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Modeling,Analysis and Simulation ofThree Phase Hybrid Power Filter forPower Quality Improvement

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Abstract:-A three-phase hybrid series power filter is constituted by a series active filter and a passive filter connected in parallel with the load. The control strategy is based on the "dual formulation of the electric power vectorial theory". The proposed algorithm eliminates the current harmonics of supply. It also improves the power factor and harmonic compensation features of the associated passive filter even if there is a change in system parameters.

A shunt hybrid power filter is constituted by a shunt active filter and a passive filter connected in parallel with the load, is proposed with same control strategy. Simulations have been carried out on the MATLAB-SIMULINK platform with different loads and with variation in the source impedance.

I.INTRODUCTION

The increase of nonlinear loads due to the proliferation of electronic equipment causes power quality in the powersystem to deteriorate. Harmonic current drawn from a supply by the nonlinear load results in 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 in parallel with the load. This compensation equipment has some drawbacks, due to which the passive filter cannot provide a complete solution.

These disadvantages are mainly the following.

—The compensation characteristics heavily depend on the system impedance because the filter impedance has to besmaller than the source impedance in order to eliminate source current harmonics.

—Overloads can happen in the passive filter due to the circulation of harmonics coming from nonlinear loads connected near the connection point of the passive filter.

—They are not suitable for variable loads, since, on one hand, they are designed for a specific reactive power, and on the other hand, the variation of the load impedance can detune the filter.

—Series and/or parallel resonances with the rest of the system can appear.

An active power filter, APF, typically consists of a three phase pulse width modulation (PWM) voltage source inverter. When this equipment is connected in series to the ac source impedance it is possible to improve the compensation characteristics of the passive filters in parallel connection. This topology is shown in Fig. 1, where the active filter is represented by a controlled source, where is the voltage that the inverter should generate to achieve the objective of the proposed control algorithm.

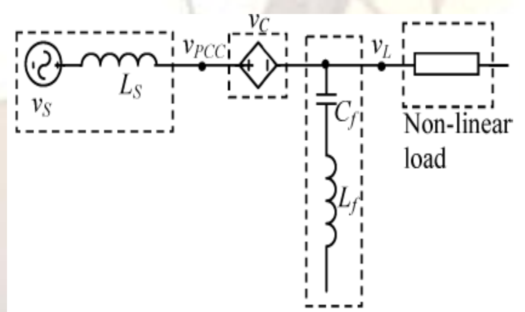

Fig. 1. Series active filter and parallel passive filter.

II. THE DUAL INSTANTANEOUS REACTIVE POWER THEORY

The instantaneous reactive power theory is the most widely used as a control strategy for the APF. It is mainly applied to compensation equipment in parallel connection. This theory is based on a Clarke coordinate transformation from the phase coordinates (see Fig 2). In a three-phase system such as that presented in Fig 3, voltage and current vectors can be defined by

$$V = [\, V_a V_b V_c \,]^T \quad i = [\, i_a i_b i_c \,]^T \quad (1)$$

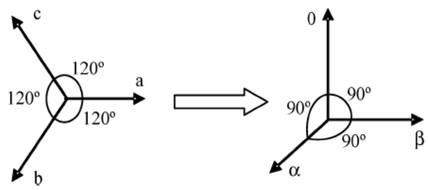

Fig. 2. Transformation from the phase reference system (abc) to the 0αβ system.

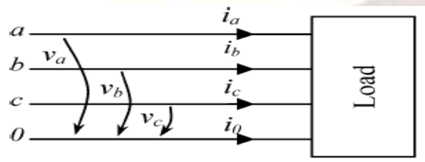

Fig. 3.Three-phase system.

The vector transformations from the phase reference system a-b-c to α-β-0 coordinates can be obtained, thus

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

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3)$$

The instantaneous real power in the α-β-0 frame is calculated as follows

$$P_{3\emptyset}(t) = V_\alpha i_\alpha + V_\beta i_\beta + V_0 i_0 \quad (4)$$

This power can be written as

$$P_{3\emptyset}(t) = P + P_0 \quad (5)$$

Where P is the instantaneous real power without zero sequence component and given by

$$P = V_\alpha i_\alpha + V_\beta i_\beta \quad (6)$$

It can be written in vectorial form by means of dot product

$$P = i_{\alpha\beta}^T V_{\alpha\beta} \quad (7)$$

Where $i_{\alpha\beta}^T$ is the transposed current vector in α-β-0 co-ordinates;

$$i_{\alpha\beta} = [i_\alpha i_\beta]^T \quad (8)$$

In the same way, $V_{\alpha\beta}$ is the voltage vector in the same co-ordinates;

$$V_{\alpha\beta} = [V_\alpha V_\beta]^T \quad (9)$$

In (5),p_0 is the zero sequence instantaneous power, calculated as follow as

$$p_0 = V_0 i_0 \quad (10)$$

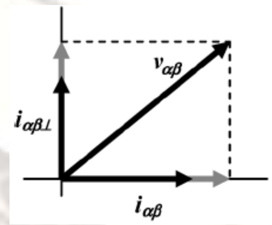

Fig.4.Decomposition of the voltage vector.

In a three-wire system there are no zero-sequence current components, so$i_0 = 0$. In this case, only the instantaneous power defined on the α-β axes exists, because the product $V_0 i_0$ is always zero.The imaginary instantaneous power is defined by the equation

$$q \cong V_\alpha i_\beta + V_\beta i_\alpha \quad (11)$$

In accordance with (7), this can be expressed by means of the dot product

$$q = i_{\alpha\beta\perp}^T V_{\alpha\beta} \quad (12)$$

Where, $i_{\alpha\beta\perp}^T$ is the transposed current vector perpendicular to $i_{\alpha\beta}$ and it can be defined as follows:

$$i_{\alpha\beta\perp} = [\, i_\beta - i_\alpha \,]^T \quad (13)$$

Both power variables previously defined can be expressed as

$$\begin{bmatrix} P \\ q \end{bmatrix} = \begin{bmatrix} i_{\alpha\beta}^T \\ i_{\alpha\beta\perp}^T \end{bmatrix} V_{\alpha\beta} \quad (14)$$

In the αβ plane, $i_{\alpha\beta}$ and $i_{\alpha\beta\perp}$ vectors establish two coordinates axes. The voltage vector $V_{\alpha\beta}$ can be decomposed in its orthogonal projection on the axis defined by the currents vectors, Fig 4. By means of the current vectors and the real and imaginary instantaneous power, the voltage vector can be calculated.

$$v_{\alpha\beta} = \frac{P}{i_{\alpha\beta}^2} i_{\alpha\beta} + \frac{q}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \quad (15)$$

In a four-wire system, the zero sequence instantaneous powerp_0 , is not null. In this case, (15) would have to include an additional term with the form $(\frac{P_0}{i_0^2})i_0$, where is the zero sequence current vector.

III. COMPENSATION STRATEGY

Electric companies try to generate electrical power as sinusoidal and balanced voltages so it has been obtained as a reference condition in the supply. Due to this fact, the compensation target is based on an ideal reference load which must be resistive, balanced and linear. It means that the source currents are collinear to the supply voltages and the system will have unity power factor. If, in Fig 3, voltages are considered as balanced and sinusoidal, ideal currents will be proportional to the supply voltages

$$V = R_e i \qquad (16)$$

R_e is the equivalent resistance, V is the load voltage vector and i is the load current vector.
The average power supplied by the source will be

$$P_s = i_1^2 R_e \qquad (17)$$

In this equation, i_1 is the square r.m.s value of the fundamental harmonics of the source current vector. Compensator instantaneous power is the difference between the total real instantaneous power required by the load and the instantaneous power supplied by the source.

$$P_c(t) = P_L(t) - P_s(t) \qquad (18)$$

In this equation, the average power exchanged by the compensator has to be null, that is

$$P_c(t) = \frac{1}{T}\int P_c(t)\mathrm{d}t = 0 \qquad (19)$$

When average values are calculated in (18), and (17) and (19) are taken into account

$$0 = \frac{1}{T}\int p_L(\mathrm{t}) - I_1^2 R_e \qquad (20)$$

Therefore, the equivalent resistance can be calculated as

$$R_e = \frac{P_L}{I_1^2} \qquad (21)$$

Where P_L is the load average power, defined as

$$P_L = \frac{1}{T}\int P_L(\mathrm{t})\,\mathrm{dt} (22)$$

The aim is that the set compensation equipment and load has an ideal behavior from PCC.

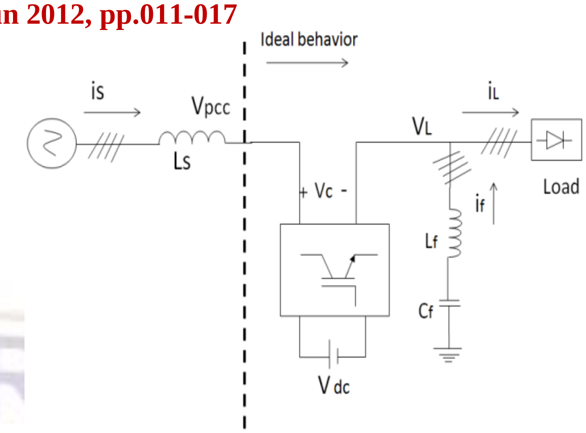

Fig.5. System with compensation equipment.

The voltage at the active filter connection point in 0αβ coordinates can be calculated as follows

$$v_{PCC\alpha\beta} = \frac{P_L}{I_1^2} i_{\alpha\beta} \qquad (23)$$

$i_{\alpha\beta}$ is the source current in 0αβ coordinates.

In this equation, the restriction of null average power exchanged by the active filter is imposed. The load voltage is given according to (15) by

$$v_{L\alpha\beta} = \frac{P_L}{i_{\alpha\beta}^2} i_{\alpha\beta} + \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \qquad (24)$$

Where, P_L is the real instantaneous power and q_L is the load imaginary instantaneous power. The reference signal for the output voltage of the active filter is

$$v_{C\alpha\beta}^* = v_{PCC\alpha\beta} - v_{L\alpha\beta} \qquad (25)$$

Considering (23) and (24), the compensation voltage is

$$v_{C\alpha\beta}^* = (\frac{P_L}{i_1^2} - \frac{P_L}{i_{\alpha\beta}^2})\, i_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} (26)$$

When the active filter supplies this compensation voltage, the set load and compensation equipment behaves as a resistor R_e. Finally, if currents are unbalanced and non-sinusoidal, a balanced resistive load is considered as ideal reference load. Therefore, the equivalent resistance must be defined by the equation.

$$R_e = \frac{P_L}{I_1^{+2}} \qquad (27)$$

Here, I_1^{+2} is the square r.m.s value of the positive sequence fundamental component. In this case, (26) is modified, where I_1 is replaced by I_1^+, that is

$$v_{C\alpha\beta}^* = (\frac{P_L}{i_1^{+2}} - \frac{P_L}{i_{\alpha\beta}^2})\, i_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \qquad (28)$$

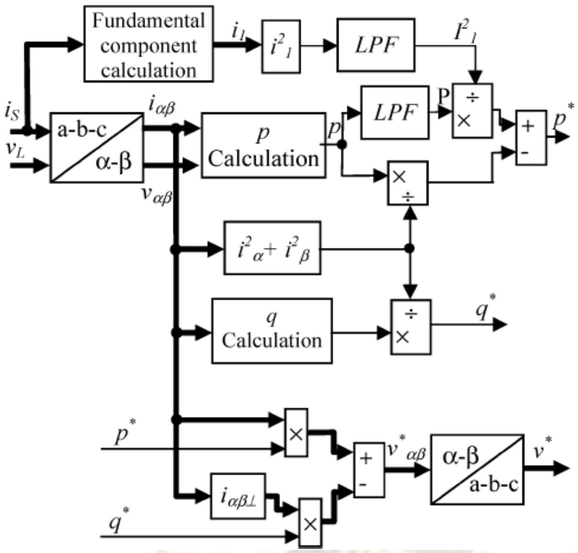

Fig.6.Control scheme.

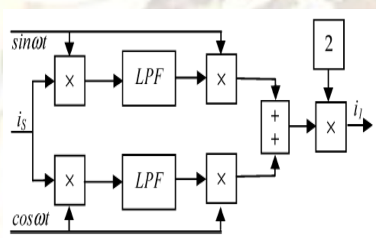

Fig.7.Calculation fundamental component.

Reference signals are obtained by means of the reference calculator shown in Fig 6 and Fig 7. In the case of unbalanced loads, the block “fundamental component calculation” in Fig 6 is replaced by the scheme shown in Fig 15, which calculates the current positive sequence fundamental component. However, a modification in the control scheme of Fig 6 is necessary. This consists in including a third input signal from the zero sequence power p_0 in the control block where $v^*_{0\alpha\beta}$ is generated.

IV. SIMULATION RESULTS

The system shown in Fig 8 has been simulated in the MATLAB-SIMULINK platform to verify the proposed control. Each power device has been modeled using the SIM Power System toolbox library. The power circuit is a three-phase system supplied by a sinusoidal balanced three-phase 100-V source with a source inductance of 5.8 mH and a source resistance of 3.6 Ω.

The inverter consists of an Insulated Gate Bipolar Transistor (IGBT) bridge. On the dc side, two 100-V dc sources are connected. An LC filter has been included to eliminate the high frequency components at the output of the inverter. This set is connected to the power system by means of three single-phase transformers with a turn ratio of 1:1.

The passive filter is constituted by two LC branches tuned to the fifth and seventh harmonics. Each element value is included in below table.

Passive filter	L5= 13.5 mH	C5= 30 µF
	L7= 6.75 mH	C7= 30 µF
Ripple filter	Lr= 13.5 mH	Cr= 50 µF

Table 1: Passive Element Values of filter

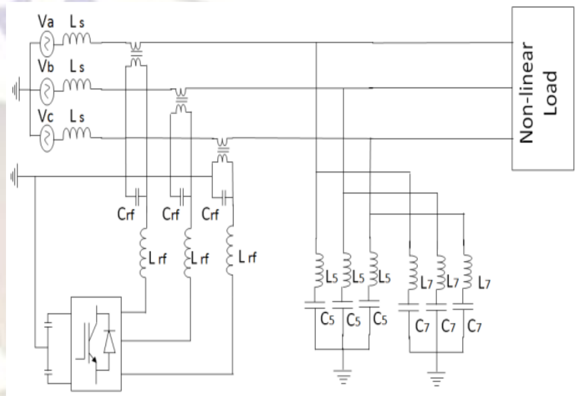

Fig.8. Series active power and passive filter topology.

The selection criteria to fix the ripple filter were, in the case of low frequency components, that the inverter output voltage be almost equal to voltage across C_{rf}. However, in the case of high-frequency components, the reduced voltage in L_{rf} must be higher than in the capacitor C_{rf}. Furthermore, L_{rf} and C_{rf} values must be selected so as not to exceed the transformer burden. Therefore, the following design criteria must be satisfied.

- $X_{Crf} \ll X_{Lrf}$, to ensure that inverter output voltage drops across L_{rf} at the switching frequency;
- $X_{Crf} \ll Z_s + Z_f$, to ensure that voltage divider is between L_{rf} and C_{rf} , where is the source impedance, the shunt passive filter, reflected by the secondary winding.

At 20-kHz switching frequency, Z_s= 728 Ω, Z_f = 565 Ω, X_{Crf}= 0.16 Ω, X_{Lrf} = 1696 Ω.

Two load types were considered:

A. Case 1: Non-Linear Balanced Load:

In this case, the nonlinear load consists of an uncontrolled three-phase rectifier with an inductance of 55 mH and a 25 Ω resistor connected in series on the dc side.

B. Case 2: Non-Linear Unbalanced Load:

In this case, the three-phase load is built with three single phase uncontrolled rectifiers with capacitors and resistors connected in parallel at the dc side with the values shown in below table.

	C	R
Phase a	2200 µF	16.67 Ω
Phase b	2200 µF	25 Ω
Phase c	2200 µF	50 Ω

Table 2: Passive Element Values of the Load

A. Case 1: Nonlinear Balanced Load:

In this case, the nonlinear load consists of an uncontrolled three-phase rectifier with an inductance of 55 mH and a 25 resistor connected in series on the dc side.

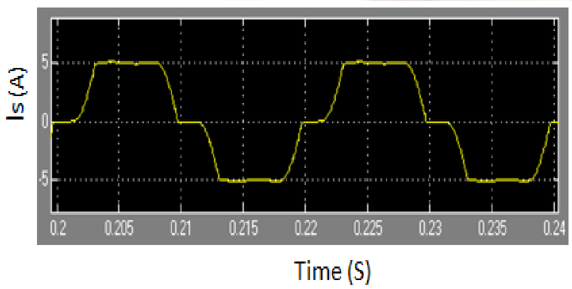

Fig.9. Source current of the phase “a”.

Fig 9 shows the phase “a” source current. The load current total harmonics distortion (THD) is 18.83% and the power factor 0.941, when the system is not compensated. The 5th and 7th harmonics are the most important in the current waveform. They are 16.3% and 8.4% of the fundamental harmonic, respectively.

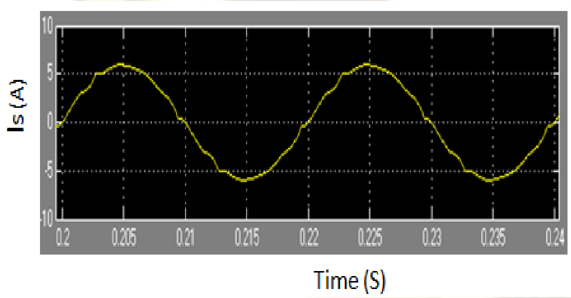

Fig. 10.Source current when the passive filter is connected.

The source current waveform with the passive filter connected is shown in Fig 10. The THD falls to 3.1% and power factor is 0.979.When the series active and passive filter is connected, the source current THD falls to 1.34%. The waveform is shown in Fig 11.

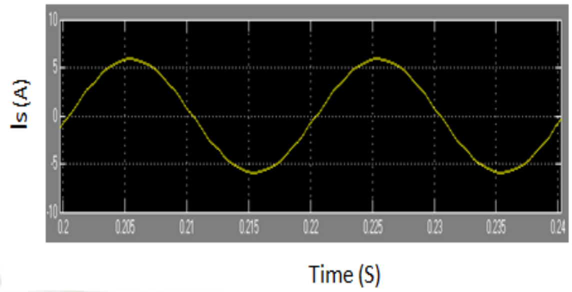

Fig. 11. Source current when the series active and passive filter is connected.

Now, thepower factor rises to 0.99. This allows the proposed control to be verified, the passive filter compensation characteristic to be improved and unity power factor is practically achieved.

The passive filter impedance has to be lower than the systemimpedance in order to be effective. When the branch LC orimpedance source quality factor is low, the harmonics filteringdeteriorates. To verify the behavior of the compensation equipmentin this situation, the source impedance is modified. It ischanged from 3.6 and 5.8 mH to 1.3 and 2.34 mH. Thesource current has a THD of 10.1%, when the active filter is notconnected and the compensation equipment is only the passivefilter.

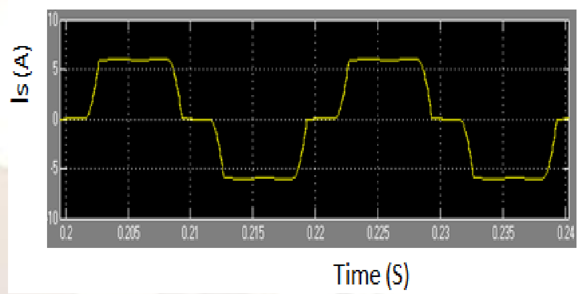

Fig.12.Source current of the phase “a”.Source impedance, 1.3 Ω and 2.34 mH.

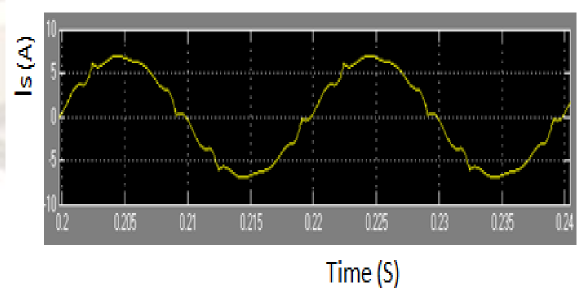

Fig.13. Source current when passive filter is only connected. Source impedance, 1.3 Ω and 2.34 mH.

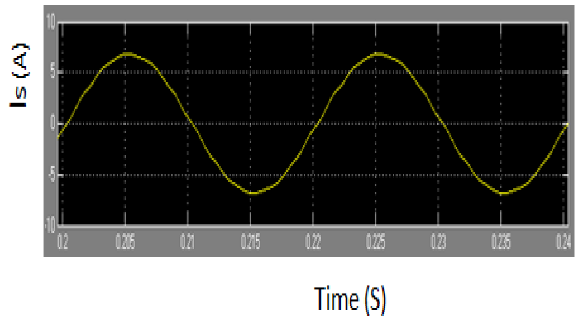

Fig.14. Source current when the series active and passive filter is connected. Source impedance 1.3 Ωand 2.34 mH.

When the series active filter is working with the proposed control algorithm, the THD of the source current improves to 1.68% and the power factor is 0.99.

Therefore, with the proposed control algorithm, the set series active filter and passive filter allow the compensation of variable loads.

B. Case 2: Non-Linear Unbalanced Load:

In this case, the three-phase load is built with three singlephaseuncontrolled rectifiers with capacitors and resistors connectedin parallel at the dc side with the values shown in Table II.

Fig 16 shows the source currents in the uncompensatedsystem. Current THDs of “a”, “b”, and “c” phase are 11.17%,36.60%, and 43.3%, respectively and power is 0.925.

The control scheme for the active filter shown in Fig 6ismodified for unbalanced loads. The block “fundamental componentcalculation” in Fig 7 is replaced by the scheme shownin Fig. 17. Now the average power P is divided by the squarer.m.s value of positive sequence fundamental component. In thiscase, the positive sequence component is calculated by meansof the block “positive sequence component”.

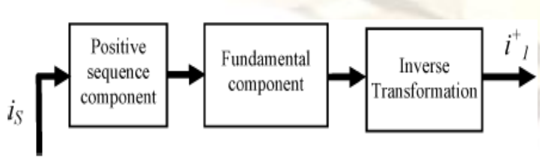

Fig.15.Modification in the control scheme for unbalanced load.

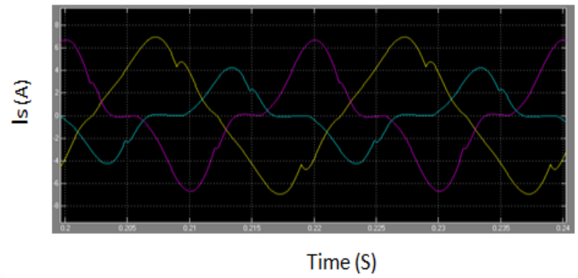

Fig.16.Source current without filters.Unbalanced load.

Fig 17 shows the three source currents when this control is applied to the active filter. The system presents a behavior similar to a resistive and balanced load. The source currents THD are 1.22%, 1.66%, and 2.21% in phases “a”, “b”, and “c” and power factor is increased from 0.925 to 0.99.

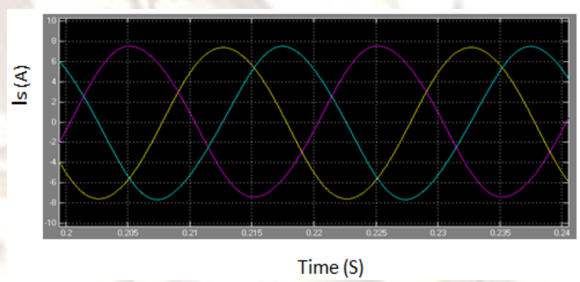

Fig.17.Source current with series active and passive filters and unbalanced load.

V. SHUNT HYBRID POWER FILTER

The system parameters and control scheme are same as in hybrid series active filter. But, active and passive filters are connected in series and both are connected parallel to non-linear load. In this circuit, isolation transformer and ripple filter is not required.

Fig 18 shows the three source currents when the shunt active and passive filter is connected, the source current THD reduced to 3.6% and power factor of the supply is increased to 0.982.

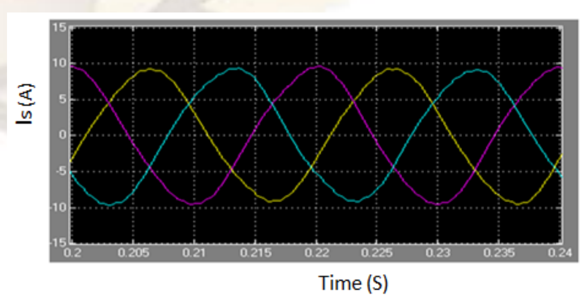

Fig.18.Source current when the shunt active filter and passive filter is connected.

VI. CONCLUSIONS

A hybrid series power filter constituted by a series active filter and a passive filter connected in parallel with the load is simulated. The control strategy is based on the dual formulation of the electric power vectorial theory.

1. In Balanced and Unbalanced load condition, the proposed hybrid series active filter is effectively reduced the source current harmonics (THD) to lower values.
2. Therefore, with the proposed control algorithm, the active filter improves the harmonic compensation features of the associated passive filter even if there is a change in system parameters and the power factor.

A shunt hybrid power filter constituted by a shunt active filter and a passive filter connected in parallel with the load, is proposed. The passive filter suppresses the 5^{th}& 7^{th} harmonics produced by the load, whereas the active filter eliminates the current harmonics of higher order and improves the power factor.

The proposed shunt active filter has the advantages of low rating as compared with the series active filter.

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