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Generalized Instantaneous Power Theory and its Application to Series Hybrid Active Power Filter

Sanjaykumar Chandubhai Patel

Lecturer, Electrical Engineering Department , Government Polytechnic, Valsad, Gujarat, India.

Abstract: Harmonic injection in supply current is most common problem arising in supply network because of the increased population of nonlinear loads. Traditionally used standalone passive and active filters have some practical drawbacks which can be overcome by hybrid active power filters (HAPF). HAPFs inherit the efficiency of passive filters and the improved performance of active filters. Here filtering characteristic of passive filter is improved by the active filter. A combined system of passive and active power filter is practically used to minimize the harmonic currents and voltage as well as to improve the power factor of the ac mains. The choice of nonlinear load, supply network parameters and the control algorithm determines the performance of HAPF. This paper presents the HAPF topology which combines series active power filter (SAPF) and shunt passive filter. Generalized Instantaneous Power Theory (GIPT) is used as a control algorithm. The HAPF configuration is tested for harmonic elimination of 28 kVA non linear load. Performance parameters like source current THD, load current THD, load voltage THD and required inverter ratings are analysed during the operation of HAPF. The transient performance is also tested and presented via simulation.

Keywords: active power filters, passive filers, HAPF, THD, FFT analysis.

I. INTRODUCTION

The increase of the nonlinear loads due to the proliferation of electronic equipments causes power quality in the power system to deteriorate. These nonlinear loads draw harmonic currents and reactive power from the supply network and renders it with the full of harmonics. Harmonic current drawn from a supply by the nonlinear load causes the distortion of the supply voltage waveform at the point of common coupling (PCC) due to the source impedance. Both distorted current and voltage may cause end-user equipment to malfunction, conductors to overheat and may reduce the efficiency and life expectancy of the equipment connected at the PCC.

Traditionally, a passive LC power filter is used to eliminate current harmonics when it is connected parallel with the load [1]. But standalone passive filter cannot provide complete solution of current harmonics because of dependency of its filtering characteristics on source impedance [2]. Following are the limitations of the passive filter.

(1) The source impedance, which is not accurately known and varies with the system configuration, influences filtering characteristics of the shunt passive filter.
(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.

Active filters have ability to overcome all these problems. It consists of voltage source inverters [3]. Different techniques have been applied to obtain control signal for the active filters. Control algorithm makes it possible for the inverter to eliminate the series and parallel resonances with the rest of the system. But active filters suffer from several practical limitations. Following are the practical limitations of active power filter.

(1) Initial and running costs are high.
(2) It is difficult to construct a large rated converter with rapid current response.

In response to these factors, a series of HAPF has been evolved and extensively used in practice as a cost-effective solution for the compensation of nonlinear loads. HAPF combines the passive and active filters so as to overcome the drawbacks of the individual filter type. The passive filter suppresses harmonic currents produced by the load, whereas the active filter improves the filtering characteristics of the passive filter. HAPFs, inheriting the advantages of both passive and active filters, provide improved performance and cost- effective solution. There are many types of HAPFs suggested in different literatures [4], [5], [6], [7].

In this paper, a study is carried out on one such HAPF that can be used to mitigate supply current harmonics. This HAPF consists of passive filter connected parallel to the nonlinear load and series active power filter connected in series with the source [8], [9].

Control algorithm used to derive the reference is based on GIPT. GIPT presents a new approach, based on geometric algebra, which can be applied to multiphase systems. Details of selected HAPF topology and GIPT are discussed. Performance of selected HAPF and control algorithm are verified by simulation study in PSIM software. Performance parameters are THD of supply current, load voltage, power factor and VA rating of inverter.

II. GENERLAL DISCRIPTION OF THE SYSTEM

Fig-1(a) shows the one line diagram of the system in which passive filter connected parallel to the load is only the means of harmonic removal. Fig-1(b) shows the harmonic equivalent circuit of the system.

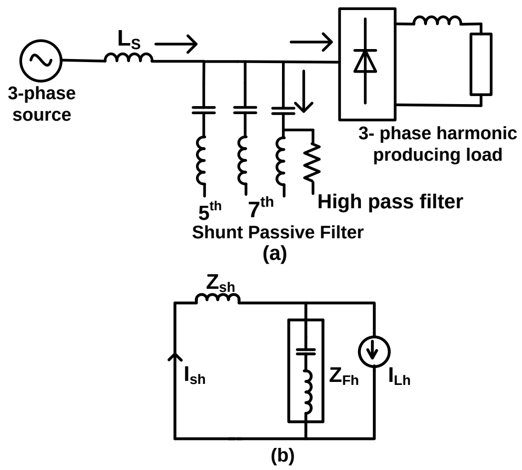

Figure 1 (a) System configuration with passive filter (b) Harmonic equivalent circuit

The ratio of source harmonic current I_{sh} to load current I_{Lh} is known as '***distribution factor***'. This can be derived from the Figure 1(b). The value of the distribution factor should be as low as possible to have fewer harmonic in supply current.

$$\frac{I_{sh}}{I_{Lh}} = \frac{Z_{Fh}}{Z_{Fh} + Z_{sh}} \qquad (1)$$

$$V_{Lh} = -Z_{Sh} I_{Sh} = -\frac{Z_{Sh} Z_{Fh}}{Z_{Sh} + Z_{Fh}} I_{Lh} \qquad (2)$$

Equation-1 implies that distribution factor depends on the source harmonic impedance Z_{sh} and harmonic impedance of the passive filter Z_{Fh}. As source impedance is usually low, distribution factor is reasonably high. Equation-2 shows the load voltage harmonics. For distribution factor to be low, source impedance should have higher value than passive filter impedance. This will reduce harmonics from entering into the supply branch. But at the same time high source impedance reduces the fundamental component of the source voltage at the point of the common coupling (PCC). This indicates that high source impedance is not the proper solution for the source current harmonics. Consequently filtering characteristics of passive filter can be improved by increasing source branch impedance such that it provides zero impedance to the fundamental component and ideally infinite impedance to the harmonics. This is achieved by using active power filter in addition to the passive filter.

Active filters were developed to mitigate the problems of passive filters. Parallel active filters are viable solution if the peak harmonic current is limited and displacement power factor constrains under light load conditions. But they require large rating for large peak harmonic current and high bandwidth PWM inverters and hence is not a cost effective solution for stiff supply system. The leakage inductance of the series coupling transformer used for series active power filter is also critical design parameter and has been designed to be low. Transformer leakage inductance entails fundamental voltage drop and fundamental VA, which has been supported by the inverter. This effectively reduces the series active filter inverter rating available for '***harmonic isolator factor***'.

III. HAPF TOPOLOGY

Fig-2(a) shows the circuit configuration of selected HAPF. In this topology, SAPF is connected in series with the source using coupling transformer and shunt passive filter is connected parallel to the load. The passive filters tuned at 5^{th} and 7^{th} harmonic frequencies as well as high pass filters are connected parallel to the load. An EMI filter is also connected between coupling transformer and active filter to filter out high switching ripples from the output of PWM inverter. Fig-2(b) shows the equivalent circuit representation of selected HAPF.

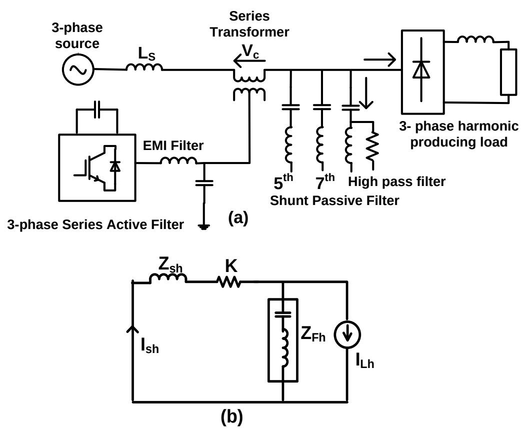

Figure 2 (a) HAPF configuration (b) Harmonic equivalent circuit

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A. Operating Principle

As just discussed above, it is apparent that the higher source impedance gives better filtering performance to the passive filter. But higher source impedance causes appreciable amount of voltage drop at fundamental frequency. These two requirements, which contradict each other, can be satisfied by inserting "***active impedance***" in series with the ac source.

The active impedance can be implemented by SAPF using voltage source PWM inverter. The SAPF is controlled in such a way as to present zero impedance to the fundamental frequency and high resistance K (gain of the control circuit) to load harmonics. The function of the active filter is not to compensate for the harmonics of the load but to isolate the harmonics between the load and the source. This way filtering characteristics of passive filter is improved. Filtering Characteristics

Fig-2(b) presents the harmonic equivalent circuit of the HAPF on per phase basis. Distribution factor for this circuit is given by,

$$\frac{I_{sh}}{I_{Lh}} = \frac{Z_{Fh}}{Z_{Fh} + Z_{sh} + K} \tag{3}$$

$$V_{Lh} = -\frac{Z_{sh} + K}{Z_{sh} + Z_{Fh} + K} Z_{Fh} I_{Lh} \tag{4}$$

Equation-3 shows that the SAPF acts as "***damping resistance***". If K is much larger than the source impedance, variations in source impedance have no effect on the filtering characteristics of the parallel passive filter. Equation-4 shows the harmonic voltage appearing across the nonlinear load. Load voltage harmonics are increased because of more and more harmonics are forced to flow through the parallel passive filters.

B. Control Algorithm: Generalized Instantaneous Power Theory

Control algorithm used to generate reference voltage waveform for SAPF is one of the parameter which affects the performance of HAPF. In this paper, GIPT is used as a control algorithm [10] to generate reference voltage. With its concise and direct expression, the theory can be applied to any kind of three phase systems, and can also be easily extended to any n-phase systems without any additional transformation. Therefore, it may find wide application in many fields. This theory introduces the concept of second order asymmetrical tensor into multiphase systems and gives a direct and simple expression of multiphase instantaneous reactive quantities.

The HAPF topology is based on three- phase four-wire system. Supply voltages v_{sa}, v_{sb} and v_{sc} as well as i_{sa}, i_{sb} and i_{sc} are sensed to derive the reference voltage waveform for SAPF using GIPT.
Three phase instantaneous voltage vector $\vec{v}$ and current vector $\vec{i}$ are expressed in vector form as shown by Equations-(5) and (6) respectively.

$$\vec{v} = \begin{bmatrix} v_{sa} & v_{sb} & v_{sc} \end{bmatrix} \tag{5}$$

$$\vec{i} = \begin{bmatrix} i_{sa} & i_{sb} & i_{sc} \end{bmatrix} \tag{6}$$

Their norms (vector's magnitude) are expressed as given in Equations-(7) and (8) respectively.

$$|v| = \sqrt{v.v} = \sqrt{v^T v} = \sqrt{{v_{sa}}^2 + {v_{sb}}^2 + {v_{sc}}^2} \tag{7}$$

$$|i| = \sqrt{i.i} = \sqrt{i^T i} = \sqrt{{i_{sa}}^2 + {i_{sb}}^2 + {i_{sc}}^2} \tag{8}$$

Instantaneous active power p and apparent power s are calculated using Equations-(9) and (10).

$$p = v.i = v^T i = v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} \tag{9}$$

$$s = |v||i| \tag{10}$$

Instantaneous reactive power is outer product of instantaneous voltage $\vec{v}$ and current $\vec{i}$ which is calculated by Equations-(11) and (12).

$$\left.\begin{aligned} q_{ab} &= v_{sa} i_{sb} - v_{sb} i_{sa} \\ q_{bc} &= v_{sb} i_{sc} - v_{sc} i_{sb} \\ q_{ca} &= v_{sc} i_{sa} - v_{sa} i_{sc} \end{aligned}\right\} \tag{11}$$

$$|q| = \sqrt{{q_{ab}}^2 + {q_{bc}}^2 + {q_{ca}}^2} \tag{12}$$

Instantaneous active power p is sum of average and oscillating components which is calculated by Equation-(13).

$$p = P + \tilde{p} \tag{13}$$

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Similarly reactive power q is also sum of average and oscillating components and calculated by Equation-(14).

$$q = Q + \tilde{q} \qquad (14)$$

P and Q are average quantities of active and reactive power respectively and they are contributed by fundamental components.

$\tilde{p}$ and $\tilde{q}$ are oscillating quantities of active and reactive power respectively and they are contributed by harmonics.

Figure-3 shows the block diagram of control strategy for the SAPF based on the GIPT used in HAPF.

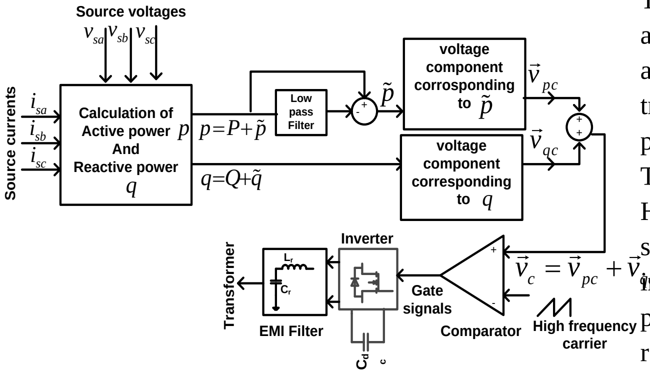

Figure 3 Control strategy based on GIPT

P is low pass filtered to extract oscillating component $\tilde{p}$ which is due to the presence of harmonics in source current. $\tilde{p}$ is utilized to calculate voltage reference corresponding to oscillating active power. $\vec{v}_{pc}$ is the voltage corresponding to $\tilde{p}$ and found by Equation-(15). $\vec{v}_{qc}$ is the voltage corresponding to reactive power q which contains both oscillating and average reactive power and calculated by Equation-(16).

$$\vec{v}_{pc} = [v_{pac}, v_{pbc}, v_{pcc}]^T = \frac{\tilde{p}i}{i.i} = \frac{\tilde{p}}{|i|^2}[i_{sa}, i_{sb}, i_{sc}]^T \qquad (15)$$

$$\vec{v}_{qc} = [v_{qac}, v_{qbc}, v_{qcc}]^T = \frac{i \times q}{i.i} = \frac{1}{|i|^2}\begin{bmatrix} 0 & q_{ab} & -q_{ca} \\ -q_{ab} & 0 & q_{bc} \\ q_{ca} & -q_{bc} & 0 \end{bmatrix}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \qquad (16)$$

Total compensating voltage $\vec{v}_c$ is obtained by adding $\vec{v}_{pc}$ and $\vec{v}_{qc}$ as given by equation-17.

$$\vec{v}_c = \vec{v}_{pc} + \vec{v}_{qc} \qquad (17)$$

$\vec{v}_c$ **is** compared with high frequency carrier wave to obtain gate pulses for inverter. Inverter reproduces the compensating voltage signal. Switching filter is used at the output of the inverter to suppress the switching frequency components. Filtered output of inverter is injected in series with the source branch through the coupling transformer such that it opposes harmonic current in source branch.

IV. SIMULATION RESULTS

For evaluating steady state and transient performance of the selected HAPF topology based on GIPT, simulations are performed in PSIM software [11].

The HAPF is considered with diode rectifier drawing 50 amperes of dc current as a nonlinear load. Supply voltages are considered balanced and sinusoidal. Coupling transformers used have transformation ratios of 1:1. HAPF parameter values used in simulation are given in Table-1. The HAPF with only passive filters is simulated first. Then HAPF with both shunt passive and series active filter is simulated which helps us to understand how SAPF helps to improve the performance of passive filters. Transient performance is checked by connecting another diode rectifier at 0.25 seconds to already existing diode rectifier. Fig-4 shows the simulation results when nonlinear load is compensated only by parallely connected passive filters. Fig-4 (a), (b) and (c) shows the load current I_{La}, source current I_{sa} and load voltage V_{La} respectively for phase-a.

Table-1 System parameters used in simulation

Supply voltage	230volt(per phase)
Source impedance	(i) resistance=0.3Ω (ii)inductance=0.5mH
5th Harmonic Filter parameters	
L_5	0.0175 H
C_5	23.1 µF
7th 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)

Table-2 shows the FFT results of the waveforms of Fig-4. Load current THD is 24.76%.This indicates high amount of harmonics in load current. Source current THD is 12.52%. Reduction in source current THD is because of presence of passive filters. Load voltage THD is 4.39%. Power factor of the system is 0.9759.

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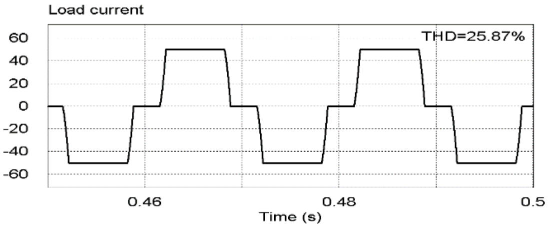

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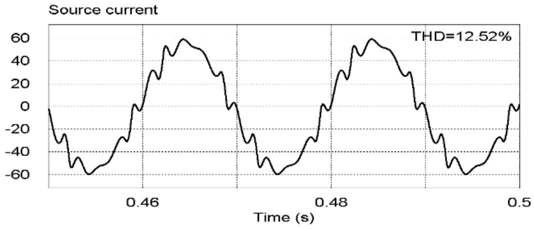

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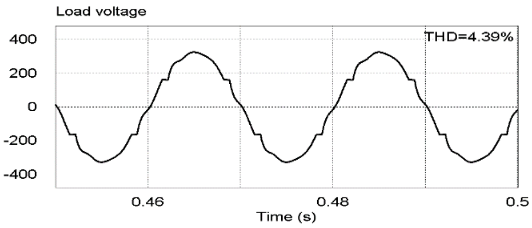
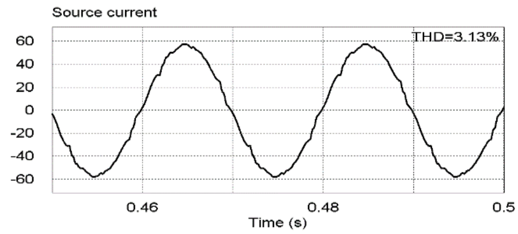
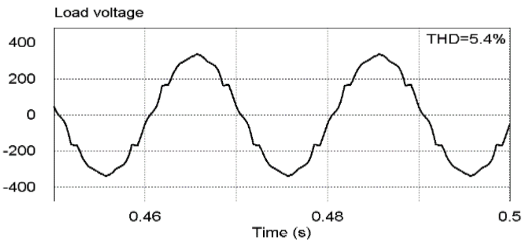


Figure 4 Simulation waveforms of system with passive filter as a harmonic eliminating device (a) Load current (b) Supply current (c) Load voltage

Table 2 Simulation results of the system with passive filters only

	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	35.38	6.69	4.55	2.52	1.95	2.29	1.75	24.76	0.9759
Source current	35.4	0.79	0.58	3.27	2.45	1.18	0.84	12.52	
Load voltage	208.06	3.88	2.25	5.75	5.06	3.18	2.51	4.39	

(a)


(b)


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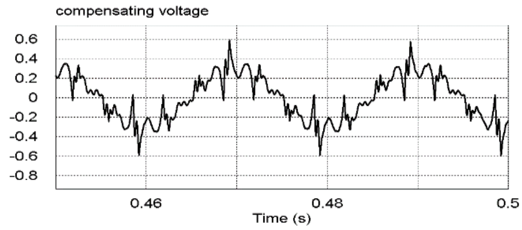


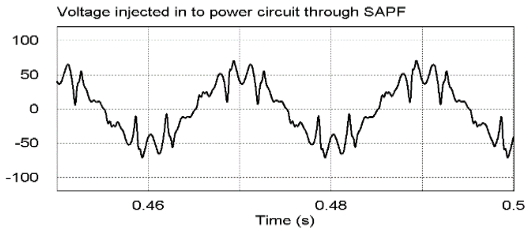
(d)


Figure 5 Simulation waveforms of HAPF topology (a) Source current (b) Load voltage (c) Compensating voltage (d) Voltage injected in to power circuit through SAPF

Fig-5 shows the simulation results of HAPF with both active and passive filters for phase-a. Fig-5 (a), (b), (c) and (d) show the source current, load voltage, compensating voltage and voltage injected by SAPF in the power circuit respectively.

Table-3 shows the FFT results of the waveforms of Fig-5. Source current THD is 3.13%. Reduction in source current THD indicates that SAPF is improving the performanc of passive filters. Load voltage THD is 5.4%. This one of the drawbacks of HAPF that load voltage harmonics are increased. Power factor is also improved to 0.9949.

Inverter rating is also one of the advantageous features of the HAPF. Rating of diode rectifier is 28 kVA. Inverter rating required to reduce source current THD to 3.13% from 12.52% is 4.63 kVA. This is reasonably less kVA requirement of the inverter as compared to standalone active filters.

Table 3 Simulation results of HAPF

	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	35.38	6.69	4.55	2.52	1.95	2.29	1.75	24.76	0.9949
Source current	36.5	0.69	0.41	0.81	0.52	0.21	0.17	3.13	
Load voltage	211.6	4.61	2.91	7.63	5.44	2.84	2.11	5.4	

Fig-6 shows the transient performance of the HAPF. For this, another nonlinear load drawing 50 amperes of dc current is connected to the system at 0.25 seconds with already existing nonlinear load drawing 50 amperes dc current. This shows that system has good transient response to change in load condition.

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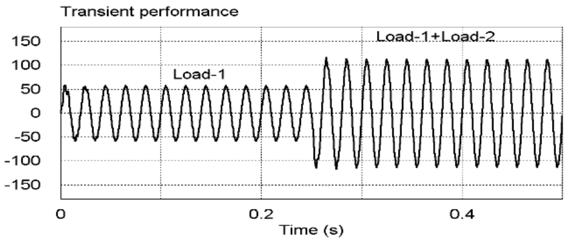

Figure 6 Transient performance of HAPF

V. CONCLUSION

Following conclusion is possible from the foregoing exercise.

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	4.39	0.9759
System with passive and active filter	3.13	5.4	0.9949

- The source current THD is reduced to 3.13% from 12.52% with application of HAPF which meets the IEEE 519 guidelines.
- Power factor improves to 0.9949 from 0.9759.
- Inverter rating to improve this current THD is 4.63 kVA. This is just 16.53% of load kVA, which is quite small if we compare with the similar rating shunt active power filter.
- The DC link voltage of inverter in this HAPF is 100 volts, which is also very small if we compare it with the similar rating shunt active power filter.
- On the drawback side, because of the series injection of harmonic voltage, the load voltage THD is increased to 5.4% which was earlier 4.39%.

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