Selective De-Tuned Harmonics Compensation for Unbalanced Composite Loads

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Abstract- Medium voltage industrial consumers for the demand up to 40 kW are experiencing several issues, including low power factor, increasing imbalance current, rising neutral current, limited utilization of active filters, and growing total harmonics distortion. Since most of the loads are current driven and prone to problems, this paper proposes a comprehensive solution using a straightforward analytical approach. The proposed solution involves a three-phase, 380 V supply system equivalent to a grid-tied renewable medium voltage supply system with both balanced non-linear loads and unbalanced linear loads. The problem is addressed by utilizing specifically designed compensators and de-tuned filters. Firstly, emphasis is placed on current balancing and power factor improvement up to unity. This is achieved by employing a compensating network with carefully designed LC components. Secondly, a harmonics assessment is conducted on the total harmonics distortion of current and the identification of dominant characteristic harmonics through network simulations. Thirdly, the individual harmonics distortion, which indicates the harmonics content in each phase, is obtained from the simulation. Frequency scanning is used to identify harmonics resonance in 5th-order harmonics in composite loads. The harmonics impedance values of the 5th-order harmonics are reduced by detuning the selected frequency between 3 % and 5 % in the design of filters. To validate the proposed solution, a test network is simulated using MATLAB Simulink, and results are verified for the recommended values of standard IEEE519.

Keywords Total Harmonics Distortion (THD), Individual Harmonics Distortion (IHD), Harmonics Impedance, De-Tuned Filter, % Unbalance

1. Introduction

Industries consume power based on the category of consumers such as commercial, start-up, and small-scale industrial consumers prescribed by the supplier. The statutory requirements such as power demand, power factor, and harmonics vary depending on the category. The imposed parameters are challenging the consumers, connected with combined linear and non-linear loads. In effect those problems such as increased neutral current, THD, low power factor, and poor demand management. Many research papers discussed on implementation of Shunt Active Power Filters and Voltage Source Inverters which provide a universal solution to non-linear loads. When combined with non-linear as well as linear order to preserve operational dependability [6]-[9]. A three-phase balanced and unbalanced load flow is carried out with a conventional backward and forward sweep technique.[10]. loads, these types of loads have various effects when employed with a voltage source inverter [1]. The problem with the three-phase four-wire supply is that current flows from the load into the neutral, harming the conductor. A proper inverter controller is essentially required for reactive power correction and harmonics reduction. [2-4].

The above load draws unbalanced currents from the source which creates additional problems such as the generation of third harmonics, increased neutral current, etc., and the varying rectifier loading condition is compensated for harmonics using active filters.[5]. The voltage unbalances generated by a current imbalance in single-phase loads in distribution networks are examined with varied features in

Non-linear reactive unbalanced loads are considered with Unified Power Quality Conditioner using an improved control method.[11]. A control scheme with a common inner inductor current loop is used for both the positive and negative sequence components, for the unbalanced load and source emulations. [12, 13]. The industries drawing power at high voltage levels are primarily focused on limiting the polluting harmonics level at the Point of Common Coupling. % current THD is reduced due to the impedance of the feeding transformer. Three-phase compensators are used for balancing, reactive power compensation and mitigation of harmonics separately in the distribution system. [14]-[16]. Higher-order harmonics are produced by speed drives with higher torque applications in the marble industry and drilling rigs [17]. Current controlled hybrid filters to overcome the problems due to harmonics.[18]. Improved control algorithms and appropriate current control employed in active filtering methods for load balancing as well as reactive power compensation investigated within these publications [19-21]. Numerical problems are solved by taking unbalanced linear loads to balance and improve the power factor [22]. The failure of power factor improvement capacitors and its contacts are due to high voltage predominantly causing insulation failure and resulting phase and ground faults. It is needed to study the network with the supply system using a frequency scan [23-28]. An advanced thyristor-switched detuned capacitor is used to improve harmonic filtering in the operation of AC single-phase spot welding [24,25]. LCI drive passive filter is used for eliminating detuning effects, resonance elimination, and harmonic loading of capacitors, in an Iranian large copper mine company [25-27]

Smart Photovoltaic inverter for resonance mitigation is a novel approach using virtual detuner. The power quality describes network resonance as a major contributor that has an impact on harmonic levels [28-29]. PV Transformer Reliability in Unbalanced Conditions is enhanced for Solar Power Plants. [31]. PS-PWM is used to reduce THD in a PEC-9 inverter, integrating active capacitor balancing and redundant switching states. [32] Sensorless DC voltage regulation method combined with single-phase p-q theory for improved power quality in shunt active power filters to reduce sensor and costs. [33] Matrix converter-based D-STATCOM is used to mitigate LED-induced harmonics in low voltage distribution networks. [34] A simplified model of a SAPF for power quality enhancement in a modern grid includes a single current control loop with an LCL filter output as feedback, using a PI controller confirm its effectiveness. [35]

This paper considered a 3P-4W load network combined with linear and nonlinear loads. As most of the research is done with common loading, this work is taken with different operating conditions. Also, the load balancing and reactive power compensation are done simultaneously in the test network. This work is divided into three parts. Part 1 is the modeling of test work in different combinations with a stiff supply system in MATLAB. Simulink. Part 2 is the design of a compensator for load lancing and reactive power compensation to determine the reduction in unbalance and improvement in power factor. Part 3 evaluates the THD, IHD, and impedance using frequency to avoid resonance. The results are verified with the recommended IHD limit prescribed by IEEE 519-2014 [30].

2. Method

2.1.Network Description Load Modeling

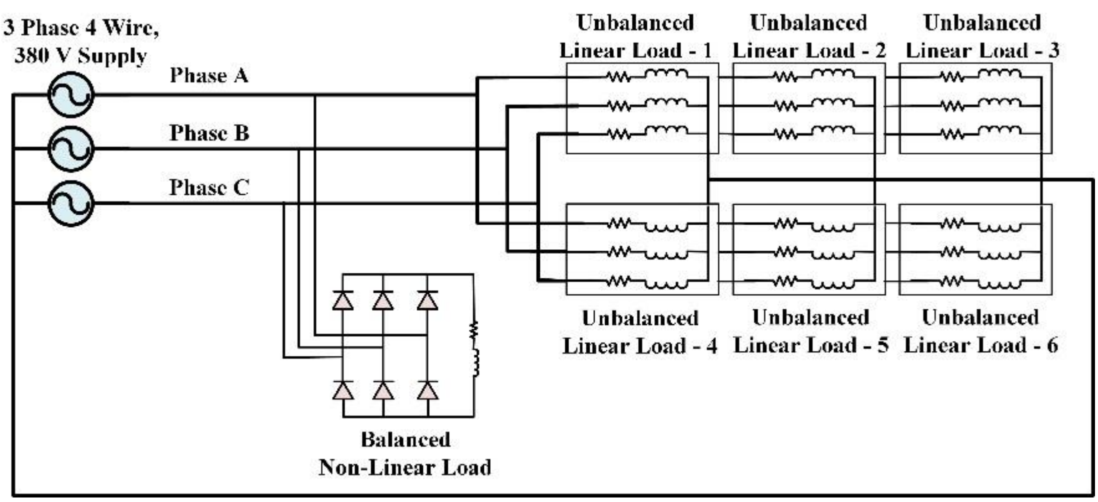


Fig 1. Three-phase four-wire network

Table 1. R, X values of Linear and Non-Linear Loads

Non-Linear Load		Load -1		Load -2		Load -3	
R(Ω)	X(Ω)	R(Ω)	X(Ω)	R(Ω)	X(Ω)	R(Ω)	X(Ω)
80	18.8	22	16.5	15	6.2	6.4	4
		12.8	13.1	17	12.4	7	5.3
		13.2	17.6	20	31.4	11	5.3
		Load -4		Load -5		Load -6	
		3.5	1.9	3.1	1.9	3	1
		11	5.3	9.7	8.6	5.5	4.1
		5.4	4.2	8.1	3.4	16.5	14.6

Table 2. Three-Phase Supply Parameters

Supply Voltage (Line)	SCC (MVA)	X / R
38	100	10

Table 2a. kW rating of Composite Loads

Composite Loads	Phase a	Phase b	Phase c
1	1.9	2.1	1.8
2	2.9	2.1	1.3
3	3.7	3.2	3.1
4	4.8	3.1	3.4
5	4.7	2.5	3.7
6	5.8	3.6	1.9

The industries are working with different supply voltage according to their power demand. The nominal medium and low voltages are 381V and 220 V. The source data for the three-phase four-wire supply system are given in Table 2. As per Table 1. the R and X values for the unbalanced linear and balanced non-linear loads in each phase are used in the network. And the composite loads are rated 220 V, and 0.87 power factor with the power rating as given in Table 2a. A diode bridge rectifier is used as a source of harmonics at the load side. Figure 1. Shows the test network considered for the study with single-phase loads rated 220 V. Unequal linear single-phase load impedances are considered for an unbalanced linear loading. The % unbalance of voltage is verified with the limit of IEEE 112 (1991). The drawn unbalanced current due to different loads are obtained after MATLAB simulation.

2.2 Design of Compensator for Unbalance Composite Load

The sequence quantity of load currents is considered in equations (1), (3), and (5). As per equations (2), (4), and (6), it is represented in terms of susceptance values of known unbalanced load impedances. The balanced non-linear load is considered constant.

$$I_0 = \frac{I_a + I_b + I_c}{\sqrt{3}} \tag{1}$$

$$I_0 = \frac{\{(G_a + a^2 G_b + a G_c) + j (B_a + a^2 B_b + a B_c)\} V_{ph}}{\sqrt{3}} \tag{2}$$

$$I_+ = \frac{I_a + a I_b + a^2 I_c}{\sqrt{3}} \tag{3}$$

$$I_+ = \{(G_a + G_b + G_c) + j (B_a + B_b + B_c)\} \sqrt{3}\ V_{ph} \tag{4}$$

$$I_- = \frac{I_a + a^2 I_b + a I_c}{\sqrt{3}} \tag{5}$$

$$I_- = \frac{\{(G_a + a^2 G_b + a G_c) + j (B_a + a B_b + a^2 B_c)\} V_{ph}}{\sqrt{3}} \tag{6}$$

The sequence components of the unbalance load current and compensator currents cancel each other and the sum of following components are made equal to zero. The susceptance values for the star and delta configuration are obtained in equations (7)-(12).

$$B_{a\,compY} = -B_a + (G_b - G_c)/\sqrt{3} \tag{7}$$

$$B_{b\,compY} = -B_b + (G_c - G_a)/\sqrt{3} \tag{8}$$

$$B_{c\,compY} = -B_c + (G_a - G_b)/\sqrt{3} \tag{9}$$

$$B_{ab\,comp\Delta} = (2/3)(G_a - G_b)/\sqrt{3} \tag{10}$$

$$B_{bc\,comp\Delta} = (2/3)(G_b - G_c)/\sqrt{3} \tag{11}$$

$$B_{ca\,comp\Delta} = (2/3)(G_c - G_a)/\sqrt{3} \tag{12}$$

The designed values of LC obtained from equations (7)-(9) are connected as star and from equations (10)-(12) are connected as delta in the compensating network as shown in Fig 2. The line loss components are introduced in between load, compensator and supply. This network reduces the % unbalance due to unbalanced linear load and composite loads. It improves the power factor after the composite loads connected into the load network. Primarily these two requirements for any small-scale industries are fulfilled from the passive compensating network. The designed LC values are based on linear loads and the % unbalance is comparatively less after non-linear loads are combined.

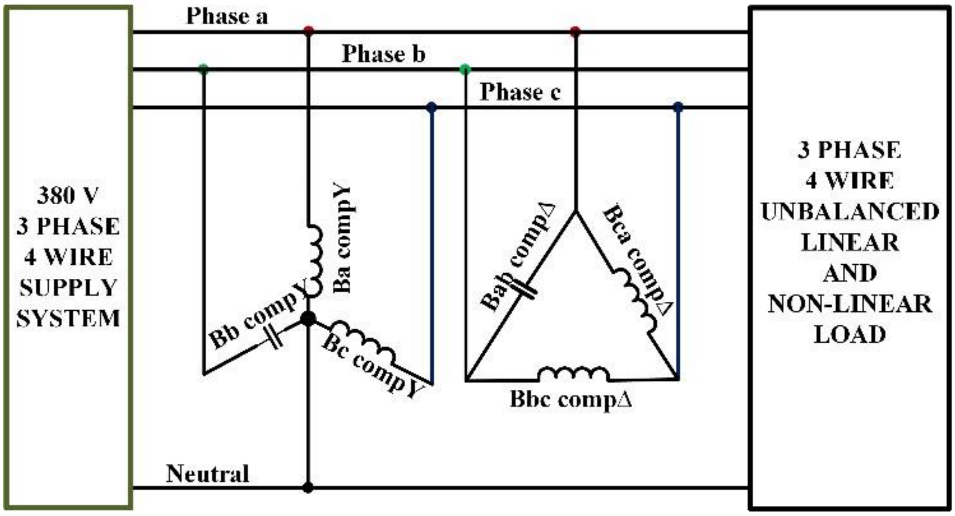


Fig 2. LC Compensating network

Table 3. LC values of Compensator for composite loads

Composite Load	Network Elements	STAR			DELTA		
1	L (mH)	-	-	-	912.6	-	1550.8
	C(MFD)	89.5	121.03	99.14	-	13.3	-
2	L (mH)				-	-	27.3
	C(MFD)	119	11.03	106.25	22.7	29.4	-
3	L (mH)	-	-	-	-	-	214.5
	C(MFD)	254.9	148	152.8	26.4	20.8	-
4	L (mH)	-	126.2	-	-	198.8	78.6
	C(MFD)	305	-	555.9	180	-	-
5	L (mH)	-	134.8	-	-	175.1	63.9
	C(MFD)	370.8	-	465.3	216.7	-	-
6	L (mH)	-	47.9	-	-	-	31.1
	C(MFD)	470.8	-	432.5	224.4	101.5	-

The LC values obtained from equations (7)-(12) are listed in above Table 3. which shows components forming star and delta connections. The star connections are predominantly used with capacitors to improve power factor of corresponding connected loads. The condition for the improvement of power factor is to unity. Later these capacitor values are used to design harmonics filters without changing its designed values for the compensator. The delta connected LC elements are mainly to balance the composite loads to the extent considerably.

2.3 Design of De-Tuned Harmonics Filter

The reason for the failure contactors in controllers and abrupt reduction of capacitance values or failures are found in industries due to harmonics resonance occurring at characteristic harmonics. This is due to increase of impedance at particular harmonics. The retained values of capacitors as given in Table 3. are used to design tuned filters with the predominant harmonics (5^{th} order) obtained from the FFT output of MATLAB Simulink for the corresponding composite loads in the test network. The equation (13) is used to design the % detuned reactor for the values between 3 % and 5 % of the tuning value for the elimination of 5^{th} order harmonics.

$$L = \frac{1}{4 \times \pi^2 \times {f_h}^2 \times C} \qquad (13)$$

Table 4&5. shows the values LC detuned between 3% and 5% for the reduction of harmonics impedance for 5^{th} order harmonics.

Table 4. LC values of Detuned harmonics Filters for Composite Loads 1.2, and 3

Phase	% Detuning	Load - 1		% Detuning	Load - 2		% Detuning	Load - 3	
		L	C		L	C		L	C
a	3 %	4.8	89.5	4 %	3.7	119	5 %	1.8	254.9
b		3.6	121.03		36	11.03		3	148
c		4.3	99.14		4.1	106.25		2.9	152.8

Table 5. LC values of Detuned harmonics Filters for Composite Loads 4,5, and 6

Phase	% Detuning	Load - 4		% Detuning	Load - 5		% Detuning	Load - 6	
		L	C		L	C		L	C
a	5 %	1.5	305	5 %	1.2	370.8	5 %	0.9	470.8
b		126.2	3.9		134.8	4.7		47.9	0.13
c		0.8	555.9		0.9	465.3		1.03	432.5

3. Results and Discussions

The network shown in Fig 3. having six composite loads with LC values as given in Table. and a diode bridge rectifier connected as balanced non-linear load. Series Line loss components assumed between loads, Compensator and supply system. Simulation is done for 3 seconds for every composite loads one after another with and without compensator whose LC values obtained from Table. % unbalance currents and improved power factors taken as output from MATLAB Simulink and compared for various operating composite loads.

The star configured compensator is used for detuned LC filter for taking harmonics impedance as output for comparison among loads with and without filters. The 5th order harmonics is selected for the result and comparison for harmonics impedance

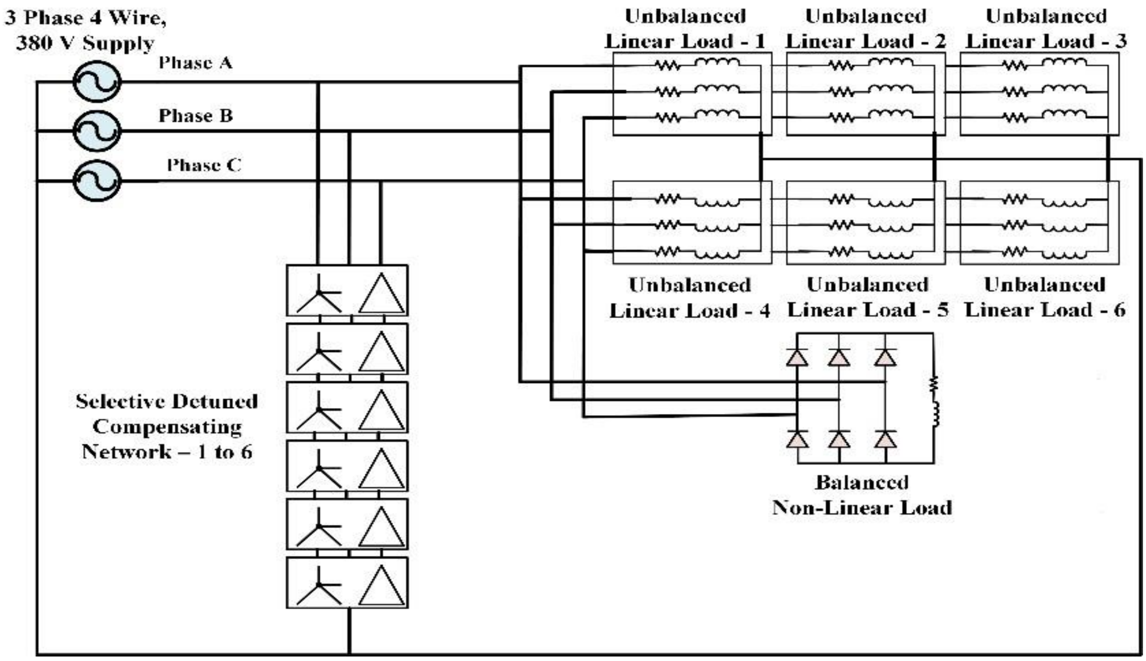


Fig 3. Test network with composite loads and compensating network

3.1 Composite Load with and without Compensator

Figure 4. shows the difference in reduction of % unbalance current with corresponding composite loads. Reduction in unbalance is found decreasing from 90 % to 60 % with increase of % unbalance from 10 % to 40 %. It is predominantly more at lower values of unbalanced loading.

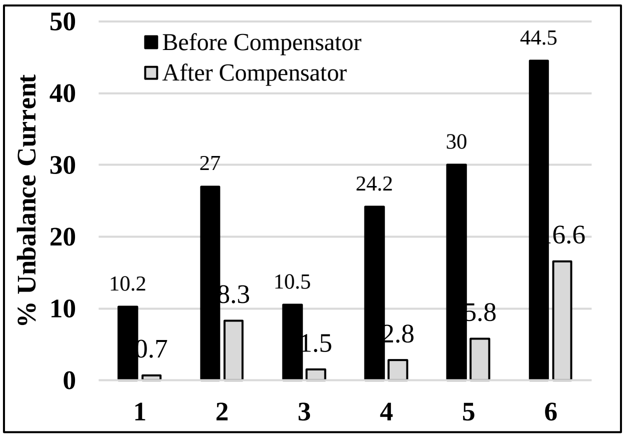


Fig 4. Average % Unbalance with and without Compensator for six loads

Figure 5. shows the improvement of power factor in different composite loads when connected with and without star connected compensated in the test network. All the loads were improved with the power factor closer to unity.

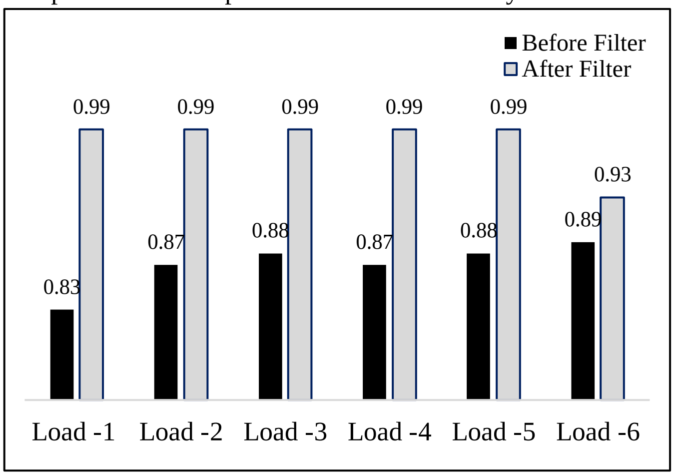
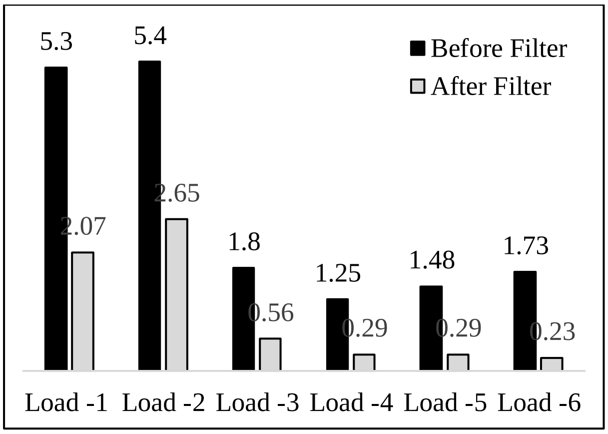


Fig 5. Power factor improvement in composite loads

3.2 THD Analysis

The test network is run for harmonics analysis to obtain % current THD in individual phases for the corresponding composite loads. As per IEEE 519, for the minimum ratio of current, the individual harmonics distortion is 4 % limiting to the harmonics order between 3 and 11. This value is verified with the operation of composite loads and filter connected. Figure 6. shows the reduction of current THD after the detuned filters connected for the corresponding composite loads. The average values of three phase are taken for the result and compared among the loads. The increase % reduction of current THD from 60 % to 90 % with increase of unbalance of loads from 10 % to 40 %. The numerical values of % THD in individual phase with and without filters are tabulated in Table 6.



Fig

Fig. 6. Average value of Current THD (%)

Table 6. Values of % THD_I with / without Detuned filter - Phase wise

Loads	Before Detuned Filter			After Detuned Filter		
	a	b	c	a	b	c
1	5.6	1.0	4.6	2.5	5.6	2.6
2	3.2	2.0	5.1	3.1	7.9	2.7
3	1.5	0.4	1.9	0.4	1.9	0.7
4	0.7	0.1	1.7	0.6	1.3	0.7
5	0.8	0.1	2.3	0.6	1.3	0.1
6	0.5	0.2	1.6	0.2	3.1	0.2

3.3 Frequency Scan

Harmonics measurement is required to track the resonance for avoiding failure of capacitors used for improving power factor and reducing the stress on implementation of shunt active power filter. 5^{th} order harmonics impedance is found predominantly high in frequency scan of different composite loads. For that, reactor value is so detuned to the value between 3 % and 5 % of the 5^{th} order tuning frequency. After the value designed and connected into the test network, output from harmonics impedance measurement in MATLAB to determine the reduced value of impedance to avoid harmonics resonance in the network.

Figure 7 & 8 shows the reduction of 5^{th} order harmonics to avoid harmonics resonance in individual phases corresponding to composite loads. In phase a, Load -2 & 5 have larger reduction of impedance of about 96.5 %. In phase b, Load – 4 & 5 have got less reduced about 25 % and 8.7 % respectively. All other loads in phase b have got considerably above 85 %. The simulation result only for composite load-1 is presented in the Fig 9 – 14. Fig.16 & 17 shows the variation of impedance in phase a with and without detuned filter respectively. Similarly for phase b & c shown in Fig 18 – 21.

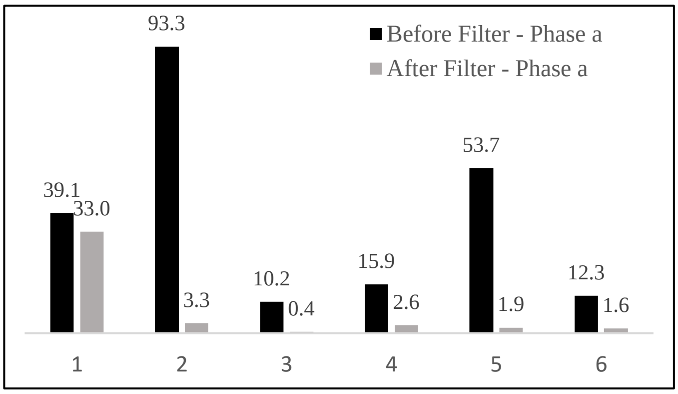


Fig 7 5th order Impedance(Ω)-phase a

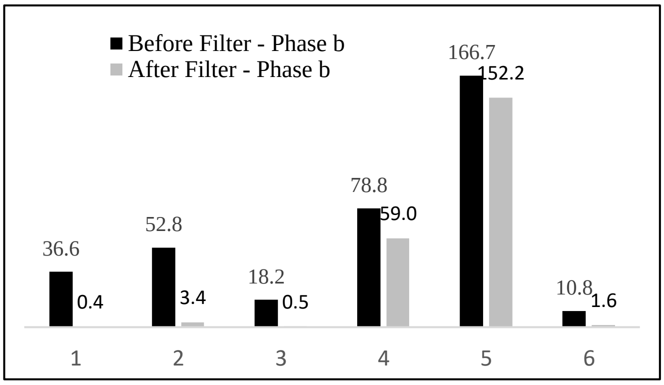


Fig 8 5thorder Impedance(Ω) – phase b

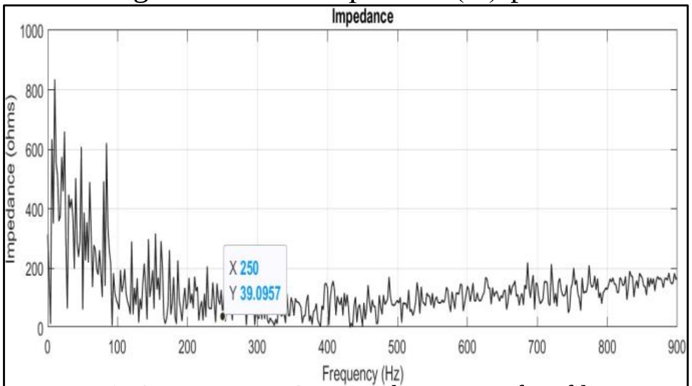


Fig 9. Frequency Scan in Phase a – Before filter

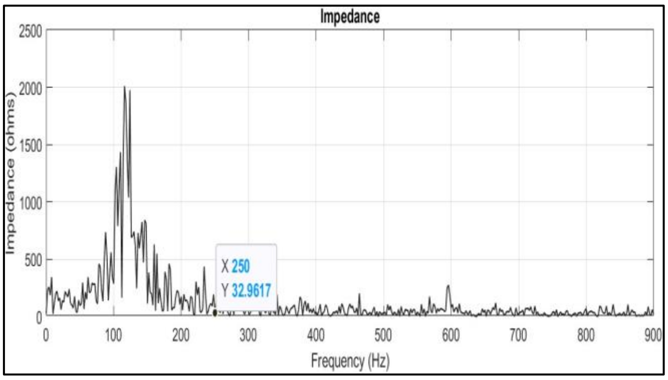


Fig 10. Frequency Scan in Phase a – After filter

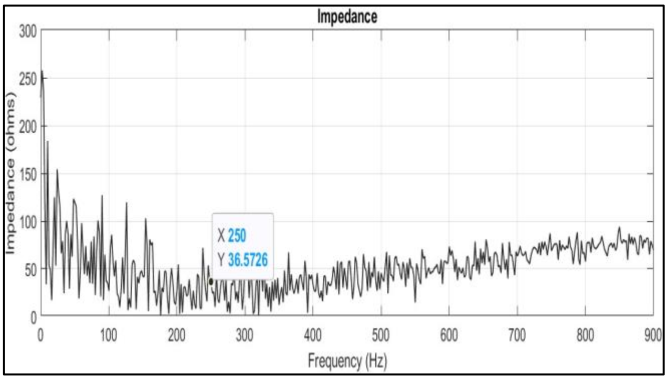


Fig 11. Frequency Scan in Phase b – Before filter

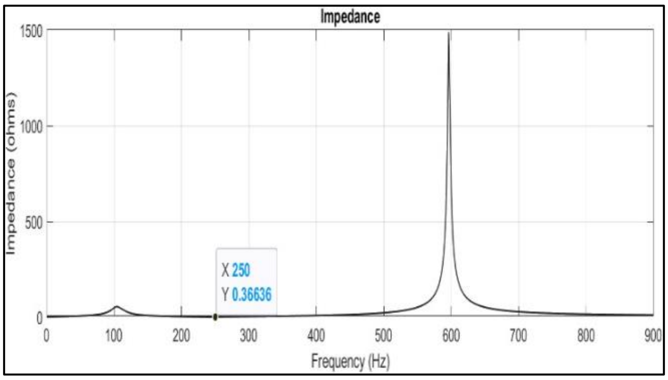


Fig 12. Frequency Scan in Phase b – After filter

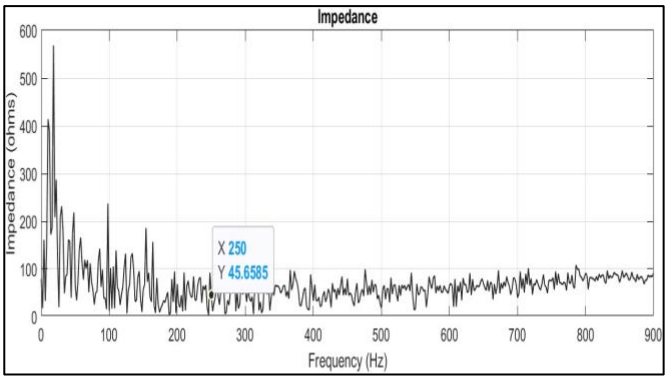


Fig 13. Frequency Scan in Phase c – Before filter

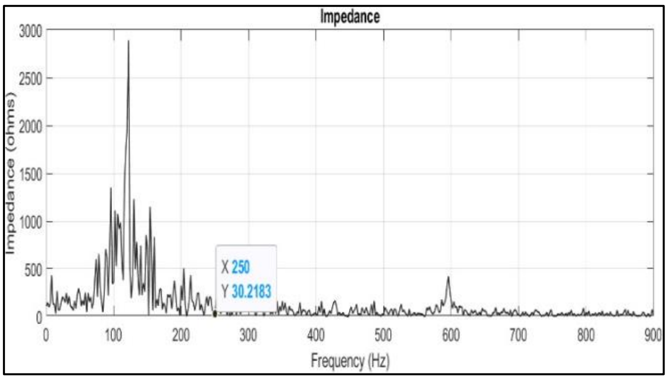


Fig 14. Frequency Scan in Phase c – After filter

4. Real Time Simulation Results

The test network is simulated for in 0.3 s for each group. The compensator is switched ON for 0.1 s in the middle of each interval. THE MATLAB Simulink results along with Hardware In Loop results were compared in Figure 22 to Figure 25 for the unbalanced load current and Figure 25 to Figure 22 for compensating current for all loads.

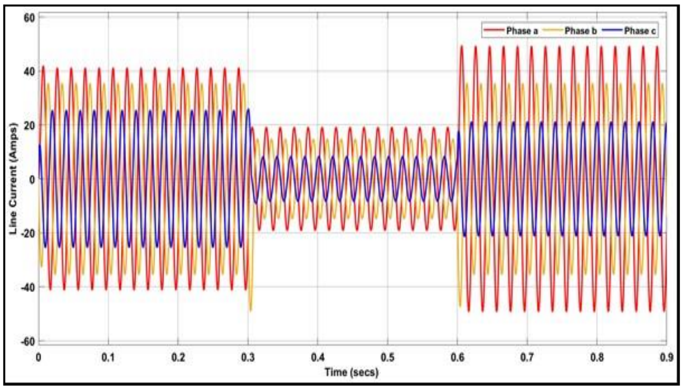


Fig 15. Load current – Loads – 1, 2, and 3

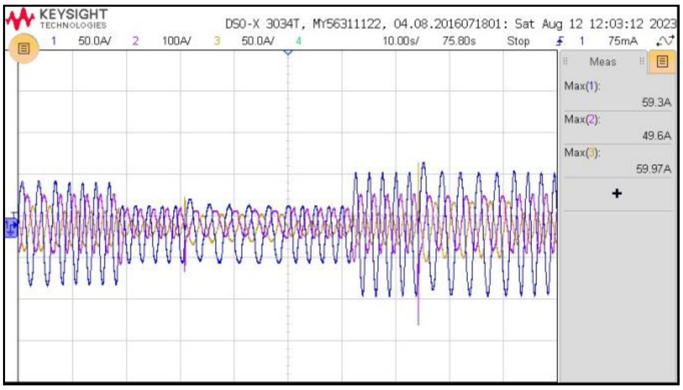


Fig 16 Load current – Loads – 1, 2, and 3 – RT Result

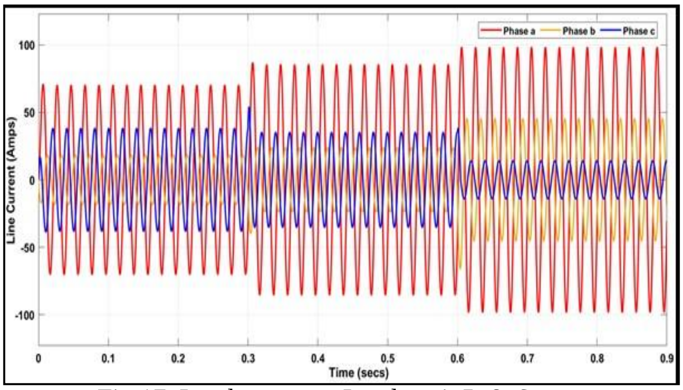


Fig 17 Load current – Loads – 4, 5, & 6

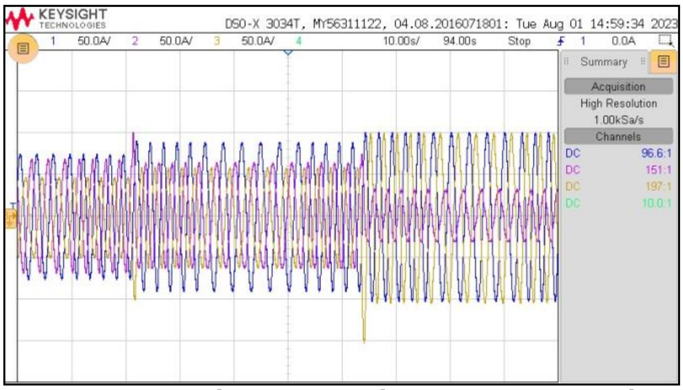


Fig 18. Load current – Loads – 4, 5 & 6 - RT Result

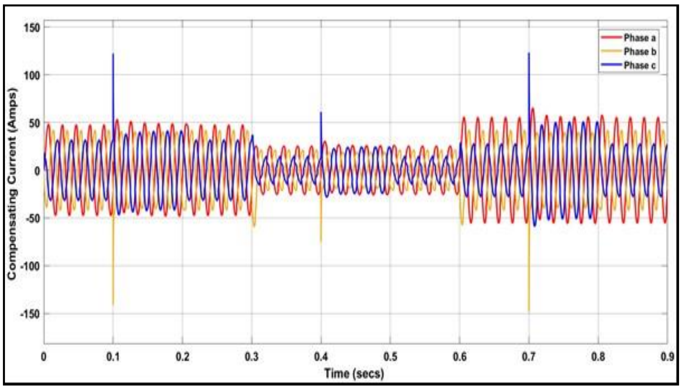


Fig 19. Compensating current – 1, 2, & 3

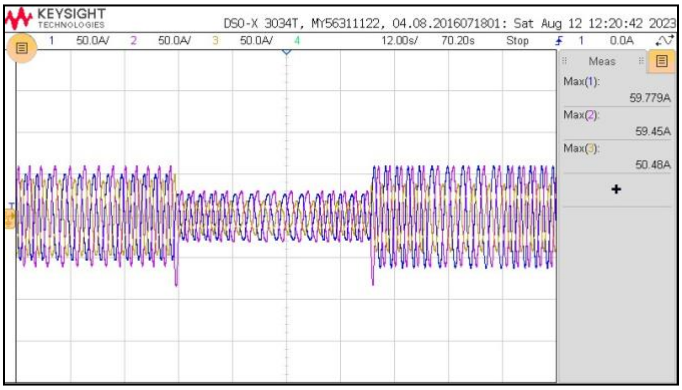


Fig 20. Compensating current – 1, 2 & 3 - RT Result

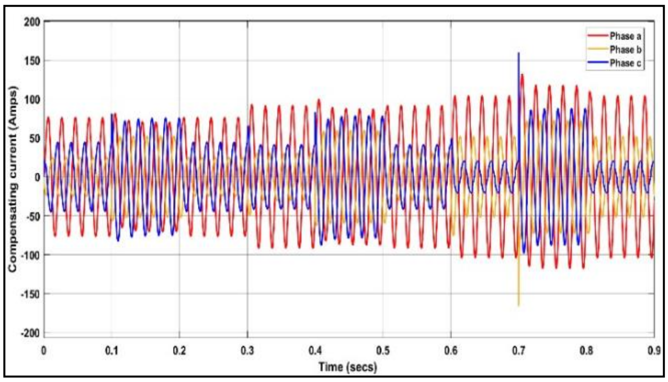


Fig 21. Compensating current – 4, 5, & 6

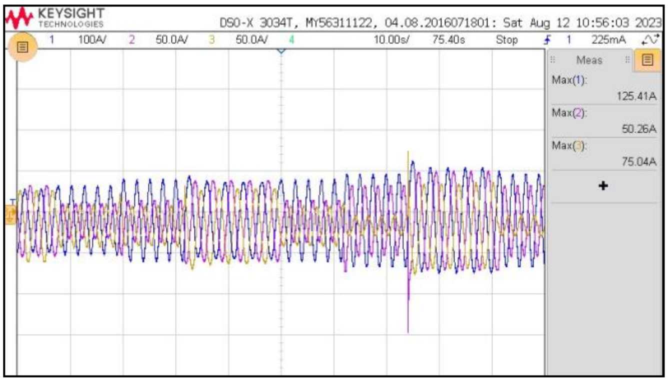


Fig 22. Compensating current – 4, 5 & 6 - RT Result

5. Comparative Analysis

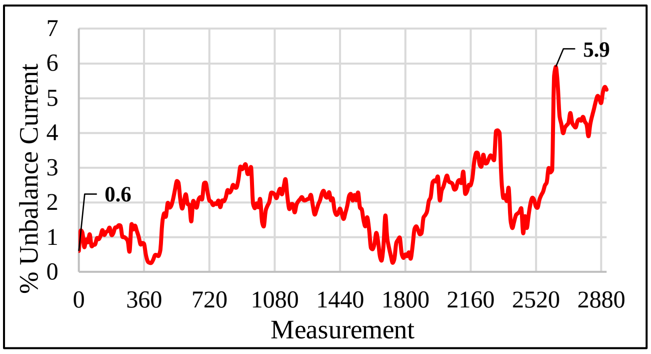


Fig 23. Percentage unbalanced current measured in a leather Tannery

Real-time measurements are shown in Figure 23 taken in a leathery tannery using FLUKE 434 Series II. The percentage of unbalanced current was found to vary between 0.6 % and 5.9 %. The test network considered more than these values for the result analysis.

Table 7. Efficiency of the supply system

Sl.No.	Average current without Filter	Average current with Filter	Difference	Efficiency
1	10.2	0.67	9.53	**70.2**
2	26.9	8.26	18.64	77.2
3	10.54	1.49	9.05	79
4	24.15	2.76	21.39	77.2
5	30.01	5.84	24.17	79
6	44.48	16.62	27.86	**91.5**

In relation to the average source rms current, Table 7 compares efficiency with and without a detuned filter. Efficiency was found to be higher with a higher percentage imbalance and current magnitude in composite load groups

Table 8. Overall comparison of unbalanced current and power factor

.Loads	Without Compensator		With Compensator		Reduction (%)
	UB (%)	Power Factor	UB (%)	Power Factor	
1	10.2	0.83	0.6	0.99	**93.3**
2	26.9	0.87	8.2	0.99	69.3
3	10.5	0.88	1.4	0.99	85.8
4	24.1	0.87	2.7	0.99	88.5
5	30.0	0.88	5.8	0.99	80.5
6	44.4	0.89	16.6	0.93	**62.6**

The Table 8 shows that the percentage reduction of unbalance is high in lower values of current and vice versa. The less difference in power factor determining the efficiency high.

Table 9. Overall comparison of percentage current THD - Phase wise

Loads	Without De-Tuned Filter			With De-Tuned Filter		
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
1	**5.6**	**4.68**	**5.64**	1.04	2.57	2.6
2	**3.2**	**5.1**	**7.91**	2.09	3.13	2.73
3	1.53	1.94	1.99	0.49	0.49	0.71
4	0.73	1.72	1.32	0.16	0.64	0.07
5	0.75	2.39	1.31	0.12	0.67	0.08
6	0.46	1.64	3.1	0.24	0.23	0.23

6. Conclusion

The test network having six composite loads is considered with different % unbalanced currents between 10.2 % and 44.5 %. These loads are compared for reduction of % unbalanced currents and improvement of power factor. After the compensator connected reduction of unbalance is found between 62.6 % and 93.3 % for and the power factor improved from 0.83 to 0.99. The average Current THD is considerably reduced with the range between 51 % and 87 %. Current THD is considerably reduced between 51 % and 87 %. Loads -1 & 2 have got more current THD as shown in Table 9 closer to the limit prescribed by IEEE 519- 2014. A case study also needs to be conducted for different ratios of load current due to linear and non-linear loading. And different patterns of harmonics can be taken for the study using different/multi-level pulses of converter, loads having dual conversion and, arc loads. The designed LC value of the star and delta-connected network is required to change and switch according to the operating loads. Hence an exclusive controller for switching the LC network at a faster rate will be effective for the changing load pattern in industries. This arrangement is useful for the different processes in small-scale industries having unique loading cycles with respect to batch products.

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