Progressive Harmonic Compensation of Power System using Shunt Active Power Filter

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ORIGINAL ARTICLE

Progressive Harmonic Compensation of Power System using Shunt Active Power Filter

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Abstract

Harmonic pollution has a major detrimental effect on the power quality of low voltage distribution networks as a result of the proliferation of non-linear loads. The filter injects compensating current equal to the harmonic current needed by non-linear loads at the point of common coupling. Progressive harmonic compensation can be achieved by using shunt active filters at the metering point of each non-linear consumer. This paper proposes a modification in the control scheme of filter based on resistive load synthesis approach. The analysis of the proposed method is carried out in MATLAB Simulink. The control algorithm is used to calculate the filter current by identifying the harmonic current contribution of source at each consumer location. The efficiency of the suggested method in enhancing power quality of system is validated by real time simulation using OPAL-RT.

KEYWORDS
harmonic distortion, power quality, power factor, shunt active power filters

1 | INTRODUCTION

A greater percentage of non-linear loads are now present in the power system as a result of advances in power electronics technology. When these loads are present in the system, they introduce harmonic current, which causes the voltage at the point of common coupling (PCC) to be distorted as it travels through the system impedance. These harmonics create a variety of harmful effects, including the transformer and motor overheating, false relay trips, malfunctioning of electronic devices, damage to capacitor banks, etc. IEEE standard 519 places restrictions on the distortion of the current and voltage to maintain the system's power quality[1]. According to this regulation, the utility and the consumer both have equal responsibility for reducing the harmonic pollution at the PCC.

Filters are used to provide harmonic compensation. Earlier, harmonics were eliminated using a passive filter tuned to a specific harmonic frequency[2]. Over time, passive filters were replaced with active filters. Voltage source type inverters known as active power filters have the ability to add current or voltage to the system. Both series and parallel connections of active and passive filters are possible. In reality, active and passive filters are combined to lower the capacity of active power filters. Depending on how passive and active filters are combined, many filter topologies exist. Harmonic correction frequently uses passive filters in conjunction with active filters.

The schematic representation of the shunt active power filter coupled to the PCC is indicated in Fig. 1. Shunt active power filters work by resistive load synthesis and sinusoidal current synthesis methods[3,4]. By injecting harmonic current into the PCC in phase opposition, the filter creates sinusoidal line current using the sinusoidal current synthesis method. This method works better if the PCC voltage is sinusoidal[5,6]. However, the current scenario has resulted in distorted voltages with the proliferation of power electronic loads. The power factor will not be improved since the voltage is distorted. In the resistive load synthesis (RLS) approach, the load is assumed to be resistive with identical waveshape for voltage and current at PCC[7,8]. The dampening effect won't change even if the power factor is increased to unity. Both sinusoidal and distorted power systems can be used with this strategy.

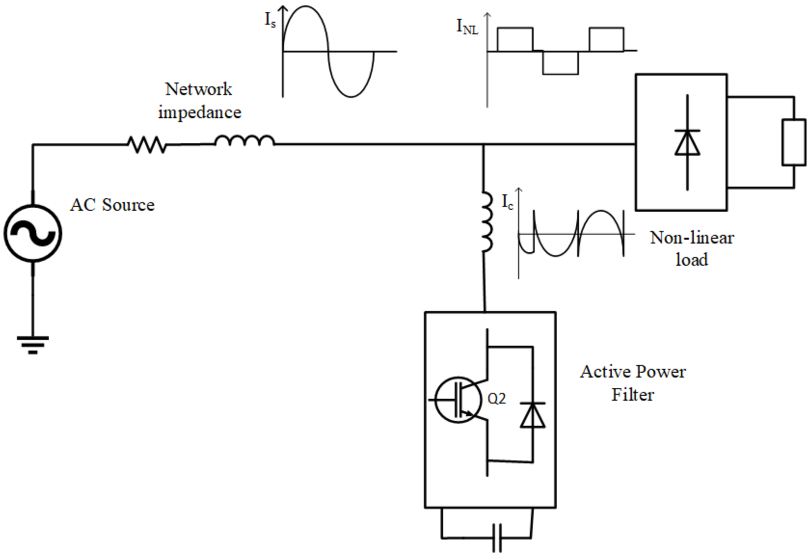

FIGURE 1 Schematic representation of the PCC-connected shunt active power filter

The filter can be connected at each consumer location. It ought to be able to distinguish between the utility's and the consumer's harmonic contributions. If the filter can supply the harmonic current required by the consumer, the source current will become sinusoidal. By connecting shunt active filter at each consumer ends, progressive harmonic compensation can be achieved. The system will not be polluted due to the non-linear load. Any distortion on utility side will affect the PCC current and voltage. But the use of shunt active filter helps the consumers to have identical waveshape for both voltage and current at their locations improving the power factor. The control algorithm of shunt active power filter needs to be changed in order to deliver the harmonic currents needed by the non-linear load.

The computation of the compensating reference current is necessary for controlling the shunt active power filter. There are numerous methods for generating reference current in frequency and time domains. In[9 10 11], different control algorithms are used for designing shunt active filters. This study uses the RLS approach and suggests a control algorithm such that the current injected by the filter will make utility current waveform identical to the waveform of PCC voltage.

A brief description of the shunt active power filter is provided in Section 2. Section 3 provides an explanation of the filter's modified control algorithm. Simulation results using MATLAB Simulink is presented in section 4. Section 5 explains the verification of the suggested algorithm by real time simulation using OPAL-RT.

2 | SHUNT ACTIVE POWER FILTER

Shunt active power filter consists of voltage source inverter with the AC side connected to the consumer end at the PCC and the DC side to a DC link capacitor. Filter current is controlled by choosing a dc link voltage that is more than the maximum PCC voltage. The dc link voltage is selected as 400V for a 230V single phase system. The filter is connected at the PCC using an inductor for reducing the ripple present in the filter current. The DC link capacitor is designed with the understanding that when a load is applied, the DC link voltage will decrease, and when the load is removed, the DC link voltage will rise. The values of inductance and capacitance selected is given in Table 1. A first order high pass RC filter, also known as a ripple filter, is connected at the PCC and tuned at half the switching frequency in order to remove high frequency noise from the voltage. High frequency noises can pass through the ripple filter because of its high impedance to fundamental frequency and low impedance to switching frequency.

The IGBTs inside the shunt active filter experience switching losses as the filter injects current, lowering the dc link voltage[12 13]. In order to maintain the constant dc link voltage, a comparison is made with a dc reference voltage V_{dcref} and the error signal is then provided to a PI controller to obtain I_{dc}. Since the source must provide the active power necessary to offset the filter's loss, this I_{dc} is utilized to determine the reference source current.

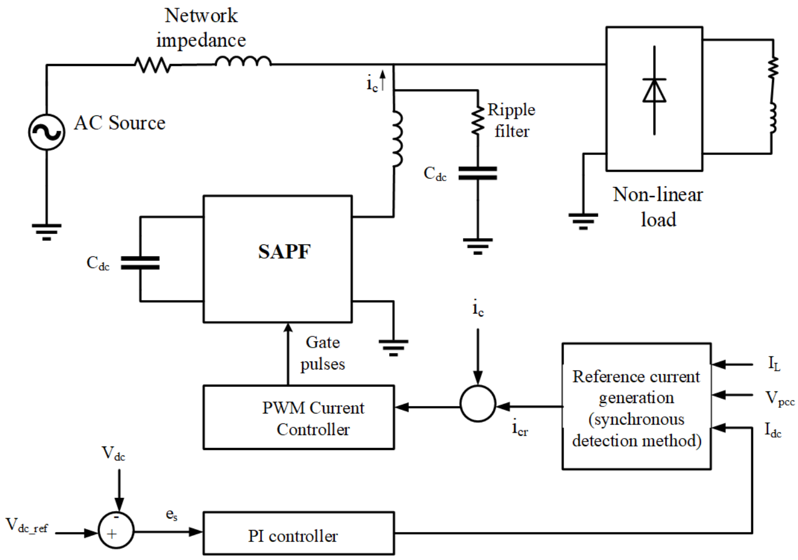

FIGURE 2 Model for simulating the proposed method.

The two main elements of the active filter's control strategy are generation of reference compensating current and gate signals [14]. The synchronized detection approach is utilized to produce the reference current and controller using PWM technique is employed for generation of gate signals for IGBT. The reference compensating current is calculated using the load current, PCC voltage, and I_{dc}. These currents are compared and the output signal is fed to a PWM current controller to generate the required triggering pulses for the IGBT switches. Figure 2 indicates the system configuration used in the study. Table 1 contains a list of the system parameter values that were used for the simulation study.

3 | MODIFIED CONTROL ALGORITHM OF SAPF

This section discusses a modified control algorithm for a shunt active power filter. The algorithm uses the load's actual harmonic current contribution to identify the reference compensating current. Utilizing the synchronous detection approach, the reference current is calculated. An error signal is sent to a PI controller after the computed reference current and the real filter current are compared. Using pulse width modulation techniques, the output of the PI controller is used to provide the required gate pulses for triggering switches in the SAPF. Figure 3 illustrates the reference compensating current computation using the proposed methodology. It can be described in the following steps:

Step 1: Equations (1) and (2) convert the load current and voltage into the two axes current and voltage.

$$\begin{bmatrix} v_{Sa} \\ v_{Sb} \end{bmatrix} = \begin{bmatrix} v_{S1}(\omega t) \\ v_{S2}(\omega t - \frac{\pi}{2}) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_{La} \\ i_{Lb} \end{bmatrix} = \begin{bmatrix} i_{L1}(\omega t) \\ i_{L2}(\omega t - \frac{\pi}{2}) \end{bmatrix} \tag{2}$$

Step 2: Equation(3) is used to compute the instantaneous power.

$$p = v_{Sa} i_{La} + v_{Sb} i_{Lb} \tag{3}$$

Step 3: Low pass filter can be used to extract the fundamental power (P_{dc}) from the instantaneous power.

Step 4: This approach requires the utility to provide the fundamental current required by load, a small amount of DC current to compensate for the filter's losses, and harmonic current contribution of utility. Equation(4) gives the fundamental magnitude of utility current.

$$I_S = \frac{P_{dc}}{V_S} + I_{dc} \tag{4}$$

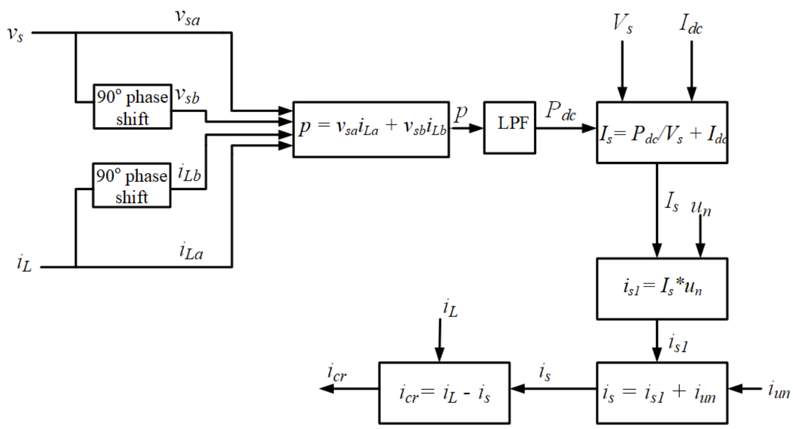

FIGURE 3 Calculation of reference current using proposed method

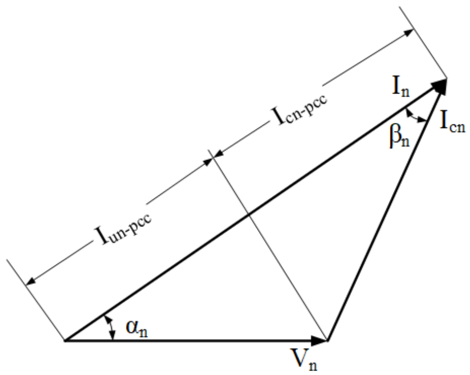

FIGURE 4 Phasor representation of the n^{th} harmonic quantities.

where V_S is the magnitude of the utility voltage.
I_{dc} is the current required to compensate for the filter losses.
This magnitude is multiplied by a unit template of PCC voltage to yield the fundamental utility current, i_{s1}. The instantaneous value of utility current is computed as in (5).

$$i_S = i_{S1} + i_{un\text{–}pcc} \tag{5}$$

where $i_{un\text{–}pcc}$ is the current harmonics contributed by utility and is computed as follows.
Step 5: A comparison of the normalized voltage and current at the PCC gives the harmonic current injected by the non-linear load. The n^{th} harmonic normalized voltage vector and n^{th} harmonic normalized current vector at the PCC are represented by the voltage V_n and current I_n in Fig. 4. Current I_n contains the harmonic contributions from both consumer and utility [15 16]. By projecting I_{cn} onto I_n separates I_n into $I_{un\text{–}pcc}$ (utility contribution) and $I_{cn\text{–}pcc}$ (consumer contribution).

$$I_{un\text{–}pcc} = V_n \cos \alpha_n \tag{6}$$

$I_{un\text{–}pcc}$ can be found for all harmonics present in the load current. By multiplying the entire utility harmonic current contribution by the PCC voltage unit template, $i_{un\text{–}pcc}$ is achieved.
Step 6: The compensating current reference value is found using equation (7).

$$i_{cr} = i_L - i_S \tag{7}$$

After comparing the actual compensating current and the reference compensating current, PI controller receives the error signal. The PI controller's output is utilized to produce gate pulses that operate the shunt active filter's IGBT switches. The filter injects

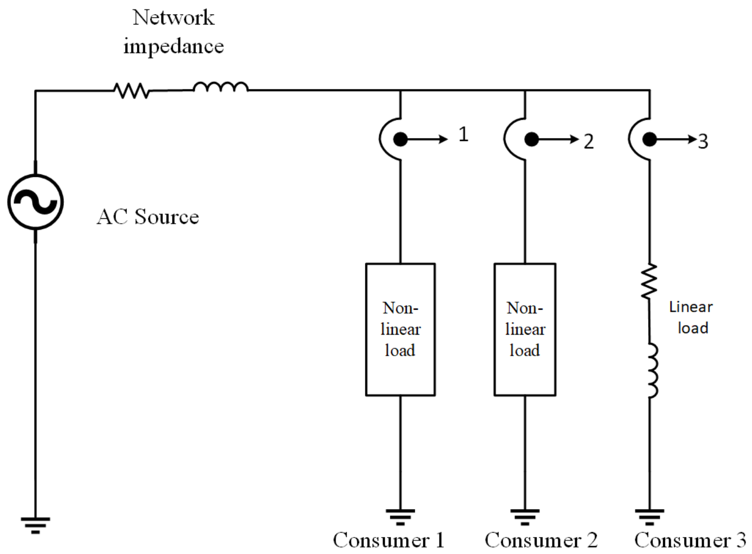

FIGURE 5 Simulation model

only current harmonics generated by non-linear loads. Because of the distorted source voltage, the source current continues to carry the harmonic current, giving the voltage and current waveforms the same waveform.

4 | SIMULATION RESULTS

Simulation analysis of the suggested algorithm is done in MATLAB Simulink.For analysis, a network impedance of (0.6+j4) ohm and a source voltage of 230 V, 50 Hz are chosen. The utility is feeding two non-linear and one linear consumer. The non-linear load considered is a single phase bridge rectifier feeding RL load and linear load is RL load. The system's simulation model is indicated in Fig.5. Table 1 indicates the parameters chosen for simulation study.

For analysis, five cases are taken into consideration.

Case 1: Only consumer 3(linear) is connected to the PCC.
Case 2: Consumers 2(non-linear)and 3(linear) are connected to the PCC without APF.
Case 3: All three consumers are connected to the PCC without APF.
Case 4: All three consumers are connected to the PCC with APF connected at consumer 2.
Case 5: All three consumers are connected to the PCC with APF connected at consumer 2 and 3.

Two different scenarios are used to analyze each case.

1. Utility voltage is purely sinusoidal.
2. Utility voltage is polluted having a THD of 9%.

4.1 | Utility voltage is purely sinusoidal

Table 2 shows the voltage and current THD values for different cases when utility voltage is purely sinusoidal.

TABLE 1 System parameters chosen for simulation model

Parameters	Values
V_s	230V , 50 Hz
Network impedance	0.50 ohm, 0.01H
V_{dc}	400V
Interfacing Inductor	5mH
DC link Capacitor	4700 μF
Switching frequency	20kHz

TABLE 2 Current and voltage THD values when the utility voltage is purely sinusoidal.

Case	V_s	I_s	V_{pcc}	I_1	I_2	I_3
1	0%	0%	0%	-	-	0%
2	0%	8%	6%	-	17%	2%
3	0%	9%	9%	14%	14%	3%
4	0%	6%	6%	19%	6%	2%
5	0%	1%	1%	1%	1%	0%

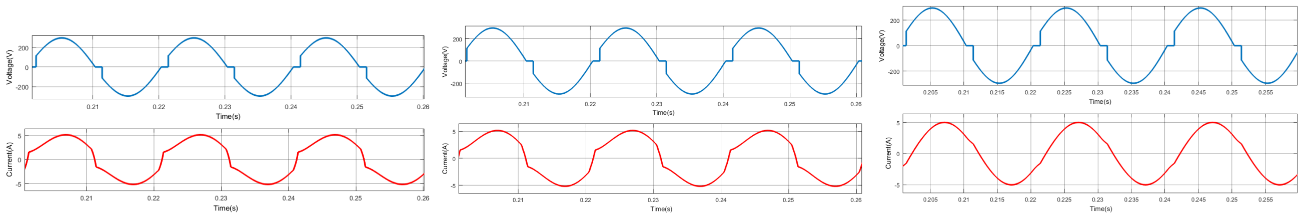

FIGURE 6 Waveforms at consumer ends for case 3 without APF when source voltage is sinusoidal.

4.1.1 | Case1: Only consumer 3(linear) is connected to the PCC.

Initially when the system is carrying a linear load, both current and voltage at the utility and consumer ends are sinusoidal with 0% THD.

4.1.2 | Case 2: Consumers 2(non-linear) and 3(linear) are connected to the PCC without APF.

While connecting non-linear load at consumer end 2, the utility current is polluted with 8% THD resulting in a 6% voltage distortion at the PCC. The linear load now carries some harmonic current with a THD of 2% due to the distorted voltage.

4.1.3 | Case 3: All three consumers are connected to the PCC without APF.

In case 3, another non-linear consumer is connected at consumer end 1 leading to further voltage distortion at PCC. In the absence of SAPF, the current and voltage THD values at the measuring point of each consumer is different indicating that the utility is supplying the harmonic current required by the loads. Fig.6 shows the waveforms at the consumer ends without APF. It is seen that the load currents of non-linear consumers are highly distorted with 14% THD leading to distortion of PCC voltage with 9% THD. Due to the distorted voltage at the PCC the current drawn by linear consumer 3 is not purely sinusoidal but have a THD of 3%. Fig.8 displays the frequency spectrum of the source current. The magnitude of different harmonics is expressed as percentage of magnitude of fundamental current. 3^{rd}, 5^{th}, and 7^{th} harmonics are the most prominent, with a THD of 9.05%.

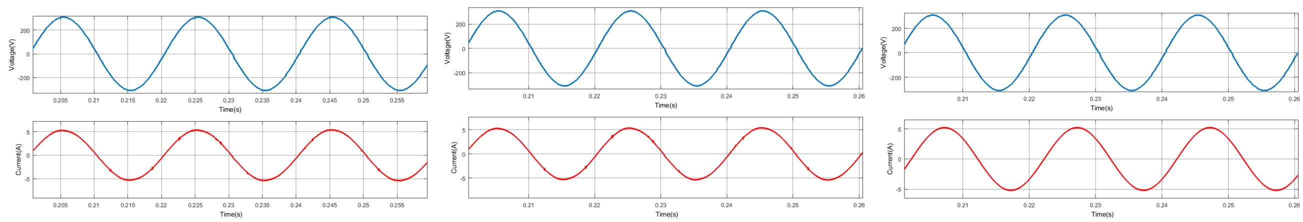

FIGURE 7 Waveforms at consumer ends for case 5 with APF when source voltage is sinusoidal.

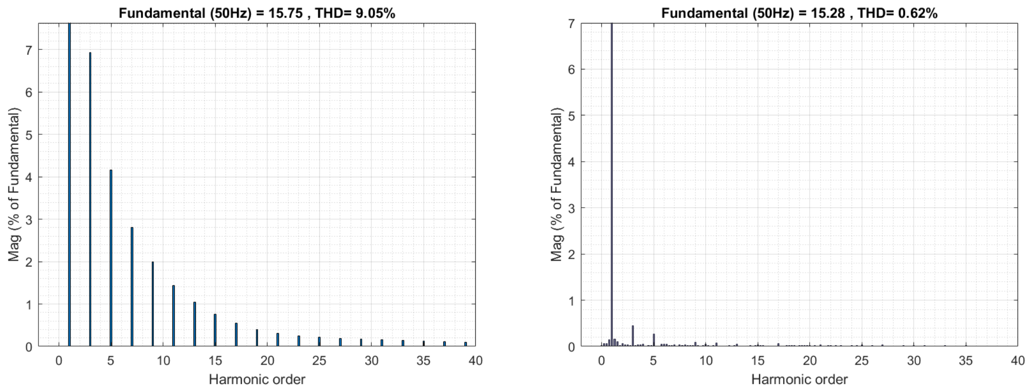

FIGURE 8 Frequency spectrum of source current without and with APF when source voltage is sinusoidal.

4.1.4 | Case 4:All three consumers are connected to the PCC with APF connected at consumer 2.

By connecting a shunt active power filter at consumer end 2, a considerable reduction of source current harmonics is observed reducing the distortion of PCC voltage. The filter is capable of supplying the current harmonics required by consumer 2 which makes the current and voltage THD values at consumer 2 to be 6%.

4.1.5 | Case 5: All three consumers connected to the PCC with APF connected at consumer 2 and 3.

In case 5, both non-linear consumers have shunt active filter connected at their ends. It is found that voltage and current at each consumer location have become sinusoidal with THD values 1%. The line current is also made sinusoidal improving the system's power quality. Fig.7 indicates the waveforms at different consumer locations after connecting filters at the location of non-linear consumers. The voltage and current waveforms are observed to exhibit a sinusoidal appearance, suggesting that the suggested method is beneficial in enhancing the system's power quality. Fig.8 shows the frequency spectrum of source current with APF indicating a THD value of 1%. Only 3^{rd} and 5^{th} harmonics have considerable magnitude less than 0.5% of fundamental and all other higher order harmonics are negligible. Therefore, by maintaining sinusoidal source current, the suggested method can enhance the system's power quality.

4.2 | Utility voltage is polluted having a THD of 9%

4.2.1 | Case1: Only consumer 3(linear) is connected to the PCC.

Table 3 shows the current and voltage THD values when utility voltage is polluted. Due to the system impedance, the distortion in source voltage has resulted in distortion of voltage at PCC forcing the linear load at consumer 3 end to carry harmonic current with a THD of 3%.

TABLE 3 Current and voltage THD values when utility voltage is polluted having a THD of 9%.

Case	V_s	I_s	V_{pcc}	I_1	I_2	I_3
1	9%	3%	8%	-	-	3%
2	9%	11%	9%	-	20%	3%
3	9%	11%	10%	17%	17%	3%
4	9%	9%	9%	22%	9%	3%
5	9%	6%	8%	8%	8%	3%

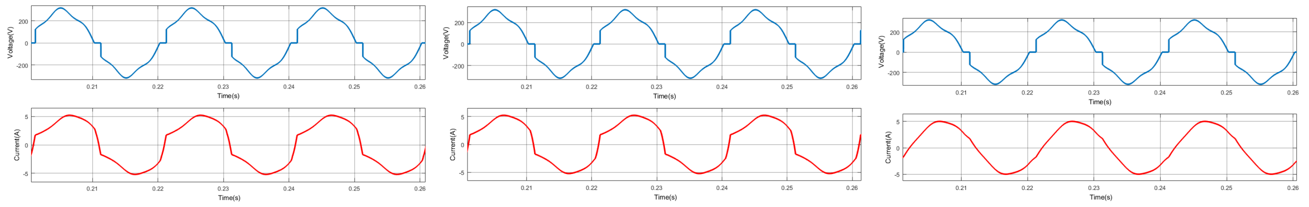

FIGURE 9 Waveforms at consumer ends for case 3 without APF when source voltage is distorted.

4.2.2 | Case 2: Consumers 2(non-linear) and 3(linear) are connected to the PCC without APF.

With the introduction of non-linear load at consumer end 2, harmonic pollution in the system is increased indicated by the higher current and voltage THD values at consumer locations.

4.2.3 | Case 3: All three consumers are connected to the PCC without APF.

In case 3, a non-linear load is further connected at consumer end 1. A slight reduction in THD value of current drawn by consumer 2 can be observed from the table. This can be due to the cancellation of certain harmonic components of currents. But the THD value of PCC voltage is increased to 10%. The waveforms at the consumer ends without APF is indicated in Fig.9. It is seen that the load current is highly distorted with 17% THD leading to distortion of PCC voltage with a THD of 10%. Consumer 2 is drawing highly distorted current and the current drawn by linear consumer 3 is also not purely sinusoidal. The source current frequency spectrum is shown in Fig.11. The magnitude of different harmonics is expressed as percentage of magnitude of fundamental current. 3^{rd}, 5^{th}, and 7^{th} harmonics are the most prominent, having a THD of 11.48%.

4.2.4 | Case 4:All three consumers are connected to the PCC with APF connected at consumer 2.

By connecting a shunt active power filter at consumer end 2, a considerable reduction of source current harmonics is observed reducing the distortion of PCC voltage. The filter is capable of supplying the current harmonics required by the consumer 2 which makes the current and voltage THD values at consumer 2 to be 9%.

4.2.5 | Case 5: All three consumers connected to the PCC with APF connected at consumer 2 and 3.

In case 5, both non-linear consumers have shunt active filter connected at their ends. It is found that voltage and current at consumer locations have identical waveshape with THD values of 8%. The filters connected at the consumer ends supply the current harmonics needed by non-linear loads. However, the utility carries some current harmonics due to its distorted voltage. Fig.10 indicates the waveforms at different consumer locations after connecting filters at the location of non-linear consumers. It is observed that both waveforms have identical waveshapes indicating that the voltage at PCC is not affected by the non-linear load connected at consumer ends 2 and 3. The distortion in PCC voltage is entirely due to source side distortion. Fig.11 indicates the source current frequency spectrum with APF when utility voltage is polluted indicating a THD value of 5.64%. Only 5^{th} harmonics have considerable magnitude of less than 6% of fundamental and all other higher order harmonics are negligible. Hence, the suggested method improves the power quality of the system with distorted source voltage.

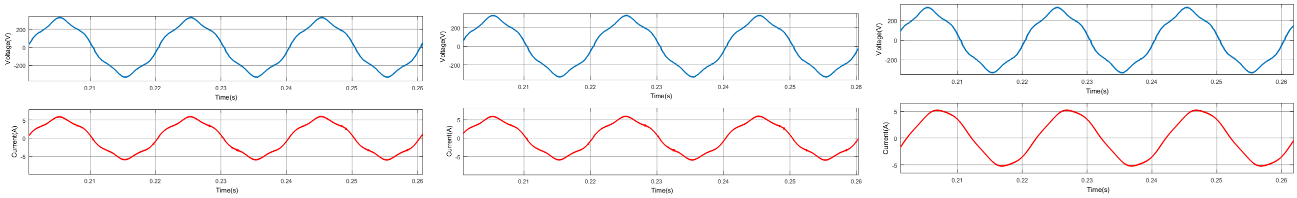

FIGURE 10 Waveforms at consumer ends for case 5 with APF when source voltage is distorted.

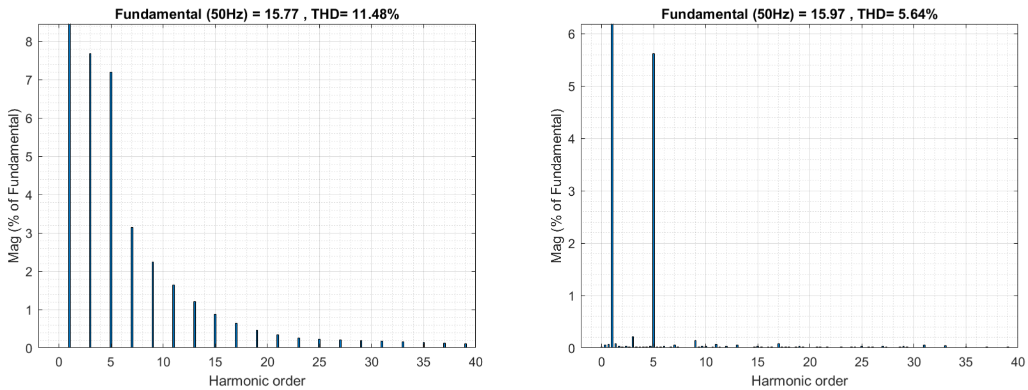

FIGURE 11 Frequency spectrum of source current without and with APF when source voltage is distorted.

5 | REAL TIME SIMULATION RESULTS USING OPAL-RT

The real-time simulation is carried using the shunt active power filter model in OPAL-RT. The experimental setup for real-time simulation is depicted in Fig.12 and includes a DSO, I/O interface card, host PC with RT-Lab software and MATLAB.

MATLAB model is converted to C language using RT-LAB and then loaded onto the OPAL-RT. The complete simulation diagram is divided into a console and master unit, with the controller being a component of the master subsystem. The displays in the console subsystem allow users to access the necessary waveforms.

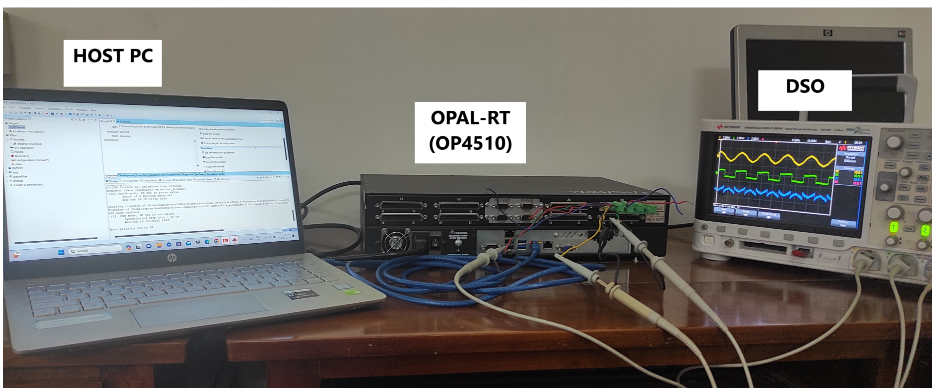

FIGURE 12 Real Time experimental setup using OP4510

Analysis is carried out for a non-linear consumer connected to the utility with shunt active filter connected at the PCC.

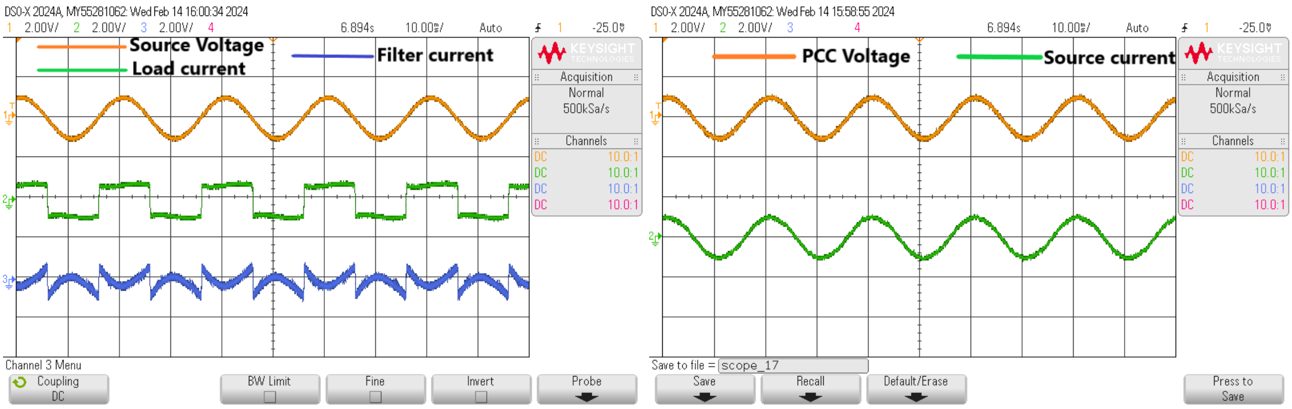

FIGURE 13 Voltage and current waveforms with sinusoidal source voltage

5.1 | Utility voltage is purely sinusoidal

Fig.13 shows the waveforms of source current, load current, PCC voltage, filter current and source voltage . The current drawn by non-linear load is highly distorted eventhough the utility voltage is sinusoidal. The suggested algorithm determines the compensating current that the filter should provide while taking each consumer's contribution to the harmonic current into account. The waveforms of source current and PCC voltage are identical giving a sinusoidal appearance. The identical voltage and current waveforms results in improvement of power factor.

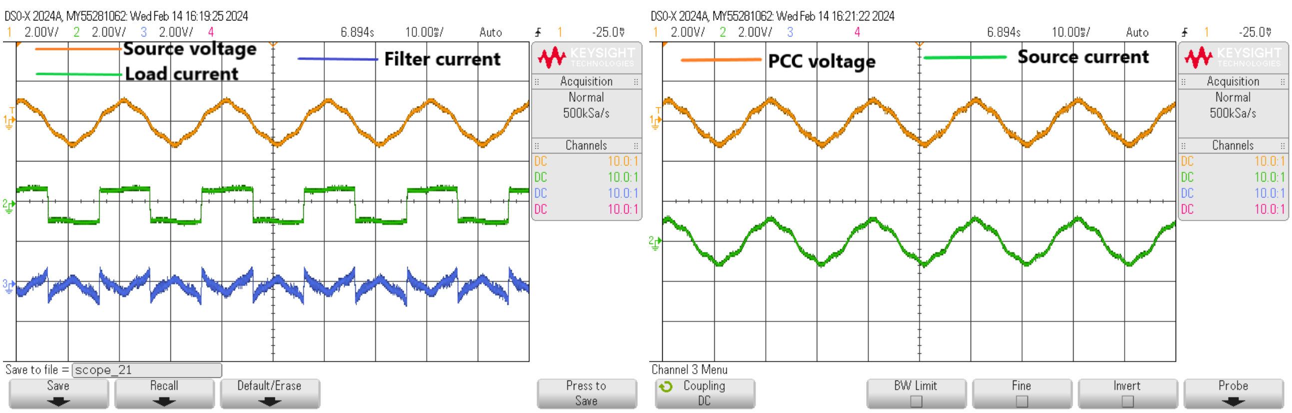

FIGURE 14 Current and voltage waveforms with distorted source voltage

5.2 | Utility voltage is polluted having a THD of 9%

Fig.14 shows the waveforms of source current, load current, PCC voltage, filter current and source voltage . Since the utility voltage is distorted, the harmonic current drawn by the load consists of contributions from both consumer and utility. The proposed algorithm calculates the compensating current to be supplied by the filter taking into account harmonic current contributed by the individual consumer. The source current has to carry the current harmonics contributed by utility in order to make the voltage and current at the PCC identical. The suggested method's ability to improve the system's power quality is validated by real-time analysis.

6 | CONCLUSIONS

In this work, a modified algorithm for shunt active filter control is suggested. The approach is based on resistive load synthesis, where the load is assumed to be linear. The reference compensating current is determined using the source contribution of the harmonic current. By using this technique, source current is made to adhere to the same waveform as PCC voltage. Each consumer location is equipped with a filter to deliver the harmonic current contributed by each individual consumer. Progressive harmonic correction is possible by connecting shunt active filters to each consumer end. Because of the non-linear load, the system will not become polluted. Source current and PCC voltage distortion will be impacted by any distortion on the utility side. However, installation of a shunt active power filter with the proposed topology enables consumers to have identical current and voltage waveforms at their locations and hence increasing power factor as well. Real time simulation done using OPAL-RT also indicates the effectiveness of the proposed algorithm.

CONFLICT OF INTEREST
The authors declare no potential conflict of interests.

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