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Original Article

A Comprehensive Approach to Passive Compensation in Unbalanced Composite Network

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Abstract - *In medium voltage supply systems, most loads commonly used are current-driven, leading to increased neutral current, unbalance, harmonics distortion, harmonics resonance, and low power factor. These problems can adversely affect the neighbouring loads and consumers in the distribution network. This research article presents a novel comprehensive approach to address these issues using a simple analytical method. The study considers a test network consisting of a three-phase, 380 V supply with different percentages of unbalanced composite loads. The proposed solution comprises three main parts. Firstly, a passive compensator in delta and star configuration is designed to minimize the unbalance and the power factor improvement. Secondly, the index of harmonics distortions is obtained from the harmonics analysis of the network. Thirdly, based on evaluating individual harmonics distortion (IHD) in all phases, a frequency scan is conducted for the selected harmonics in the network. The series LC network in star configuration is modified by appropriately detuning its frequency. The results are verified against the recommended harmonics values per IEEE 519 – 2014. The test network is simulated in MATLAB Simulink to obtain the harmonics spectrum and frequency scan results.*

Keywords - *Detuned filter, Harmonics impedance, Individual Harmonics Distortion (IHD), Total Harmonics Distortion (THD), % Unbalance.*

1. Introduction

Industries consume power based on consumer categories such as commercial, start-up, and small-scale industrial consumers. The supplier sets specific requirements for power demand, power factor, and harmonics based on each category. These parameters pose challenges for consumers who have a combination of linear and non-linear loads. Consequently, issues such as increased neutral current, THD, low power factor, and poor demand management arise. Several research papers have explored the implementation of Active Filters and VSI as a universal solution for non-linear loads. However, when composite loads are connected, effects occur, such as those current flows from the load damages the neutral conductor. The load drawing in the previous discussion results in unbalanced currents from the source, leading to additional issues such as producing third harmonics and raising the current in neutral.

Active filters compensate for harmonics under varying rectifier loading conditions to address these challenges. To ensure operational reliability, an analysis is conducted on the current imbalance due to single-phase loads in the distribution network. Industries drawing power at high voltage levels focus on limiting harmonics at PCC to minimize pollution. Three-phase compensators are utilized for load balancing, reactive power management, and harmonics mitigation in the LV supply system. Numerical problems are addressed by balancing unbalanced linear loads and improving the power factor. The failure of power factor improvement capacitors and related contractors is predominantly caused by high voltages, leading to insulation failure and resulting phase and ground faults. Therefore, a study of the network with the supply system using a frequency scan is required.

This paper investigates a 3P-4W load network that incorporates both linear and non-linear loads, focusing on operating conditions that differ from previous research. The study addresses balancing load and power factor improvement in the test network.

The work is presented in three parts: Part 1 describes modeling the test setup using MATLAB Simulink, considering various combinations with a stiff power supply system. Part 2 uses a compensator to achieve load balancing and reactive power compensation to reduce unbalance and improve power factor. Finally, Part 3 evaluates % THDi, % IHDi, and impedance across different harmonics frequencies to prevent resonance. The results are compared against the IHD limits IEEE 519 – 2014 recommended. [25]

2. Literature Survey

A minimally switched control algorithm with reduced switching frequency and a new hysteresis band control method to track neutral current in the Inverter is addressed to compensate for unbalanced and non-linear loads. [1] A controller model used for three-phase four-wire to compensate reactive power and harmonics distortion connected to unbalanced source and loads and gamma component of load current control demonstrates the neutral current reduction. [2] A novel control scheme for four-leg voltage source inverters uses a central control for balanced three-phase voltage output and separate control for neutral currents, and it avoids complex modulation techniques and reduces error, response, and harmonics mitigation. [3] The ignored losses due to current physical components are overcome by an improved calculation method for passive compensation parameters considering voltage distortion, load unbalances, and line impedances.

It ensures a balanced working current and avoids harmonics amplification. [4] A PI controller regulates the DC bus voltage of a hybrid combination of active filters to control improved hybrid filter system topology. This control demonstrated effectiveness in safeguarding passive filters in distorted supply conditions. [5] This paper explored the emerging characteristics in recent years to address voltage fluctuations, frequent three-phase unbalance, sub-synchronous harmonics, and ultra-harmonics in distribution networks. [6, 7] The impacts of load unbalance on losses in Low voltage networks caused due to uneven connection of single-phase loads influencing public lighting and micro generation on load unbalance is well-examined to highlight the potential of reduction in three-phase unbalance and losses. [8] The challenges in distribution networks, such as phase rebalancing, scalability, data scarcity, and adaptability, are overcome with the existing solutions on load re-phasing, phase balancers, and control of distributed generation, micro grid, and energy storage, which are categorized, analysed in this paper for its limitations. [9]

The unbalance levels due to electric chargers connected to LV grids causing high power consumption and prolonged operations are analysed, and an analytical solution to evaluate the impacts for efficient vehicle charging installations in the LV grid is done and validated. [10] A novel and efficient load flow technique is used for an unbalanced distribution system based on a load-impedance matrix and a backwards-forward sweep approach. It accommodates the network topology change and performs well in various distribution system scenarios. [11] The parallel active compensator method optimizes the utilization of series and shunts active power filters by sharing reactive power burdens. The proposed method avoids Unified Power Quality Conditioners overloading and employs a mean block for balanced source currents. [12] A novel control scheme and an emulator based on four-leg VSI accurately resembling unbalanced sources and loads. It accommodates both three-wire and four-wire systems with advancements in power-level emulation. [13]

A neutral-displacement power measurement was derived using the Buchholz source and load powers method for evaluating energy deterioration in the neutral conductor of a low-voltage distribution network. [14] This literature review focuses on a three-phase active power compensator to address reactive power compensation and load balancing in a three-phase four-wire power distribution system. To estimate reference current, the compensator is implemented with VSI bridges, shared DC bus, and P-I control. [15]

This article introduces an innovative approach using a dynamic model of the entire system to analyze the steady state and transient behaviour of the proposed compensator in a three-phase four-wire distribution system. [16] This paper discusses the implementation of indirect current control for a parallel hybrid filter system with a rectifier load to mitigate harmonics during unbalanced and fault conditions.

The control is addressed using synchronous reference frame-based current control. [17] This paper presents an innovative control algorithm for a three-phase shunt active power filter which employs a current-controlled voltage source inverter that incorporates two closed-loop P-I controllers to generate reference supply currents. [18] This book solved numerical problems in the section passive compensation for three-phase four-wire to design compensators for only a three-phase unbalanced linear load network. [19]

This paper provides a unique insight into designing a C-type harmonics filter using the parameter tuning frequency and R-ratio to prevent harmonics resonance caused by shunt capacitors used to improve power factor. [20] This paper presents an advanced thyristor-switched detuning capacitor bank to improve power quality and energy efficiency in AC spot welding applications. The proposed fast reactive power compensating solution enhances the power quality of the distribution system. [21]

A passive filter is designed to mitigate the problems of using load-commutated inverter drives in industries discussed in this paper. [22] This paper proposes a new fuzzy approach using the Nonhomogeneous Cuckoo Search Algorithm for optimal allocation of detuned passive filters implemented on an IEEE 69 bus network. [23] This paper proposes a novel application utilizing a smart PV inverter as a virtual detuner to mitigate network resonance. It incorporates anti-wind-up and droop characteristics, presenting potential benefits for the distribution system. [24]

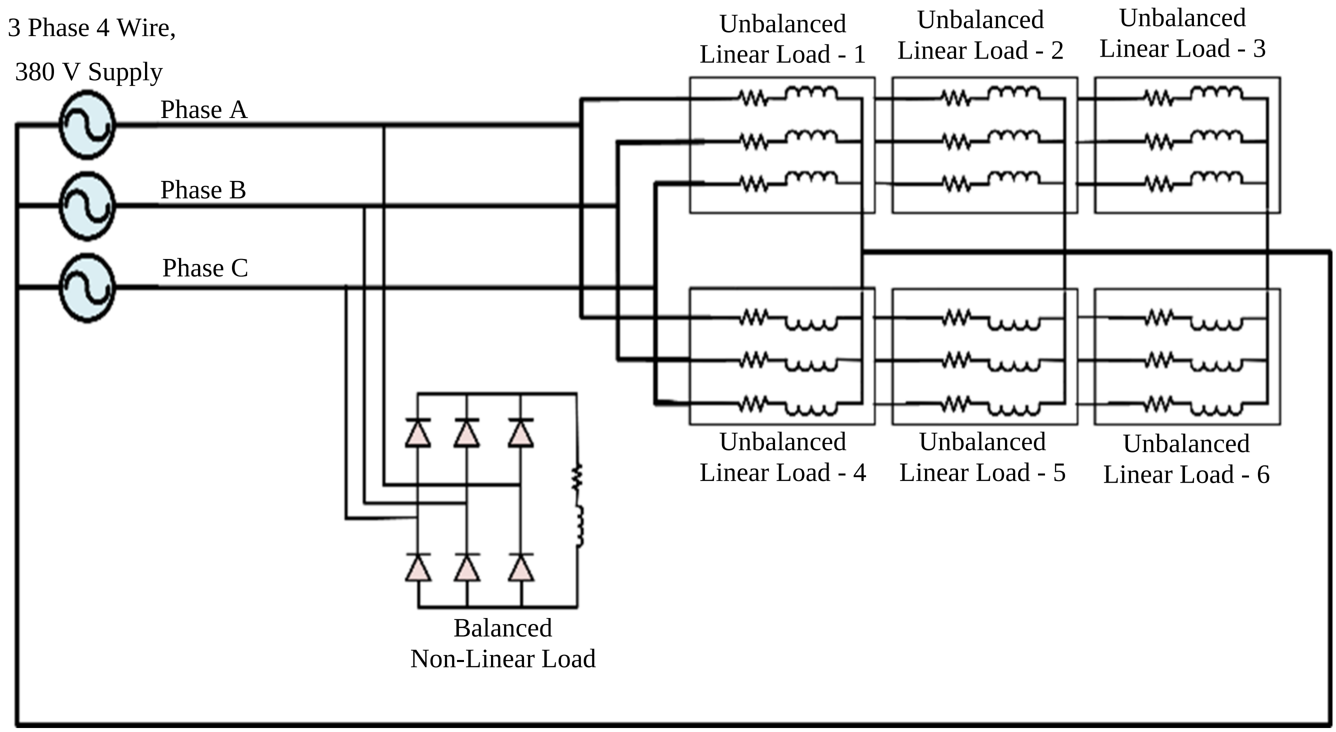

Fig. 1 Unbalanced linear and balanced non-linear load network

Table 1. Supply parameters

Supply Voltage (Line)	SCC (MVA)	X / R
381	100	10

Table 2. Load impedances (Ω)

<table>
<tr><th colspan="2">Non-Linear Load</th><th colspan="2">Load -1</th><th colspan="2">Load -2</th><th colspan="2">Load -3</th></tr>
<tr><th>R</th><th>X</th><th>R</th><th>X</th><th>R</th><th>X</th><th>R</th><th>X</th></tr>
<tr><td rowspan="7">80</td><td rowspan="7">18.8</td><td>22</td><td>16.5</td><td>15</td><td>6.2</td><td>6.4</td><td>4</td></tr>
<tr><td>12.8</td><td>13.1</td><td>17</td><td>12.4</td><td>7</td><td>5.3</td></tr>
<tr><td>13.2</td><td>17.6</td><td>20</td><td>31.4</td><td>11</td><td>5.3</td></tr>
<tr><th colspan="2">Load -4</th><th colspan="2">Load -5</th><th colspan="2">Load -6</th></tr>
<tr><td>3.5</td><td>1.9</td><td>3.1</td><td>1.9</td><td>3</td><td>1</td></tr>
<tr><td>11</td><td>5.3</td><td>9.7</td><td>8.6</td><td>5.5</td><td>4.1</td></tr>
<tr><td>5.4</td><td>4.2</td><td>8.1</td><td>3.4</td><td>16.5</td><td>14.6</td></tr>
</table>

3. Method

3.1. Network Description

The supply system to the industries is based on their kVA or kW demand. The test network having a 10 kW composite load with 380V three-phase, four-wire supply is shown in Figure 1. The parameters for the supply and composite loads are given in Tables 1 & 2, respectively.

As per Table 1 the impedance values for the balanced non-linear and unbalanced linear loads in each phase are used in the network. A diode bridge rectifier is used as a source of harmonics at the load side. The unequal linear load impedances are considered for different % unbalanced currents in the network.

3.2. Design of Load Compensator

The zero, positive and negative sequence currents are represented in terms of unequal conductance and susceptances of linear load in equation (1) – (3).

$$I_0 = \frac{\{(G_a + a^2 G_b + a\, G_C) + j\,(B_a + a^2\, B_b + a\, B_C)\}\ V_{ph}}{\sqrt{3}} \quad (1)$$

$$I_1 = \{(G_a + G_b + G_C) + j\,(B_a + B_b + B_C)\}\ \sqrt{3}\ V_{ph} \quad (2)$$

$$I_2 = \frac{\{(G_a + a^2 G_b + a G_C) + j (B_a + a B_b + a^2 B_C)\} V_{ph}}{\sqrt{3}} \quad (3)$$

The Compensators are designed to connect in star and delta configurations. I_{1Y}, I_{2Y}, and I_{0Y} are sequence currents in the star-connected compensator. $I_{1\Delta}$, $I_{2\Delta}$, and $I_{0\Delta}$ are sequence currents in the delta-connected compensator. In order to satisfy the condition of cancelling the sequence of the unbalanced load current and compensator currents, we have formulated the following equation (4)-(9)

$$Real\ (I_2) + Real\ (I_{2Y}) + Real\ (I_{2\Delta}) = 0 \quad (4)$$

$$Imag\ (I_2) + Imag\ (I_{2Y}) + Imag\ (I_{2\Delta}) = 0 \quad (5)$$

$$Real\ (I_0) + Real\ (I_{0Y}) = 0 \quad (6)$$

$$Imag\ (I_0) + Imag\ (I_{0Y}) = 0 \quad (7)$$

$$Imag\ (I_1) + Imag\ (I_{1Y}) + Imag\ (I_{1\Delta}) = 0 \quad (8)$$

$$Imag\ [\{ j\ (B_{ab\Delta} + B_{bc\Delta} + B_{ca\Delta})\} \sqrt{3}\ V_{ph}] = 0 \quad (9)$$

$B_{ab\Delta}$, $B_{bc\Delta}$, $B_{ca\Delta}$ are unequal three-phase load susceptances connected between phases in the delta compensator. The solution of the above equation (4) – (9) gives the susceptance values of the compensator connected in the star are given in equation (10) – (12).

$$B_{aY} = -B_a + (G_b - G_c)/\sqrt{3} \quad (10)$$

$$B_{bY} = -B_b + (G_c - G_a)/\sqrt{3} \quad (11)$$

$$B_{cY} = -B_c + (G_a - G_b)/\sqrt{3} \quad (12)$$

The susceptance values for the delta-connected compensator are given in equation (13) – (15)

$$B_{ab\Delta} = (2/3)\ (G_a - G_b)/\sqrt{3} \quad (13)$$

$$B_{bc\Delta} = (2/3)\ (G_b - G_c)/\sqrt{3} \quad (14)$$

$$B_{ca\Delta} = (2/3)\ (G_c - G_a)/\sqrt{3} \quad (15)$$

The LC values obtained from equations (10) – (15) form the passive compensating network connected, as shown in Figure 2.

The line loss components are between the load, compensator, and source. This passive compensator primarily reduces percentage unbalance and improves the power factor to unity. The LC values obtained from equations (10)-(15) are given in Tables 3 & 4.

The elements used for star configuration are to improve the power factor to unity. Moreover, the elements used for delta are to reduce % unbalance in the load current. The capacitor values in the star-connected circuit are used for designing a Detuned filter for filtering 5th-order harmonics.

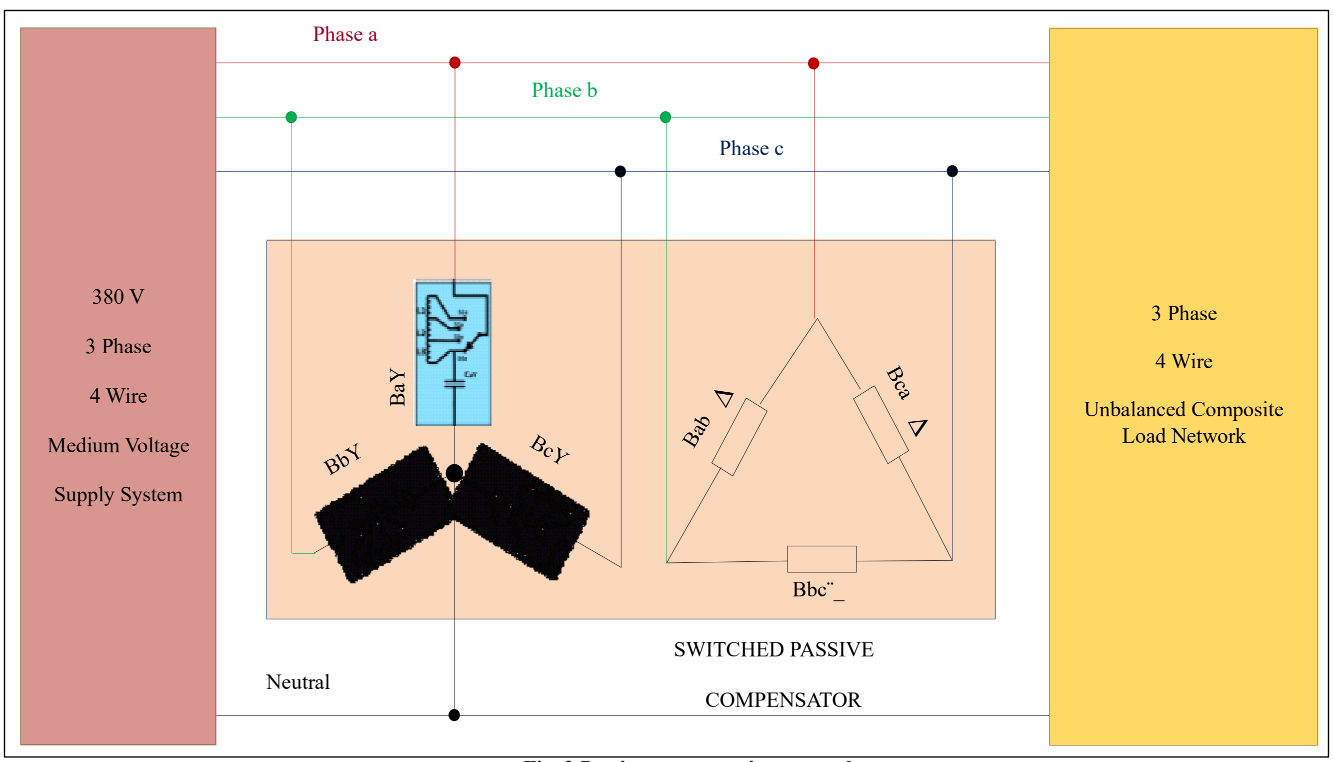

Fig. 2 Passive compensating network

Table 3. LC values of the compensator in star

Loads	Network Elements	STAR		
1	L (mH)	-	-	-
	C(MFD)	89.5	121.03	99.14
2	L (mH)			
	C(MFD)	119	11.03	106.25
3	L (mH)	-	-	-
	C(MFD)	254.9	148	152.8
4	L (mH)	-	126.2	-
	C(MFD)	305	-	555.9
5	L (mH)	-	134.8	-
	C(MFD)	370.8	-	465.3
6	L (mH)	-	47.9	-
	C(MFD)	470.8	-	432.5

Table 4. LC values of the compensator in the delta

Loads	Network Elements	DELTA		
1	L (mH)	912.6	-	1550.8
	C(MFD)	-	13.3	-
2	L (mH)	-	-	27.3
	C(MFD)	22.7	29.4	-
3	L (mH)	-	-	214.5
	C(MFD)	26.4	20.8	-
4	L (mH)	-	198.8	78.6
	C(MFD)	180	-	-
5	L (mH)	-	175.1	63.9
	C(MFD)	216.7	-	-
6	L (mH)	-	-	31.1
	C(MFD)	224.4	101.5	-

Table 5. Detuned harmonics filters parameters for loads 1, 2, & 3

Phase	Load - 1		Load - 2		Load - 3	
	L (mH)	C (MFD)	L (mH)	C (MFD)	L (mH)	C (MFD)
A	4.8	89.5	3.7	119	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 6. Detuned harmonics filters parameters for loads 4, 5, & 6

Phase	Load - 4		Load - 5		Load - 6	
	L (mH)	C (MFD)	L (mH)	C (MFD)	L (mH)	C (MFD)
a	1.5	305	1.2	370.8	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

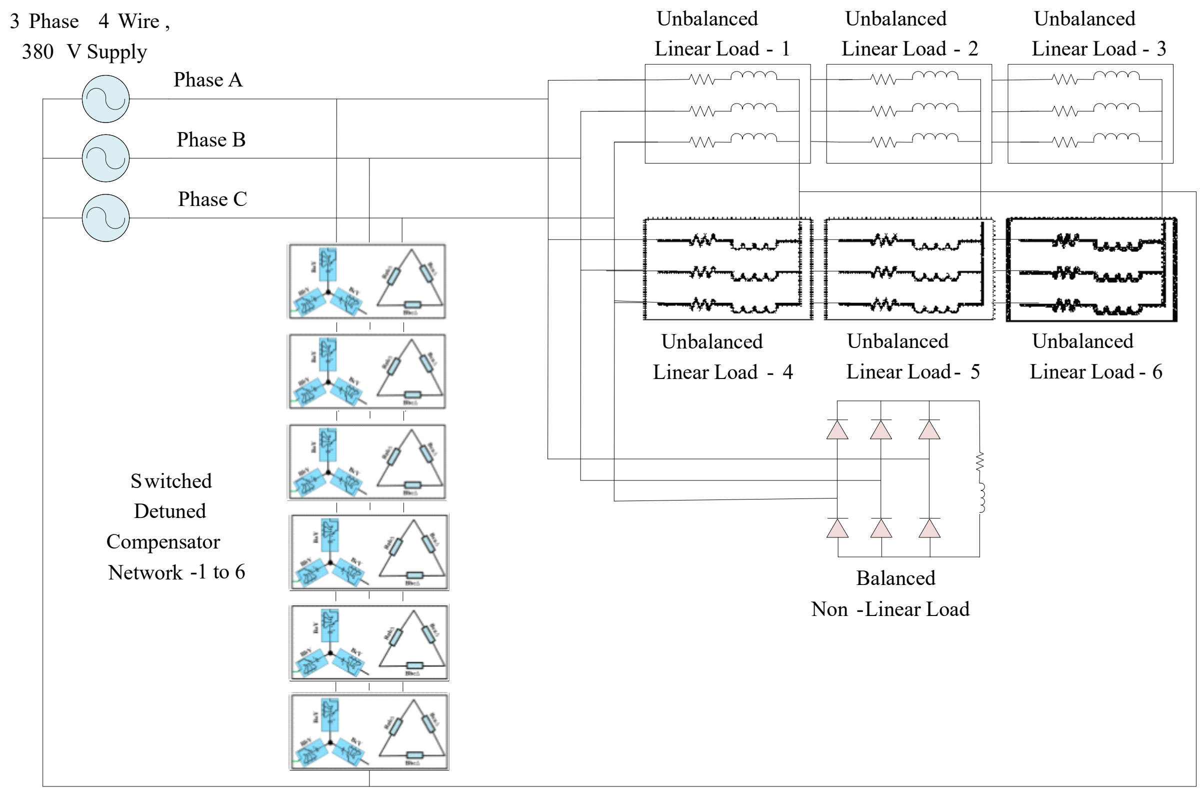

Fig. 3 Test network with loads and compensating network

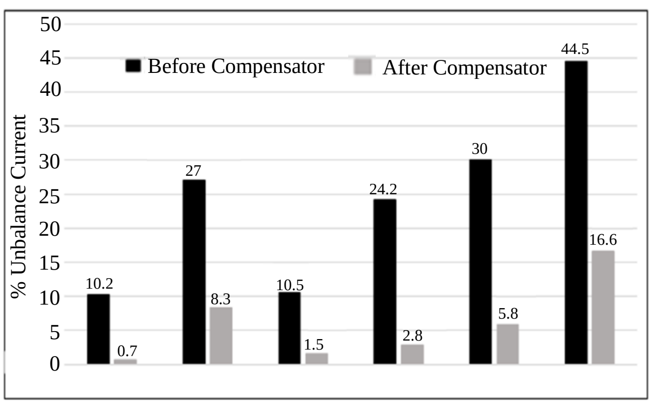

Fig. 4 Percentage unbalanced current

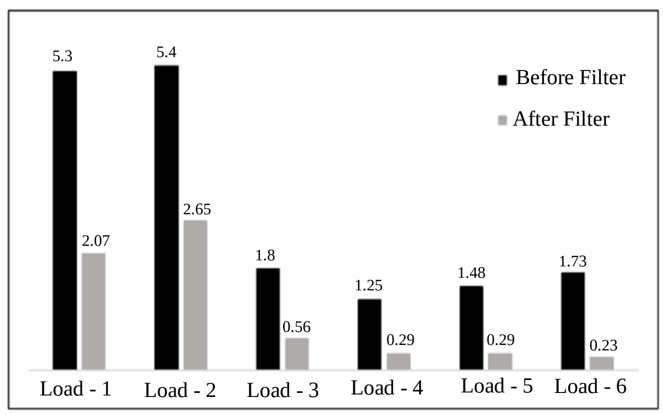

Fig. 6 Comparison of current THD

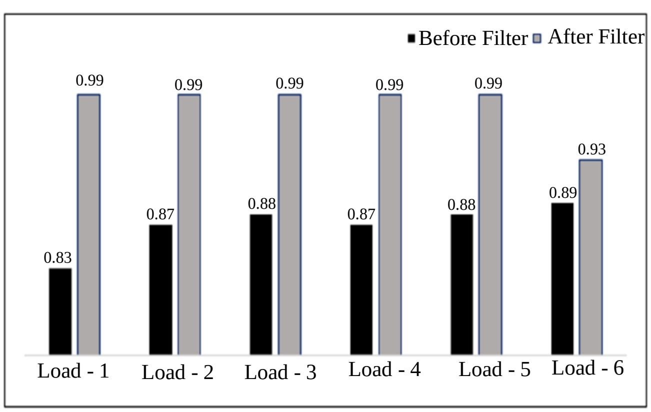

Fig. 5 Comparison of power factor

3.3. Design of Detuned Harmonics Filter

The medium voltage consumers have problems such as Capacitor contactor failures decreased capacitance values, and other insulation failures. These are due to harmonics resonance occurring at characteristics such as 3rd, 5th, 7th, and 9th harmonics. The values of capacitors in the star are used to design a Detuned filter. The equation (16) is used to find the inductor value for the different percentage detuning such that the harmonics impedance offered by the selected 5th order harmonics is minimum. The calculated value of the inductor is listed in Tables 5 & 6 for all composite loads.

$$L = \frac{1}{4 \times \pi^2 \times {f_h}^2 \times C} \tag{16}$$

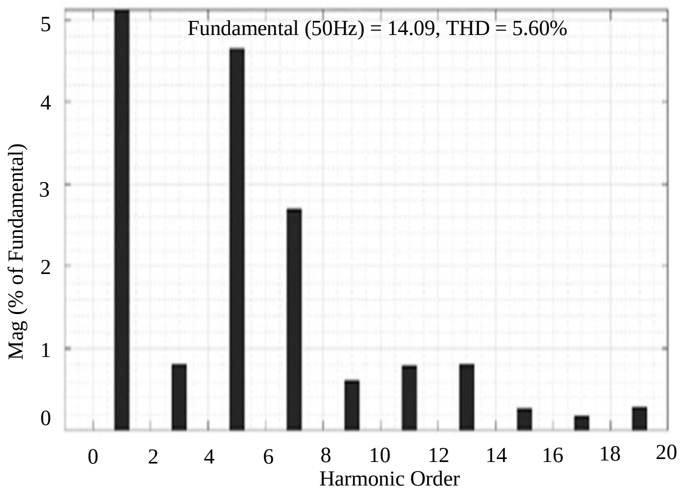

Fig. 7 THD I before detuned filter – phase A

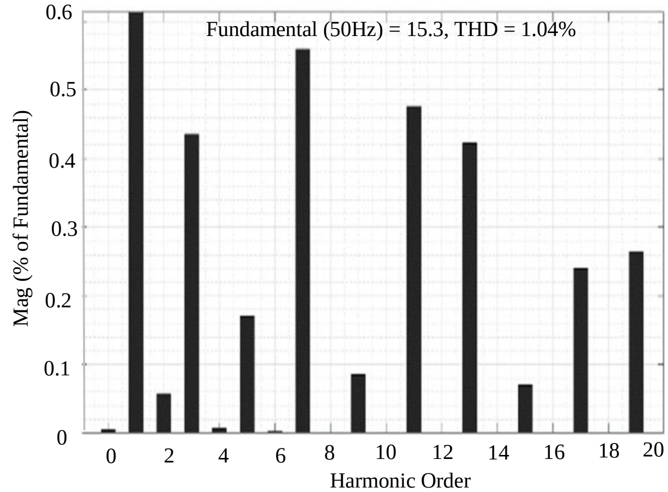

Fig. 8 THD I after detuned filter – phase A

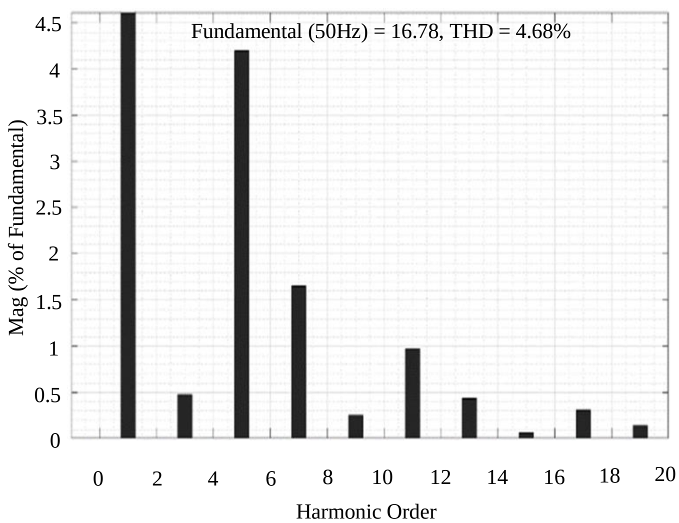

Fig. 9 THD I before detuned filter- phase B

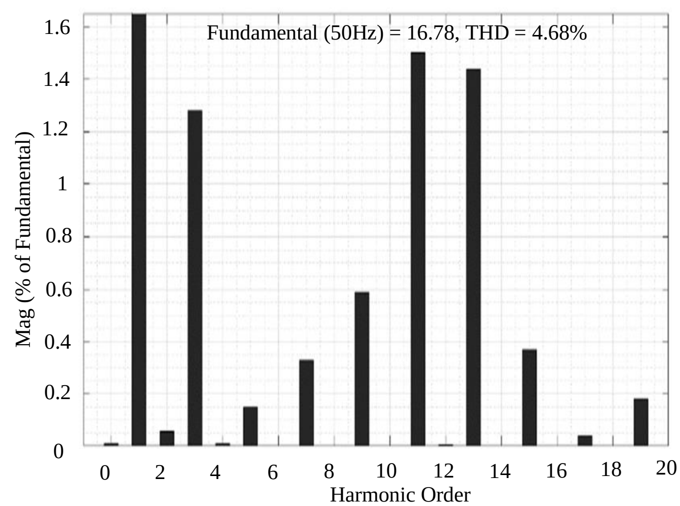

Fig. 10 THD I after detuned filter – phase B

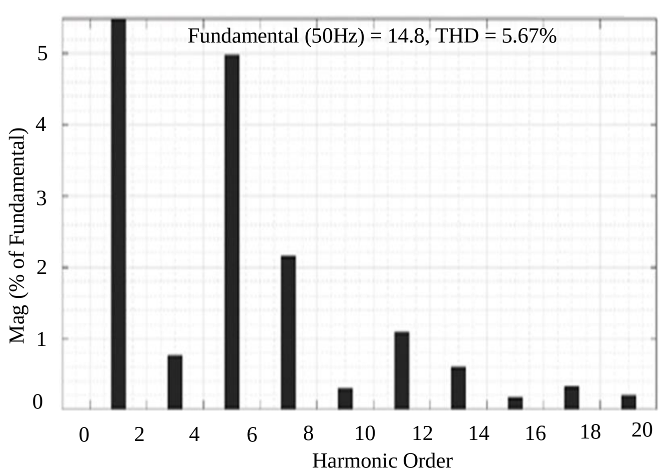

Fig. 11 THD I before detuned filter- phase C

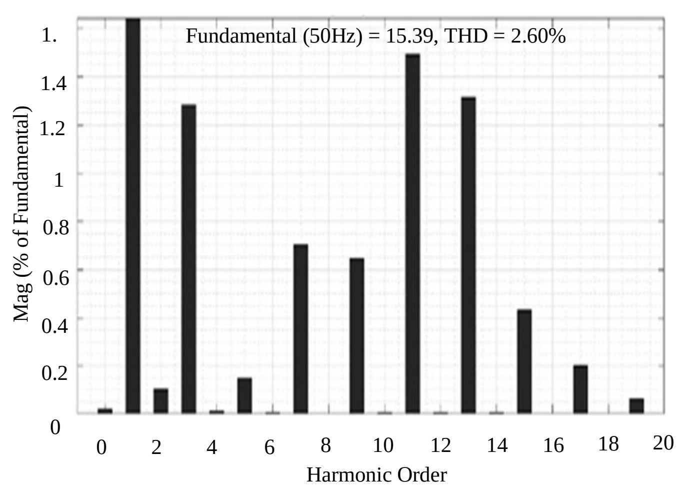

Fig. 12 THD I after detuned filter – phase C

4. Results and Discussions

4.1. Reduction of Unbalance

The network shown in Figure 3 has six unbalanced composite loads connected with a 380V three-phase, four-wire stiff supply system. Series Line loss components are assumed between loads, compensator, and supply system. MATLAB Simulation is done for 3 seconds for each load simultaneously with and without a compensator. Figure 4 shows the reduction of % unbalanced current in different composite loads. % Reduction substantially decreasing in the order of 90 % to 60 % with an increase of % unbalance from 10 % to 40 %. The reduction is more at lower loading values. Figure 5 presents the power factor improvement in different composite loads, both with and without compensators. The power factor is improved by almost unity in all loads.

4.2. THD Analysis

The % THD for each load in the test network is obtained from the output of the simulation. As per IEEE 519, for the minimum ratio of load current, the individual harmonics distortion is limiting 4 %, limiting the harmonic order between 3 and 11. This value is compared with each load's THD output for 5th-order harmonics. Figure 6 shows the reduction of current THD in each load.

The average values for the three phases are compared among the loads. The % reduction of current THD is increased in the order of 60 % to 90 % with an increase of unbalance from 10 % to 40 %. The numerical values of % THD in individual phases are listed in Table 7. The simulation results on current THDi obtained from the FFT output of MATLAB Simulink for the connected composite load-1 are shown in Figure (7) – (12).

4.3. Frequency Scan

Measurement of Harmonics impedance is essential to track the resonance for avoiding failure of capacitors 5^{th} order harmonics impedance is selected for scanning to obtain for all loads. The inductor value is detuned to between 3 % and 5 % of the 5^{th}-order tuning frequency. The output after the Filter is taken to compare impedance reduction for fifth order harmonics and is tabulated in Table 8. The complete frequency scan output for Load-1 in all phases taken from MATLAB is shown in Figure (13) – (18).

Table 7. Values of % THD_I - phase wise

Load	Without Detuned Filter			With Detuned Filter		
	Ph-a	Ph-b	Ph-c	Ph-a	Ph-b	Ph-c
1	31.5	24.8	114.1	26.1	0.4	59.5
2	93.3	52.8	24.6	4.1	4.2	0.4
3	10.2	18.2	24.6	0.4	0.4	0.3
4	15.9	78.7	121	2.9	53.4	27.1
5	31.5	77.3	142.4	2.2	31.2	72.6
6	12.3	10.8	11.5	1.5	1.4	0.2

Table 8. Harmonics impedance values – with filter on and off

Load	OFF	ON	OFF	ON	OFF	ON
	Ph- a		Ph - b		Ph - 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	0.1
5	0.7	0.1	2.3	0.6	1.3	0.1
6	0.4	0.2	1.6	0.2	3.1	0.2

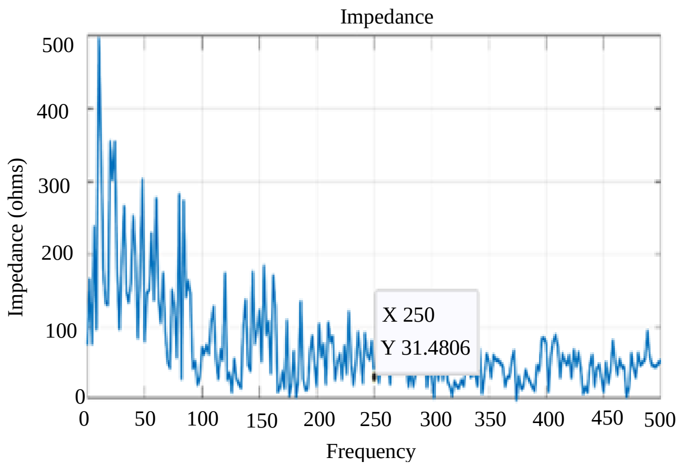

Fig. 13 Impedance in phase A - without filter

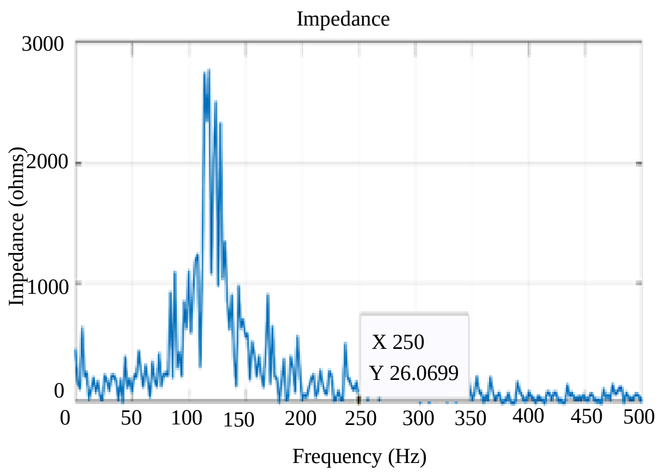

Fig. 14 Impedance in phase A - with filter

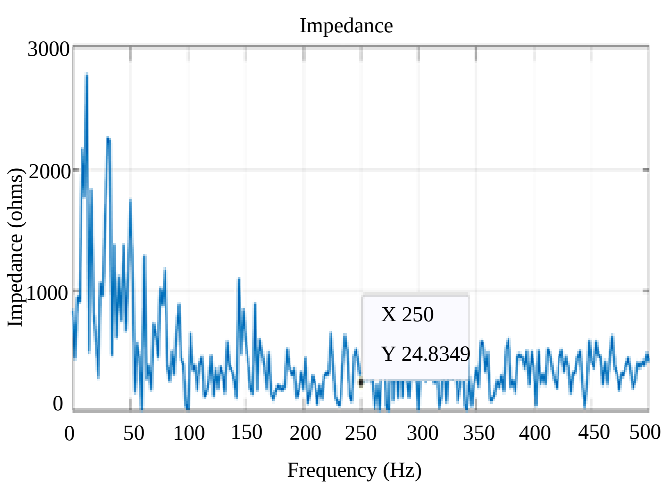

Fig. 15 Impedance in phase B - without filter

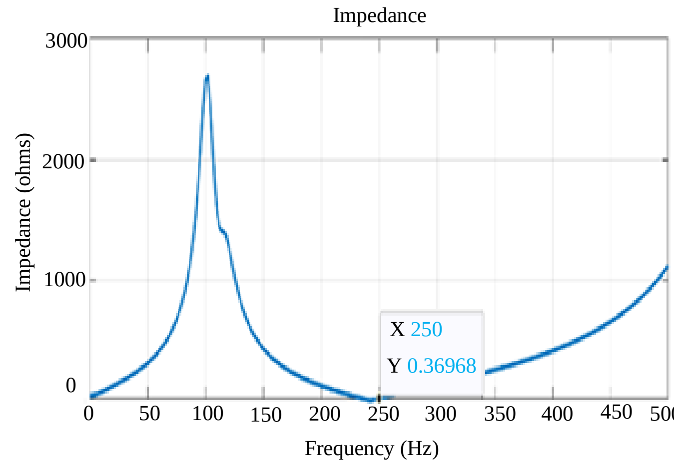

Fig. 16 Impedance in phase B - with filter

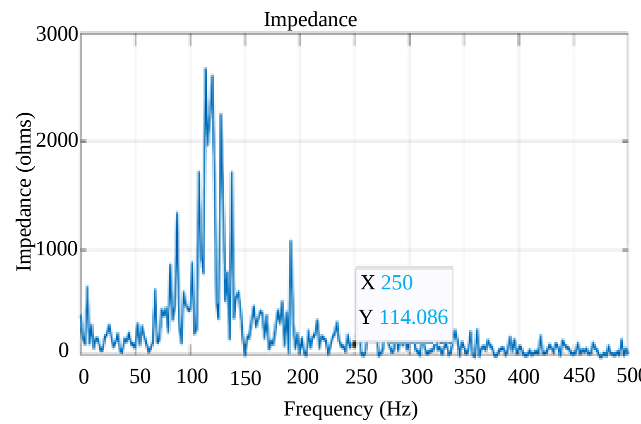

Fig. 17 Impedance in phase C – without filter

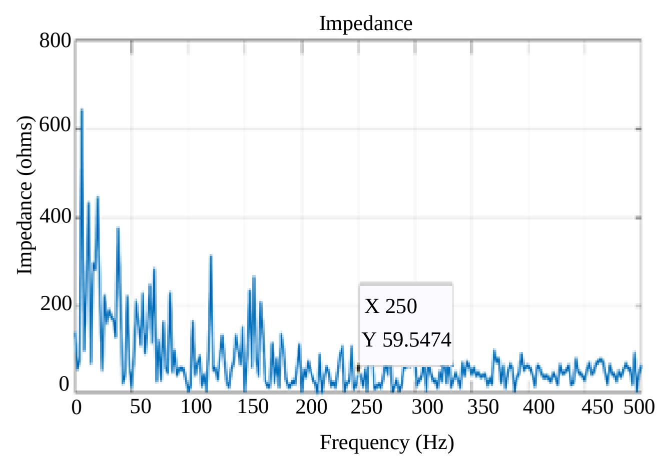

Fig. 18 Impedance in phase C – with filter

5. Conclusion

The research study examined a test network with varying degrees of unbalanced currents ranging from 10 % to 44.5 %. The objective was to compare these loads in terms of reducing the percentage of unbalanced currents and improving the power factor. After connecting the compensator, significant improvements were observed, with a reduction of unbalance ranging from 62 % to 94 % and a power factor increase from 0.83 to 0.99.

Moreover, there was a considerable decrease in current THD, with values ranging from 51 % to 87 %. Also, individual selection of detuning is done to minimize THD values in each phase. Different ratios of load current resulting from linear and non-linear loads may be considered to broaden the study's scope. Different harmonics patterns can be explored using different/multi-level pulses of converters, dual conversion loads, and arc loads as harmonics sources.

Adjusting and switching the calculated LC values of the star and delta-connected networks based on the operating loads is crucial. Hence, implementing a dedicated controller for rapid LC network switching would be highly effective for accommodating changing load patterns in various industries. This arrangement holds a significant value for different processes in small-scale industries, which exhibit unique loading cycles corresponding to batch products.

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