shows the block diagram of simplified control strategy suggested in this paper. Required quantities to be sensed are source voltages $\boldsymbol{v_{sa}, v_{sb}, v_{sc}}$ and source currents $\boldsymbol{i_{sa}, i_{sb}, i_{sc}}$. Three voltages and currents represented in vector form are shown by equations-(3) and (4) respectively.

$$\vec{v} = \begin{bmatrix} v_{sa} & v_{sb} & v_{sc} \end{bmatrix} \quad (3)$$

$$\vec{i} = \begin{bmatrix} i_{sa} & i_{sb} & i_{sc} \end{bmatrix} \quad (4)$$

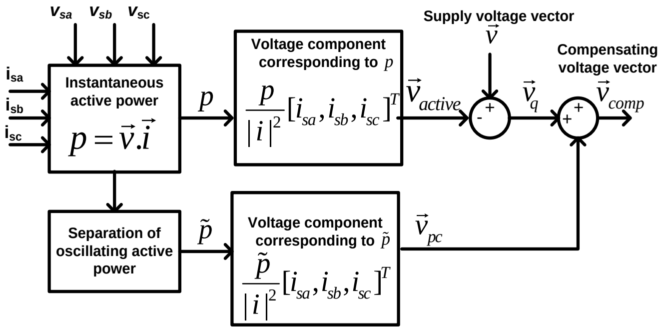


Figure 3 Simplified Control Strategy

Instantaneous active power is calculated by dot product of vectors $\vec{v}$ and $\vec{i}$ and is given by the equation-5.

$$p = \vec{v}.\vec{i} = v^T i = v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} \quad (5)$$

This $p$ consists of average as well as oscillating components $\boldsymbol{P}$ and $\tilde{p}$ respectively. Oscillating component of active power is separated from $p$ using low pass filter. Usually the quantities which need to be compensated are $\tilde{p}$ and $q$ for power quality improvement. $q$ consists of both average and oscillating reactive power. It is required to find out voltage corresponding to these quantities.
Voltage corresponding to $\tilde{p}$, $\vec{v}_{pc}$ is calculated as per the equation -6.

$$\vec{v}_{pc} = [v_{pac}, v_{pbc}, v_{pcc}]^T = \frac{\tilde{p}}{|i|^2}[i_{sa}, i_{sb}, i_{sc}]^T \quad (6)$$

Voltage corresponding to total reactive power is calculated by subtracting voltage corresponding to instantaneous active power $\vec{v}_{active}$ from supply voltage vector $\vec{v}$ . $\vec{v}_{active}$ is given by equation-7.

$$\vec{v}_{active} = [v_{aa}, v_{ab}, v_{ac}]^T = \frac{p}{|i|^2}[i_{sa}, i_{sb}, i_{sc}]^T \quad (7)$$

Voltage corresponding to total reactive power is directly obtained by equation-8.

$$\vec{v}_q = \vec{v} - \vec{v}_{active} \quad (8)$$

Total compensating voltage is addition of both $\vec{v}_{pc}$ and $\vec{v}_q$ .

$$\vec{v}_{comp} = \vec{v}_{pc} + \vec{v}_q \quad (9)$$

This compensating voltage is required to be reproduced by inverter of SAPF. For this to be done $\vec{v}_{comp}$ is compared with high frequency carrier wave which gives required gate pulses for inverter.

## IV. SIMULATION RESULTS

SHAPF with suggested simplified control strategy is verified by simulation in PSIM software. Three phase diode rectifier drawing 50 amperes of dc current is connected as a non-linear load. Shunt passive filters connected parallel to the load include $5^{th}$, $7^{th}$ order tuned filters along with the high pass filter. Another nonlinear load of diode rectifier drawing 50 amperes of dc current is connected at 0.25 seconds to the existing load to verify the transient performance of the system. Supply voltages are considered balanced and sinusoidal. Transformation ratio of coupling transformer is chosen 1:1. Switching frequency is for inverter is 30 KHz.

First the performance of supply system is verified by simulating it with only passive filter as a harmonic compensation element. Then performance is verified by simulating the system with SAPF and passive filers. Table-1 shows the values of common parameters used in simulation.

Fig-4 shows the simulation waveforms of the system with only passive filters. Fig-4 (a), (b) and (c) show the load current, supply current and load voltage respectively of phase-a.

Table-2 shows the FFT results of simulated waveforms of system with passive filters only. Rms values are used to indicate voltage and current values. Load current THD is 25.88% which is because of presence of large amount of $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ harmonics. Source current THD is 12.52% which is less as compared to load current because of presence of passive filters. Load voltage THD is 4.39%. Power factor is 0.9759.

Table 1 Common parameters

| | |
|---|---|
| Supply voltage | 230volt(per phase) |
| Source impedance | (i) resistance=0.3Ω (ii)inductance=0.5mH |
| $5^{th}$ Harmonic Filter parameters | |
| $L_5$ | 0.0175 H |
| $C_5$ | 23.1 µF |
| $7^{th}$ Harmonic Filter parameters | |
| $L_7$ | 0.00877 H |
| $C_7$ | 23.59 µF |
| High pass Filter | |
| $L_h$ | 1 mH |
| $C_h$ | 70.36 µF |
| R | 2.83 |
| Switching Filter | |
| $L_r$ | 0.716 mH |
| $C_r$ | 28.65 µF |
| Load-1 | Three phase diode rectifier drawing 50 amp DC current |
| Load-2 | Three phase diode rectifier drawing 50 amp DC current (swiched in at 0.25 seconds) |

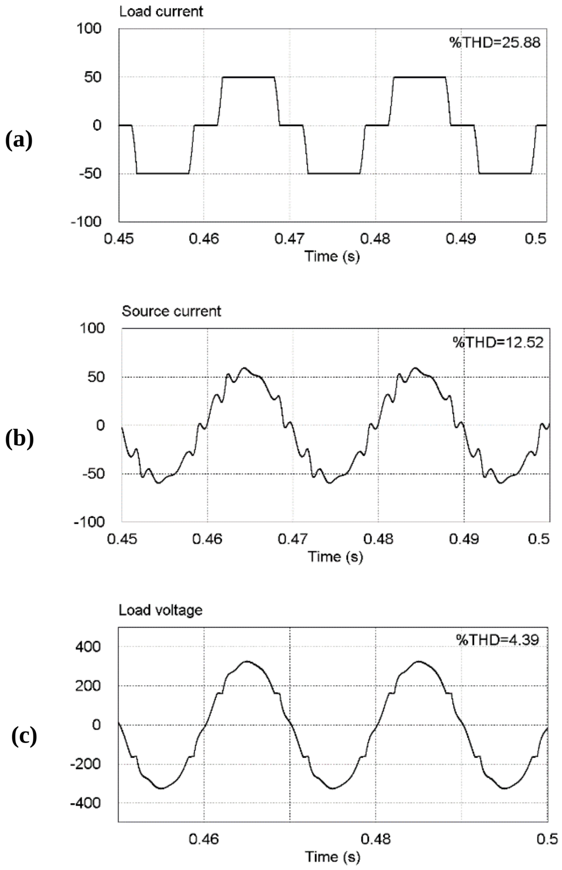


Figure 4 Simulation waveforms of the system with only passive filter: (a) Load current (b) Source current (c) Load voltage

Table 2 Simulation results with only passive filer

| | Parameters to be analyzed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fundamental | Order of harmonics | | | | | | %THD | P.F |
| | | $5^{th}$ | $7^{th}$ | $11^{th}$ | $13^{th}$ | $17^{th}$ | $19^{th}$ | | |
| Load current | 35.26 | 6.72 | 4.58 | 2.52 | 1.95 | 2.29 | 1.75 | 24.76 | 0.9759 |
| Source current | 36 | 0.79 | 0.57 | 3.27 | 2.45 | 1.18 | 0.83 | 12.52 | |
| Load voltage | 206.06 | 3.88 | 2.25 | 5.75 | 5.06 | 3.18 | 2.51 | 4.73 | |

Fig-5 shows the simulation waveforms of SHAPF with suggested simplified control strategy. Fig-5 (a), (b), (c) and (d) show the supply current, load voltage, compensating voltage and voltage injected into the system through coupling transformer respectively.

Table-3 shows the simulation results of SHAPF based on simplified control strategy. Source current THD is decreased to 3.33%. Load voltage is increased to 5.4%. Power factor is improved to 0.9949. For this, required rating of inverter of SAPF is 4.63 kVA. Rating of nonlinear load is 28 kVA.

(a) (b) (c) (d)

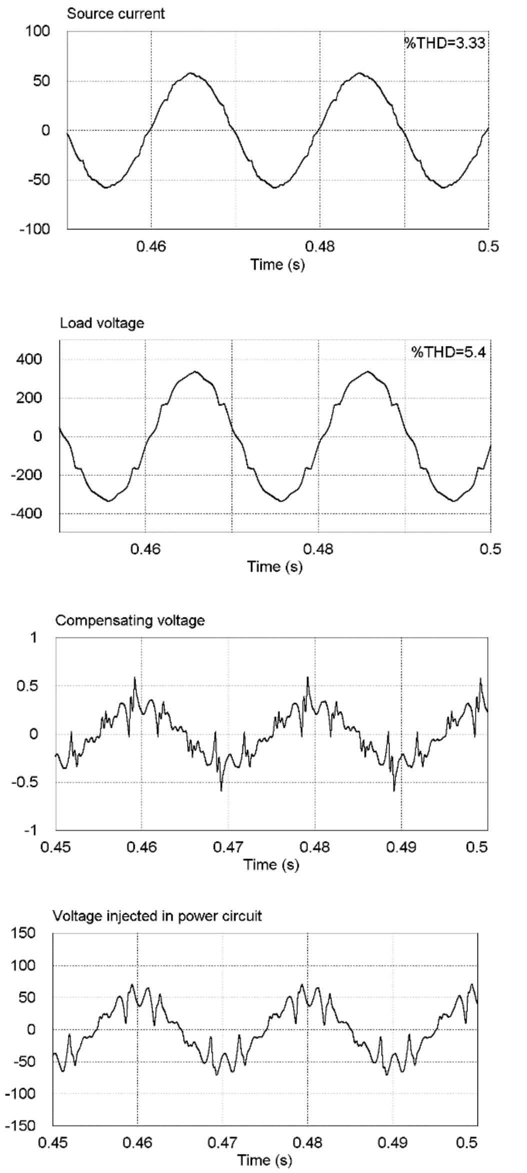


Figure 5 Simulation waveforms of SHAPF: (a) Source current (b) Load voltage (c) Compensating voltage (d) Voltage injected into the system through SAPF

Table 3 Simulation results of SHAPF

| | Parameters to be analyzed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fundamental | Order of harmonics | | | | | | %THD | P.F |
| | | 5th | 7th | 11th | 13th | 17th | 19th | | |
| Load current | 35.26 | 6.72 | 4.58 | 2.52 | 1.95 | 2.29 | 1.75 | 24.76 | 0.9949 |
| Source current | 36.34 | 0.69 | 0.41 | 0.81 | 0.52 | 0.21 | 0.17 | 3.33 | |
| Load voltage | 210.6 | 4.61 | 2.91 | 7.63 | 5.44 | 2.78 | 2.22 | 5.4 | |

Fig-6 shows the transient performance of SHAPF. At 0.25 seconds another nonlinear load of diode rectifier drawing 50 amperes is connected to already existing diode rectifier load. This shows that system is stable under varying load condition.

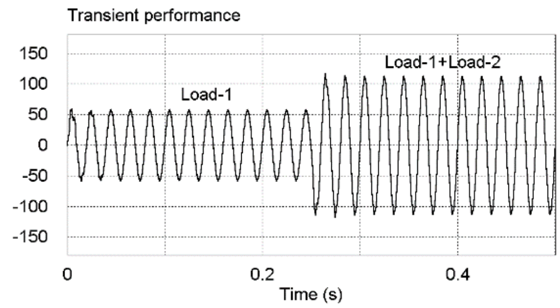


Figure 5 Transient performance of SHAPF

## V. CONCLUSION

Simulation results of SHAPF with suggested simplified control strategy enables us to understand the reduction of harmonic injection in supply branch with the help of SAPF and passive filters.

Following table compares the results of the system without any filter, with only passive filters and with the both SAPF and passive filters.

Table 4 Comparison table

| | %THD of source current | %THD of load voltage | Power Factor |
|---|---|---|---|
| System without any filter | 25.44 | 5.77 | 0.9577 |
| System with passive filter only | 12.52 | 4.73 | 0.9759 |
| System with passive and active filter | 3.33 | 5.4 | 0.9949 |

- With only passive filters as the harmonic eliminating element, source current THD is 12.52% which is very high according to IEEE 519 guidelines. After connecting SAPF, performance of passive filer is improved and source current THD is reduced to 3.33%.
- HAPF improves power factor of the supply system to 0.9949 which was 0.9759 when only passive filters were connected to the system.
- Inverter rating of SAPF required to improve the performance of passive filter and in turn of supply system, is only 4.63 kVA which is only 16.53% of load kVA.
- The DC link voltage of inverter in this SHAPF is 100 volts, which is also very small if we compare it with the similar rating shunt active power filter.
- System shows good transient response to the changing load condition.

- One of the drawbacks of SHAPF is the increase of load voltage THD. Before connecting SAPF to the system i.e. with only passive filters as the harmonic eliminating element, load voltage THD is 4.73%. This is increased to 5.4% when SAPF is connecting in addition to already existing passive filters.

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