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Effect of harmonics on reduction of unbalance in three-phase four wire composite network

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ABSTRACT

The unbalanced current drawn by the composite loads in small-scale industries is mainly due to single-phase loads. Any operation of single-phase loads will cause unbalance of current and produce distortion due to non-linear loads. The neutral current is increased and voltage at the load end is reduced due to an increase in unbalanced linear loads. Industries find it difficult to balance the load and control the neutral current. To overcome the problem, this work aims to add a passive network in different configurations along with shunt active power filter. A set of linear and non-linear loads are considered in the network and the results are discussed in this paper. The L and C values are designed to compensate for the required reactive power and the canceling of negative and zero sequence current quantities due to unbalance in the circuit. This paper also reviewed the effect of active filter RMS current at an unbalanced load current.

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1. INTRODUCTION

Large single-phase loads used in three-phase four-wire supply system are causing problems such as unbalance, excessive neutral current, and third harmonics. These loads are in combination with Linear and Non-Linear loads have different impacts when it is used with a voltage source inverter [1]. The idea for solving it required reducing the unbalancing, neutral current, and possibly the harmonics. A three-phase four-leg topology of voltage source inverter is used with hysteresis control of current and reduced switching frequency to compensate for unbalanced non-linear loads. Three-phase four-wire load passive compensation with different VSI topologies is used to track reference currents for unbalanced and nonlinear loads [2]. The problem of the three-phase four-wire supply is in the neutral having flow of current from load affecting the conductor. A suitable controller of the inverter is absolutely necessary for reactive power compensation and harmonics eliminations. The homopolar components of the current are used in the controller to mitigate it [3]. Improved control algorithm and suitable current control used in the active filtering methods for load balancing, reactive power compensation analyzed in this paper [4]. Improved control algorithm and suitable current control used in the active filtering methods for load balancing, reactive power compensation analyzed in these papers [5]. A shunt compensating device used for mitigating harmonics is investigated for non-linear loads in the distribution system [6]. Speed drives produce higher-order harmonics with higher torque applications in marble industries and drilling rigs [7], [8]. Several topologies of the high-order passive filters interfacing voltage source converters are considered to determine damping capability [9] A universal solution to the harmonics problem is active harmonics filtering [10]. Active power filters for a three-phase four-wire network are taken for study [11] and also verified with reactive power compensation [12]-[16]. Several algorithms with improved control are used for active filtering [17]. Performance evaluation on active filter overloading is investigated using a scaling power algorithm [18]. A common control algorithm is used to overcome all the problems using composite loads [19]. The best effective algorithm using the synchronous reference frame theory is used for the distribution system [20], [21]. The effect in third harmonics, inverter type, and hybrid filter environment are applied in distribution static compensator (DSTATCOM) and distributed generation (DG) applications [22]-[24]. The passive compensator design is considered from the sample network which is worked out for unbalanced linear and non-linear loads [25]. The voltage unbalances caused due to current imbalance in single-phase loads in distribution networks are reviewed with various characteristics for maintaining the reliability of operation [26]-[30].

This paper Part-3 for the compensator for load balancing (CLB) is subdivided into three parts with the simulation of the balanced non-linear and unbalanced linear network. Part 3.1 explains the output for only an unbalanced linear network along with compensator for load balancing and Part 3.2 is discussing harmonics elimination with only a non-linear network. Also, Part 3.3 illustrates both the combined network to study the reduction of neutral and filter root mean square (RMS) current.

2. METHOD

2.1. Network description

The small-scale industries are using a 415 V/220 V supply system which is easy to feed power using a three-phase four-wire supply with sufficient stiffness. Shunt active power filter is used suitable for use of non-linear loads. The impedance values for the unbalanced linear and balanced non-linear are used in the network. A full-bridge diode rectifier with a balanced non-linear load is considered in the test network shown in Figure 1.

Low voltage 415 V/220 V three-phase four-wire supply system is taken for the study. A simple diode rectifier is used with the balanced RL load. Unequal linear single-phase load impedances are considered for an unbalanced linear loading. The amount of unbalanced voltage limit due to unbalanced current is checked with IEEE 112 (1991). The simulation uses a shunt active power filter with dqo theory for the distorted current. The rms load current, neutral current and % unbalance before filter and filter compensating current are observed from the simulation result.

The passive network is designed from the values of impedances in each phase. The unbalanced current drawn is observed from the result of MATLAB simulation. The passive network containing L and C values in star and delta configuration is generated is used to reduce neutral current, filter rms current and % unbalance load current in the test network. The simulation results are verified in the reduction of neutral current and filter current and compared for the test network.

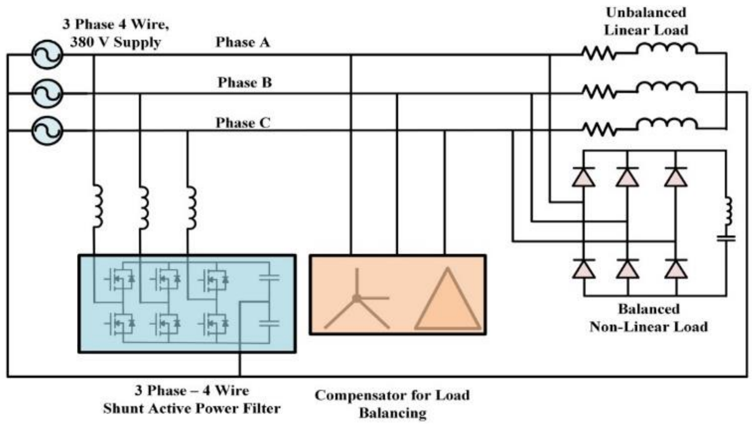

Figure 1. Three-phase four-wire network

2.2. Shunt active power filter (SAPF)

The load currents are drawn by the composite loads given as input to the shunt active power filter using the dqo theory. The schematic diagram of the filter is shown in Figure 2. The filter is having voltage source converter (VSC) with a DC capacitor having the fourth wire as neutral. The three-phase quantities are converted into two-phase quantities to separate harmonics components. Error signals generated by the controller and current-controlled gating signals are sent to VSC.

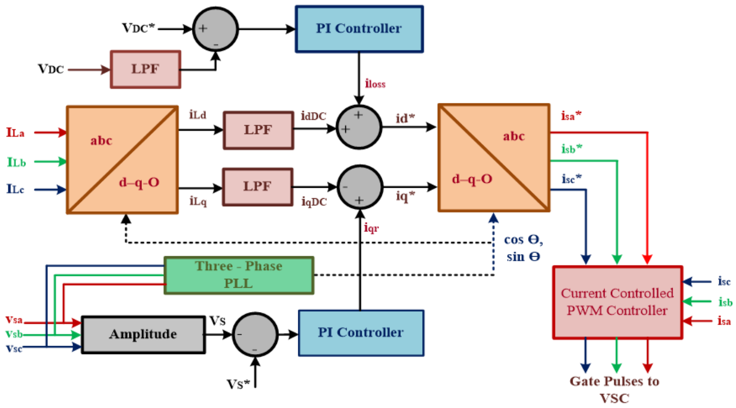

Figure 2. Block diagram of shunt active power filter (SAPF) using dqO theory

The a, b, c components are converted into d, q, o quantities using the following transformation matrix as shown in (1).

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{Lo} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{1}$$

The controller extracts DC quantities and harmonics signals and is separated from the reference alternating current (AC) signals. The current controller is used to generate the gating signals are generated which are sent to VSC. SAPF parameters are designed from the rectifier RMS input current of the non-linear load and fast fourier transform (FFT) values are verified from the simulation results. The designed values of filter parameters in Table 1.

Table 1 SAPF parameters

Parameters	Values
VDC	750 V
CDC	5100 MFD
Interfacing Inductor	0.9 + j 0.314
Kp	0.08
Ki	0.2

2.3. Proposed LC compensator for load balancing (CLB)

The three-phase compensator for load balancing is designed with LC elements in grounded star and delta connections used for reducing neutral current, reducing harmonics, and improving power factor respectively. The symmetrical components of unbalanced currents are considered in terms of voltage and its susceptances. In the design of the compensator, the following conditions from (2) to (5) are considered to cancel the negative and zero sequence currents of load and compensator, and (6) and (7) are to used cancel the imaginary part of the positive sequence for improving power factor to unity.

$$\mathrm{Real}(I_{-}) + \mathrm{Real}\,(I_{-\,compY}) + \mathrm{Real}\,(I_{-\,comp\Delta}) = 0 \tag{2}$$

$$\mathrm{Imag}\,(I_{-}) + \mathrm{Imag}\,(I_{-\,compY}) + \mathrm{Imag}\,(I_{-\,comp\Delta}) = 0 \tag{3}$$

$$\mathrm{Real}\,(I_{0}) + \mathrm{Real}\,(I_{0\,compY}) = 0 \tag{4}$$

$$\mathrm{Imag}\,(I_{0}) + \mathrm{Imag}\,(I_{0\,compY}) = 0 \tag{5}$$

$$\text{Imag}(I_{+}) + \text{Imag}(I_{+\,compY}) + \text{Real}(I_{+\,comp\Delta}) = 0 \quad (6)$$

$$\text{Imag}(I_{+\,comp\Delta}) = B_{ab\ comp\Delta} + B_{bc\ comp\Delta} + B_{ca\ comp\Delta} = 0 \quad (7)$$

From the above conditions, the LC values are computed from the solution of its susceptances with (8) to (13) and Table 2.

$$B_{a\ compY} = -B_a + (G_b - G_c)/\sqrt{3} \quad (8)$$

$$B_{b\ compY} = -B_b + (G_c - G_a)/\sqrt{3} \quad (9)$$

$$B_{c\ compY} = -B_c + (G_a - G_b)/\sqrt{3} \quad (10)$$

$$B_{ab\ comp\Delta} = (2/3)(G_a - G_b)/\sqrt{3} \quad (11)$$

$$B_{bc\ comp\Delta} = (2/3)(G_b - G_c)/\sqrt{3} \quad (12)$$

$$B_{ca\ comp\Delta} = (2/3)(G_c - G_a)/\sqrt{3} \quad (13)$$

The obtained values of L and C from (8) to (13) are tabulated vide Table 2. These values are calculated from the load current for the specified network condition.

Table 2. Values of R, L and C for LC compensator for load balancing (CLB)

Compensator	R (Ω)	L (mH)	C (MFD)
Star – Phase a	27.33	-	119.02
Star – Phase b		-	11.03
Star – Phase c		-	106.25
Delta – Phase a-b	27.33	-	22.73
Delta – Phase b-c		-	29.38
Delta – Phase c-a		194.65	-

3. RESULT AND DISCUSSION

The designed LC values are used in the compensator circuit with the balanced non-linear and unbalanced linear loads. Simulation is carried out for 0.5 s with switching of compensator at 0.25 s for the combinations of linear and non-linear loads. The SAPF in the network is used to study the change in filter current and harmonics with and without a compensator. The results are verified for the conditions and discussed the solution to the network.

3.1. Unbalanced linear load with and without compensator for load balancing (CLB)

Table 3 shows the R and X values for the unbalanced linear loads. The shunt active power filter in the network is working in synchronous reference frame (SRF) algorithm for the values of linear load. As the loads are linear, the total harmonic distortion (THD) values were found negligible.

Table 3. Unbalanced linear load

Phase A		Phase B		Phase C	
R(Ω)	X (Ω)	R (Ω)	X (Ω)	R (Ω)	X (Ω)
15	6.2	17	12.4	20	31.4

The neutral current is reduced from 10 A to 7.3 A peak as shown in Figure 3. Due to the introduction of CLB in the circuit the percentage unbalanced is reduced from 35.9% to 21.2% and reduced filter RMS current. The reduction of filter current obtained from the simulation is shown in Figure 4 The filter currents in individual phases in Table 4. The power factor is improved from 0.75 on average to 0.99 with CLB and its values in Table 5. The reduction of filter power is found 28% from the simulation results which are tabulated in Table 6.

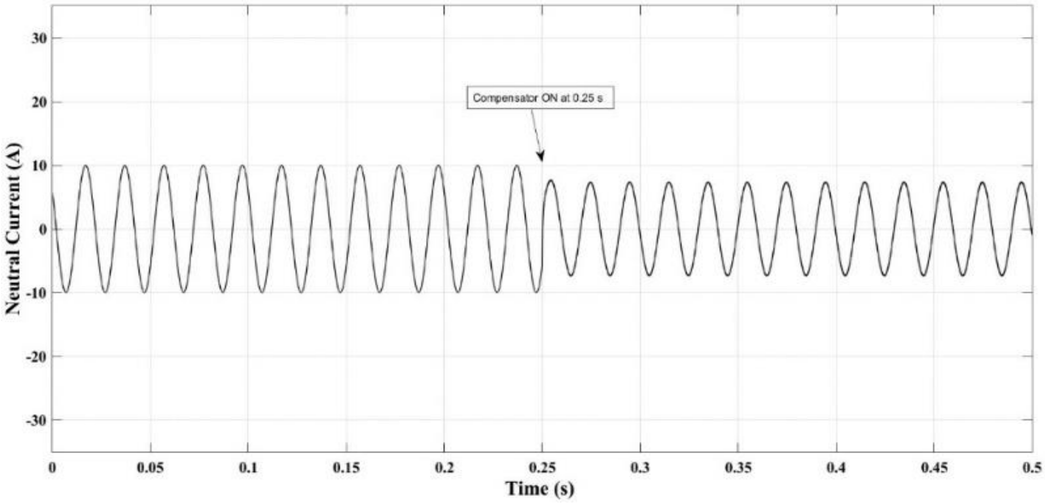

Figure 3. Neutral current at load side

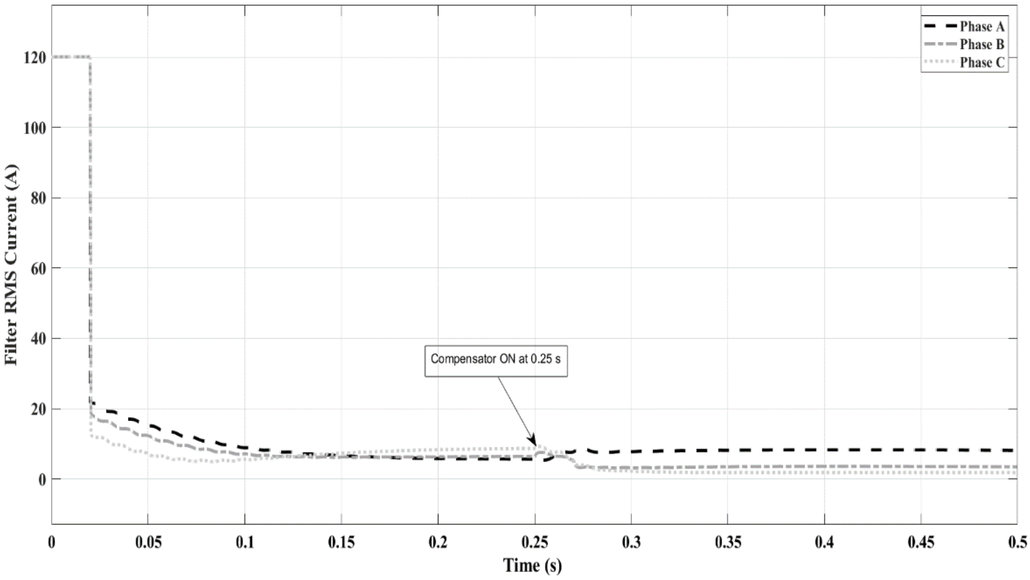

Figure 4. Filter RMS current

Table 4. Filter RMS current

Before compensator			After compensator		
Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
6.63	6.152	7.196	4.511	4.418	1.839

Table 5. Power factor

Before compensator			After compensator		
Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
0.9244	0.8084	0.537	0.9926	0.999	0.991

Table 6. Filter power (kW)

Before compensator			After compensator		
Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1.35	1.09	0.85	.985	.971	.401

3.2. Balanced non-linear load with and without shunt active power filter (SAPF)

A simple diode bridge rectifier is considered as non-linear source feeding to a RL load. Balanced RL load parameters as given in Table 7. As the load is balanced the simulation is done without compensator. The current THD is reduced from 28.44% to 0.51% by harmonics elimination due to SAPF connected into the circuit at 0.25 sec as shown in Figure 5. The spectrum of harmonics current at the source with individual harmonics due to SAPF connected into the circuit is shown in Figure 5.

Table 7. Non-linear load

V (Ph)	R (Ω)	L (mH)
220	80	60

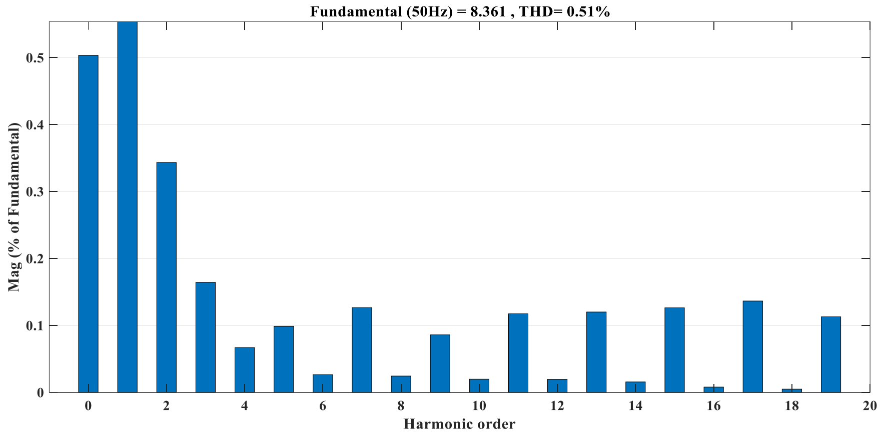

Figure 5. Harmonics Spectrum after SAPF

3.3. Composite loads with and without compensator for load balancing (CLB)

Simulation with both balanced non-linear and unbalanced linear loads done without and with compensator (CLB). The current THD is reduced from 14.7% to 7.43% due to the compensator in the circuit and the values as shown in Table 8 and the harmonics spectrum shown in Figure 6. The simulation is done for 0.6s with CLB on at 0.3 s. The average filter RMS current is reduced considerably to 40% and its values before and after compensator as shown in Table 9. The corresponding simulation output is shown in Figure 7.

Table 8. Current % THD (Load side)

Before compensator			After compensator		
Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
7.68	9.49	14.7	6.8	9.8	7.43

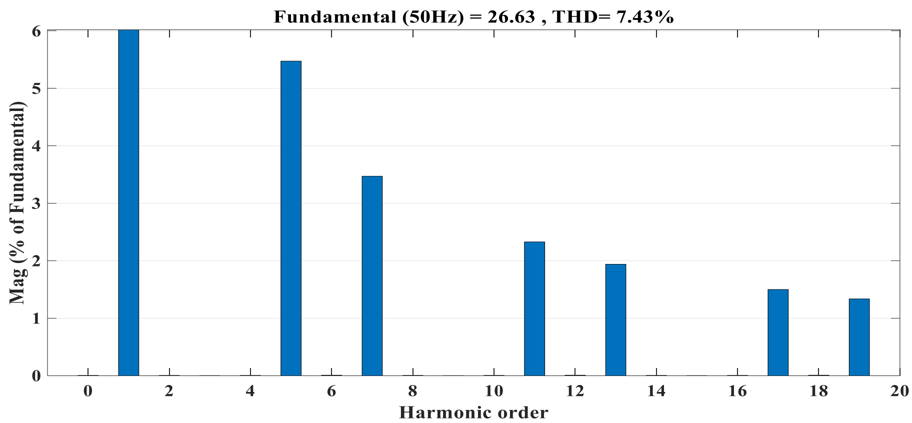

Figure 6. Current THD with CLB

Table 9. Filter RMS current

Before compensator			After compensator		
Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
5.532	8.464	12.14	4.93	4.36	2.45

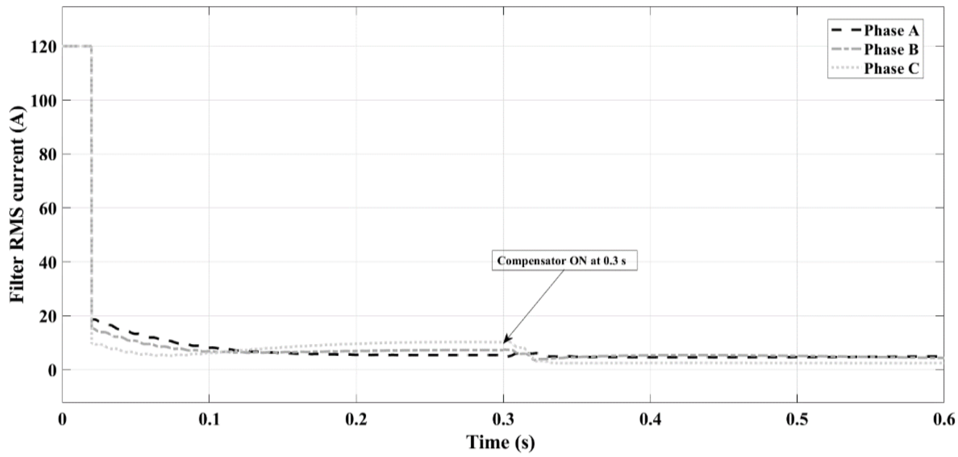

Figure 7. Filter RMS current

The simulation result on neutral current and the improved power factor before and after the compensator (CLB) in the circuit is shown in Table 10. It is observed that the neutral current is reduced to 25% due to compensator. The power factor is increased from 0.905 to 0.99. The kVA rating of the filter also reduced proportionately to 40% after the compensator connected into the circuit. The reduction of filter current and unbalance due to CLB used in different load network shown in Figure 8.

Table 10. Power factor

Before compensator			After compensator		
Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
0.9583	0.9075	0.8499	0.977	1	0.995

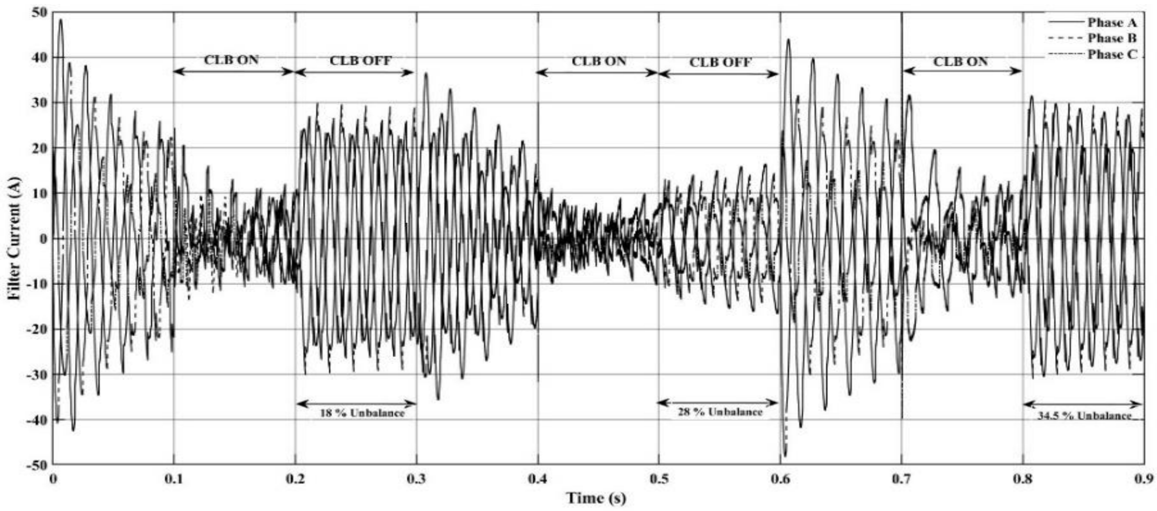

Figure 8. Filter current in different percentage unbalance loads

4. CONCLUSION

The network consisting of combined unbalanced linear and balanced Non-linear loads is considered for balancing of load using LC compensation for load balancing (CLB). The percentage of unbalance is reduced from 28.3% to 14.8%. This reduction is marginally less from the expected value. In the future scope the line current for unbalanced non-linear loads and its power factor for the total load may considered for designing the LC values of the compensator for load balancing (CLB). The neutral current is reduced to 25% with CLB connected into the circuit. The rating of SAPF in kVA reduced into 40% of its rating without Compensator. The average current THD without CLB of 10.62% is reduced to 8.01% without any harmonics filter. A 3rd order De-tuned filter can be used for not only to suppress the 3rd harmonics but also to reduce its kVA rating of SAPF. It also aids in preventing resonance from occurring at or near 3rd order frequency. A suitable controller with the ratio of linear to non-Linear loads can be devised. The different percentages of unbalance may be considered for the reliability of CLB supporting SAPF for its saving on the cost and for its utilization based on the demand of SAPF.

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