Research Article

TRI-LEVEL CASCADING CONTROL TO AUGMENT POWER QUALITY CONCERNS IN DISTRIBUTION NETWORKS

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ABSTRACT: Power distribution systems have been affected by harmonic problems for decades. Harmonic currents can affect line voltage and direct to numerous adversative results including equipment overheating, failure of solid-state equipment, and restraint with communication systems. They deteriorate power quality by causing poor power factors and increasing total harmonic distortion. To reduce harmonics and to improve power quality, a grid-tie active power filter (APF) is introduced which eliminates both lower and upper-order harmonics. In this proposed paper, APF is used along with an LCL filter with versatile controlling techniques, Clarke's and Park's transformations are implemented in the paper. The proposed scheme can fulfill the problem faced in the power system due to non-linear loads. The results are simulated and validated using MATLAB/Simulink environment.

KEY WORDS: Active Power Filter, Total Harmonic Distortion THD, Harmonic Compensation, Controller

INTRODUCTION

The increase of non-linear loads in the power system results in several unwanted phenomena in the functioning of the energy system. Major issues are harmonic problems, an increase of reactive power pressure, and power energy system fluctuations/ variations. In a power system, transformer losses are increased due to higher levels of distortion which causes overheating. Due to too much heat rapid corrosion of the insulation leads to early disaster. Power quality is also a key factor for the steadfast working of power grids. The unnecessary harmonics cause a severe decline in power quality, and this problem gets further observable for DGs attached to a microgrid (MG) [1].
Harmonics are originated when a non-linear device pulls in current with short pulses. Sometimes, harmonics in load current cause overheating of transformers, blow-up fuses, and trip circuit breakers [2]. Harmonics cause non-sinusoidal current and voltage waveforms [3]. In both industrial and energy-intensive distribution systems, much higher amplification in power harmonics in the distribution feeder is a serious issue [4]. Harmonic currents can change line voltage and direct to many adversative effects including mechanical over-heating, failure of solid-state equipment and disruption of communication systems, decrease network efficiency and raise power cost [5- 6]. Harmonic problems get worse in the MG when different distributed (DG) units work together/ collectively for solving load sharing issues as a result of mismatching of feeder impedances and an increase in ratings of DG. However, load sharing can be accomplished but in addition, MG suffers THD and voltage unbalanced sequences at the end points of DG terminals and the point-of-coupling PCC [7]. Passive LC filters are generally employed to

eliminate line current harmonics and to increase power factor, however, they have many shortcomings in practice. For example, they are large, require constant compensation, and may cause resonance problems [8–10]. The voltage-current VI-compensator is proposed that uses a cascaded methodology with a voltage compensation unit supported by a current compensation unit. The suggested VI-compensator operates PI controllers without requiring any supplementary expensive hardware [1].

An improved harmonic droop controller was used in [6] for a low voltage islanded MG. This technique can perform two tasks i.e., one control loop is used to achieve an optimal harmonic current distribution and voltage harmonic compensation at PCC. The proposed methodology also shows resistance to mismatches among line impedances by using harmonic sharing of current. In [11-12] the suppression of the harmonical parts in the output current is lesser than the pre-set value in the grid-tied inverter which is challenging. It is also problematic to balance the unbalanced loads, especially when the grid is under congestion. Effective and efficient strategies are required in the working of MG, for controlling the grid parameters by the mass deployment of DG many problems are encountered such as reverse power, an imbalance between power generation, and nonlinear load. The synchronous Reference Frame (SRF) method is used in the understudied papers. In [13], To regulate power insertion and harmonic current compensation, the Adjustable Synchronous Reference Frame (ASRF) and SRF are introduced. These controlling techniques are used for interfacing power inverter to carry out direct action to mitigate harmonics. When non-linear, unbalanced loads and DGs are coupled to the grid, this policy considerably boosts and at the same time recovers the THD of the inverter for DGs and the grid current.

In [14] an adaptive approach utilizing an experiential method is presented, which can optimally control the output voltage, which is based on a DG, of the inverter to improve MG functioning in the islanded state. AI algorithm is implemented which improves the constraints of the smart PI controller by shrinking the error assimilating part. Designing of the controller introduced in the paper contains 3 loops i.e., droop power loop, current control loop, and voltage control loop. The method controls the voltage and frequency of the DG-based inverter by fine-tuning the PI controller in real-time or offline, depending on viability. For current and voltage harmonics compensation, an improved control methodology is illustrated in [15] that employs a natural synchronous reference frame control for fuel cell and wind turbine with interfaced inverters in MGs. It was designed to regulate the rate of power injection to the grid, while simultaneously executing compensation functions for the voltage and current harmonics resulting from the unbalanced load and power electronics devices. An improved controller is proposed in [16] where per-phase average modelling of a four-leg inverter is performed in both fixed and rotating reference frames. Firstly, a unique uncoupled model of the four-leg inverter is displayed. Secondly, by employing an enhanced orthogonal signal formation technique, the per-phase model of a four-leg inverter is obtained in the fixed and synchronous frames. Thirdly, a per-phase multi-loop control approach for the aforementioned inverter under an unstable load situation is suggested. Finally, to successfully mitigate lower order harmonical currents, a multi-resonant harmonic compensator is used.

CHARACTERISTICS OF APF

An efficient approach for harmonic elimination is harmonic compensation by using APF. The conception of an active filter was first presented by Sasaki and Machida in 1971. The APF was a newly developed piece of equipment used to reduce current harmonics while compensating for reactive power [2]. Using voltage detection, it is suggested that information is shared between active filters with automated gain adjustment through collaborative control of numerous active filters [4]. For harmonic current sharing, a controlling scheme is made for islanded MG with non-linear unbalanced loads and irregular feeder impedances. By incorporating a direct harmonics voltage control APF with DG units, harmonic suppression performance is improved. Enhancement in power quality with sharing of load under systematic control of several DG units and APF in MG is demonstrated in [7].

Commonly APF is used to overcome problems that originate due to LC filters. In the understudy's paper, 3-phase APF with frequency converter is used. It compensates for current harmonic elements and the required reactive power by the load [17]. APFs have several merits over passive filters. First and foremost, they may suppress not just the current harmonics, but also the reactive component currents, which is a significant benefit. These filters do not generate adverse resonances with the power distribution system, unlike passive filters. As a result of its compact size, no need for tuning, and steady operation, APFs are regarded as a feasible alternative for reducing current harmonics and reactive power levels. In addition, they serve as harmonic current sources, compensating for reactive power and reducing harmonic currents. From the compensation reference signal of the estimator, the complete system controller is energized. The gate-signal-generator can then be controlled by this. Through a suitable interface, the output of the gating signal generator controls the power circuit [8].

Since APF is the filter that suppresses the order of harmonics produced by the load in 180° phase shift. When these harmonics are introduced into the transmission line at PCC, the load current harmonics are removed, resulting in a sinusoidal utility supply [18]. Figure 1 shows the current waveforms of APF with nonlinear load [3].

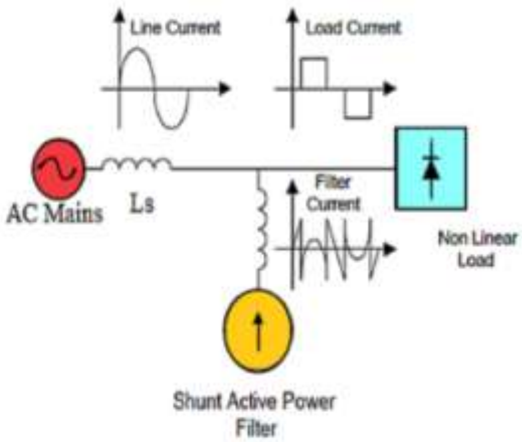

Fig. 1 Current waveforms of active power filter with nonlinear load [3]

The control mode of the APF can be divided into the voltage mode and the current model. Current-controlled power converters relate to detachable renewable-energy-sources (RES) and energy-storage-systems (ESS) to the power grid. From various studies, it has been demonstrated that voltage-controlled mode active filters are widely used due to inexpensive, lighter, and easily controlled means [9- 10, 19- 20].

RESEARCH METHOD

The proposed paper follows the flow chart given in Fig 2.

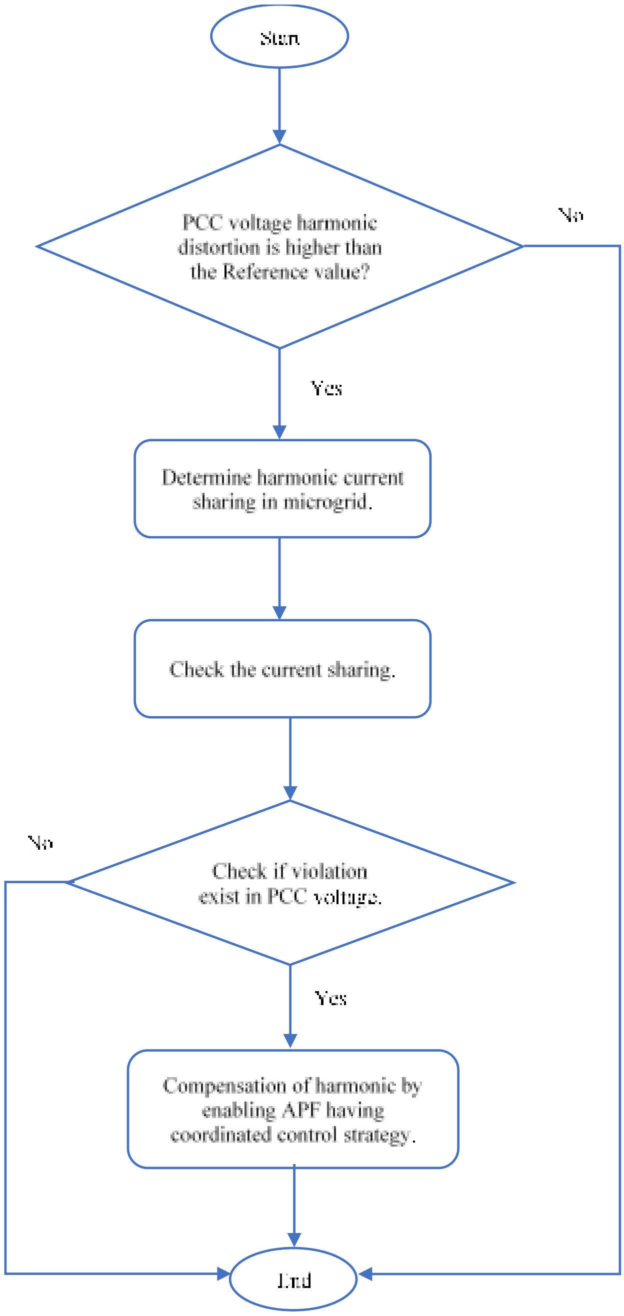

Fig. 2 Flow chart of the proposed controlling scheme of APF

The paper delineated the harmonic compensation of a 3-phase grid-tied inverter. An effectively controlled insulated gate bipolar transistor (IGBT) along with an LCL filter is used for compensation of unwanted current waveforms. The schematic diagram of the suggested model is demonstrated in Fig 3. While the controlling scheme of APF is given in Fig 4.

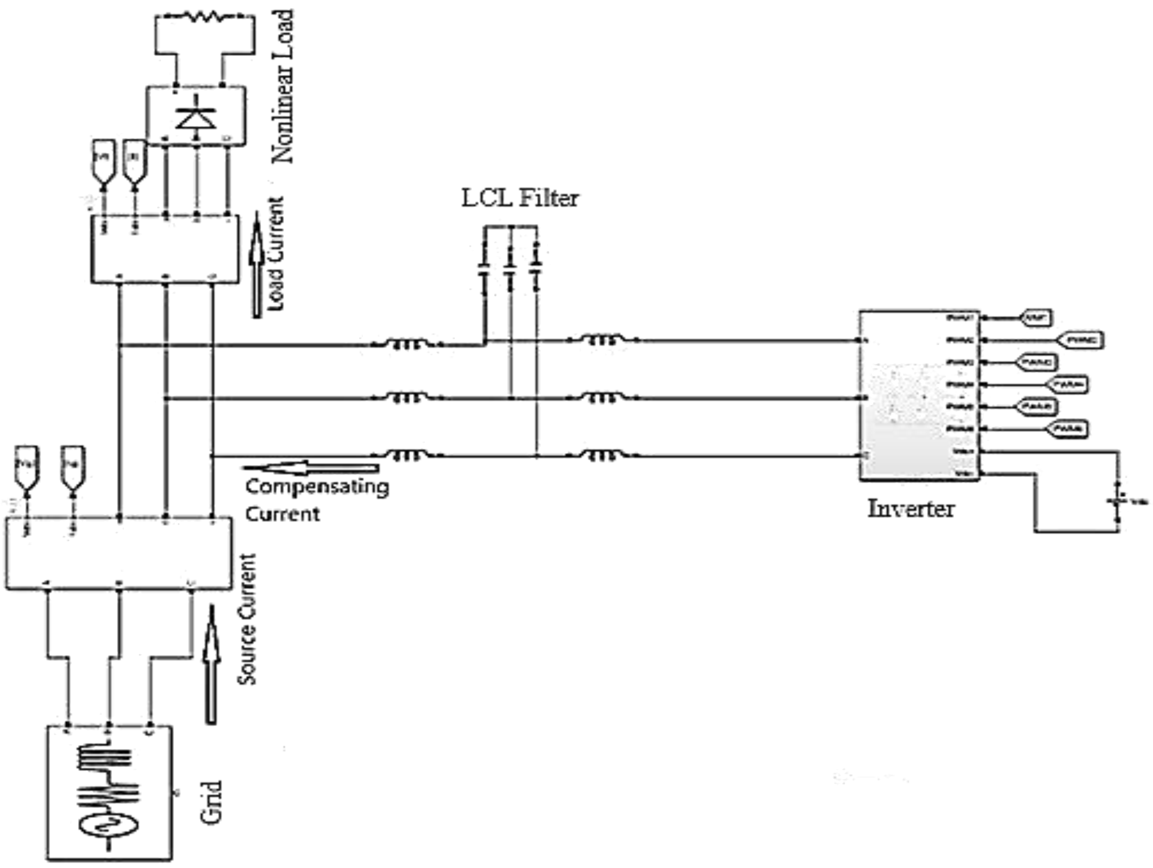

Fig. 3 Schematic Diagram İllustrating Proposed Components Connections

First by using Clark's transformation, the 3-phase grid voltage and load current are modified into a 2-phase orthogonal reference frame by using the following equations:

$$I_{\alpha\beta} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}, \quad (1)$$

$$V_{\alpha\beta} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}, \quad (2)$$

The αβ-frame representation is calculated with Clarke's transformation and then fed into Park's transformation block i.e., dq block where it is rotated about an angle θ.

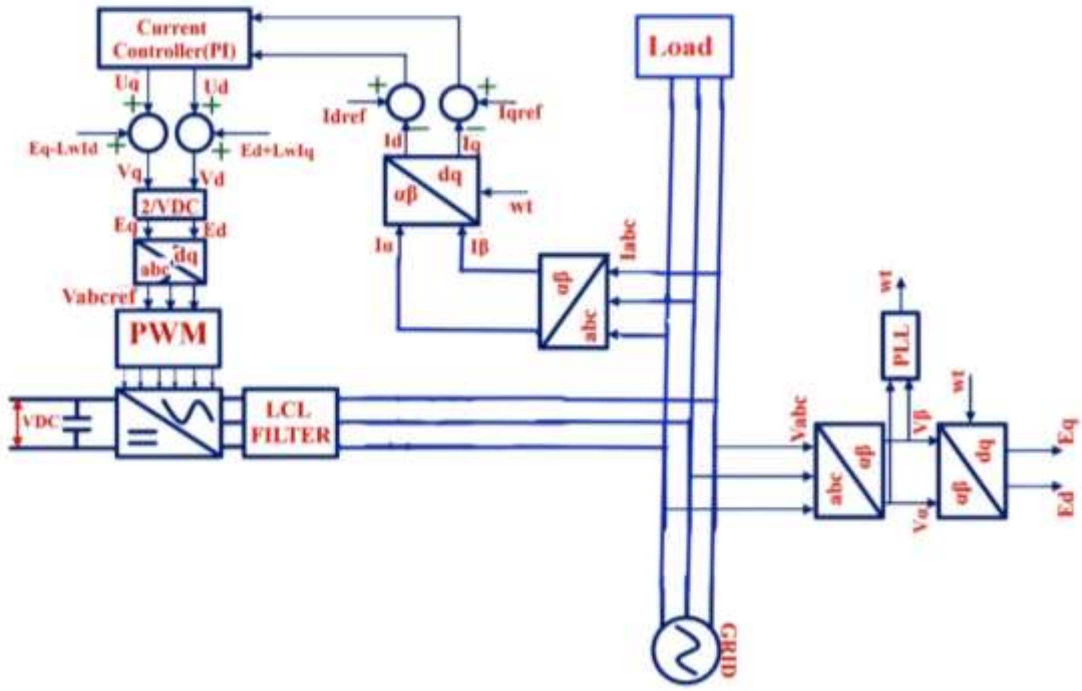

Fig. 4 Controlling diagram of APF

The rotation is over an angle θ is done by using the following formulas:

$$I_{dq} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}, \quad (3)$$

$$V_{dq} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}, \quad (4)$$

Phasor diagram of reference frames with the relationship of stationary abc-frame is represented in Fig 5.

After calculating voltage and current values in the dq-frame, the reference values are computed using the controlling method shown in Fig 3. When the reference signal is generated, it is in dq-frame but the signal which has to be fed as a gate signal into the inverter should be in 3-phase. So, first, dq components are converted into αβ -frame using Eq (5), and then αβ components are transformed into abc-frame by using Eq (6). Now, this resultant signal is then fed into the gate terminal of the APF inverter.

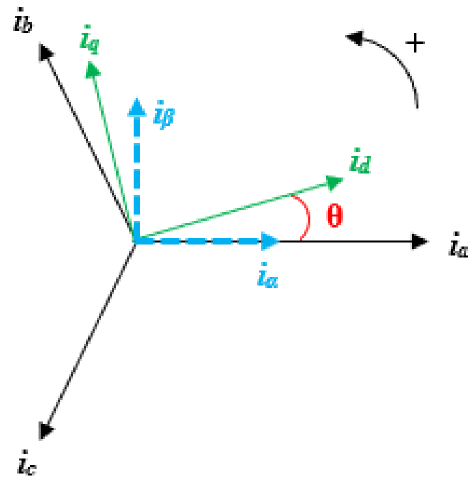

Fig. 5 Relationship of $\alpha\beta$ and dq reference frames with abc frame [21]

$$V_{\alpha\beta}=\begin{bmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}V_d\\ V_q\end{bmatrix}, \tag{5}$$

$$V_{abc}=\begin{bmatrix}1 & 0\\ -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}V_\alpha\\ V_\beta\end{bmatrix}, \tag{6}$$

Desıgnıng of LCL Fılter

Without using a filter, the current produced by the grid-tied inverter is not smooth as we required. It holds large numbers of harmonics. Power quality issues are created when such a current is injected into the grid, which deteriorates the voltage. To avoid all these issues, a filter is always used with an inverter. When the filter is connected to inverter output, a very smooth sinusoidal current is obtained without any harmonics. From Fig. 1, it is noticed that there are two inductors represented by L1 and L2, and one capacitor presented by C. First, determine the transfer function between grid current and inverter voltage. The equivalent circuit of the LCL filter is displayed in Fig 6.

Applying KCL at their common point say x:

$$\frac{V_i-V_x}{sL1}=I_g+\frac{V_x}{\frac{1}{sC}}, \tag{7}$$

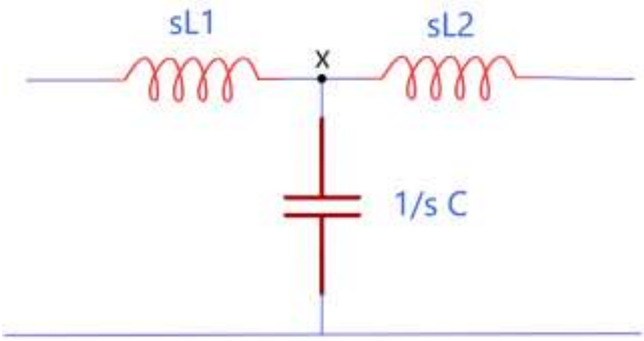

Fig. 6 Equivalent circuit of LCL filter

where V_x is the voltage at point x; Ig is the grid current; and V_i.is inverter voltage.

$$V_x = I_g sL2, \quad (8)$$

Comparing Eq (7) and Eq (8) the equation become:

$$\frac{I_g}{V_i} = \frac{1}{s^3 L1L2C + s(L1 + L2)}, \quad (9)$$

Let L1=L2=L and

$$L_p = \frac{L1L2}{L1 + L}, \quad (10)$$

Now the equation become:

$$\frac{I_g}{Vi} = \frac{1}{sL\left(1 + s^2 CL_p\right)}, \quad (11)$$

From equation (10),

$$\omega_{res} = \frac{1}{\sqrt{CL_p}}. \quad (12)$$

Switching frequency is selected on the basis of device constraints, cost of components and size, thermal consideration. As resonant frequency

$$f_{res} = \frac{F_{sw}}{10}. \quad (13)$$

$$Reactive\ power\ (Q) = 5\%\ of\ rated\ power\ (S), \quad (14)$$

Also

$$Q = \frac{V^2}{1/(2\pi f C)}, \quad (15)$$

From Eq (11) and Eq (12) value of C can be determined using formula:

$$C = \frac{0.05\ of\ S}{2\pi f V^2}. \quad (16)$$

When C is determined, the value of L can be found using Eq (11).

Results and Discussions

To elucidate the execution of the proposed system, simulation results are obtained from a 3-phase MG. The developed MG includes an APF, LCL filter along with the nonlinear load. The model was executed in MATLAB/ Simulink to certify the control for harmonic compensation in MG where a controlled APF is enabled. To demonstrate the simulation parameters, Table 1 below shows the values for the system parameters.

Table 1 System parameters with values for simulation

Parameters	Values
Switching frequency	10 kHz
Fundamental frequency	50 Hz
Source voltage	230 Vp-p
LCL inductor value	38.34 μH
LCL capacitor value	100.28 μF
Rated power	100 KVA

4.1 SIMULATION RESULTS

The simulation is done using MATLAB/ Simulink environment and results of the proposed system are demonstrated in this section. Fig 7 (a) and (b) show the waveforms of line current for phase A before and after enabling APF respectively. İt is clear that due to the presence of nonlinear load, harmonics distort the line currents but when APF is linked in the system, the compensating current signal of APF, shown in Fig 8, considerably suppressed the system's harmonics. THD of line current can be seen in Fig 9 (a) before and (b) after implementation of APF, respectively. It is noted that when APF is not enabled, the THD of line current is 23.42% and when it is connected, the THD lessened to 3.83% which is according to IEEE standard IEEE 1547-2003. The load current of phase A is marked in Fig 10.

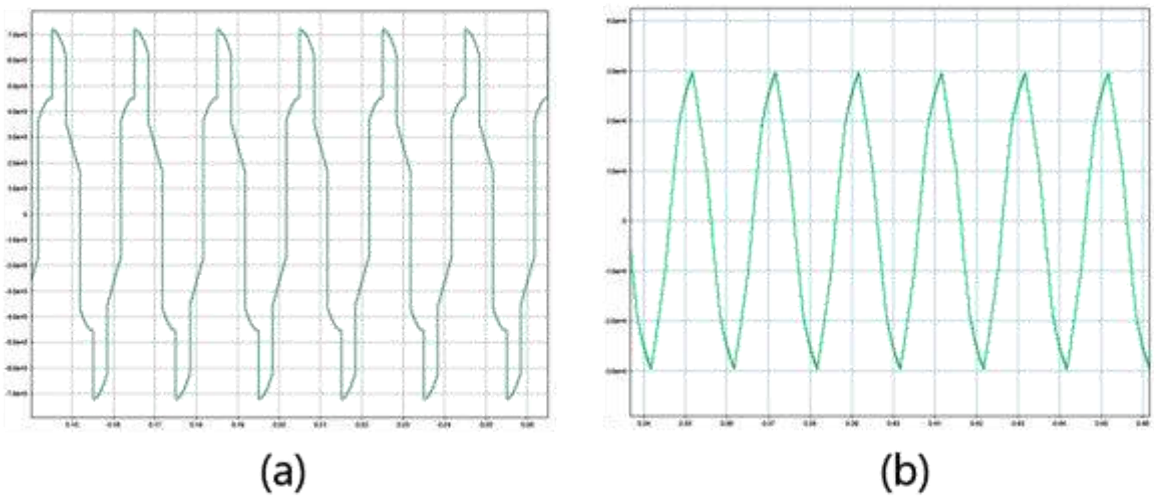

Fig. 7 Line current of phase A (a) before enabling APF (b) after enabling APF

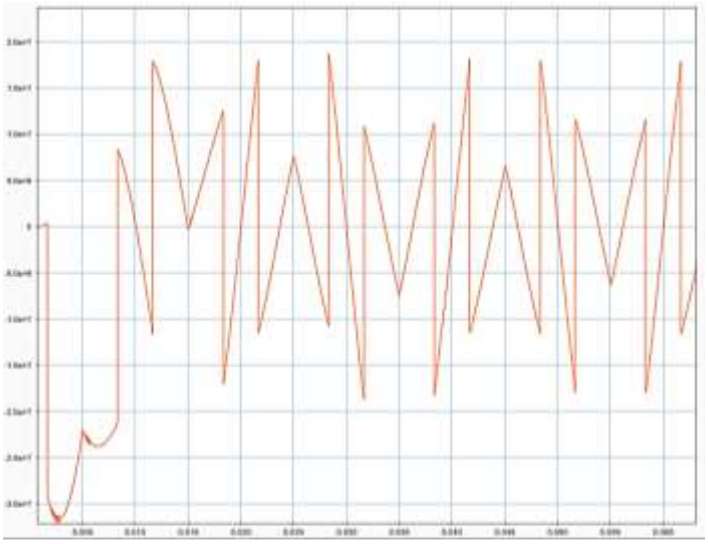

Fig. 8 Compensating signal for phase A

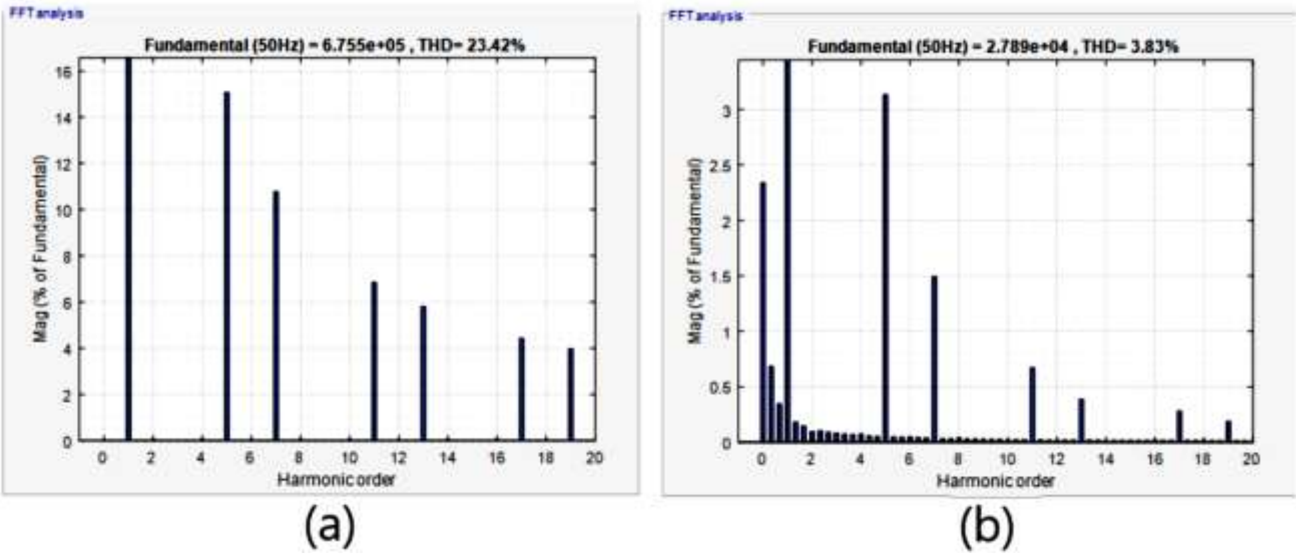

Fig. 9 FFT analysis of line current (a) before enabling APF (b) after enabling APF

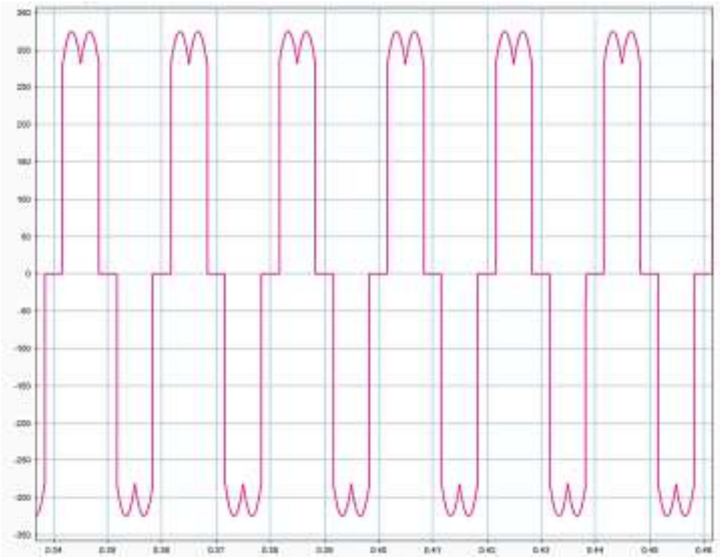

Fig. 10 Load current for phase A

CONCLUSION

Harmonics become a major issue in power systems due to an increase in nonlinear loads (NLL). This paper proposed a harmonic suppression technique applied in a 3-phase power system by using APF with an LCL filter in the presence of NLL. The controlling mechanism of APF used in this paper follows Clarke and Park transformation techniques. Simulation is performed in MATLAB software and corresponding results are displayed in the section above. From the results, it is concluded that harmonics are mitigated effectively by using APF. In short, the paper revealed that grid-tied APF is the best option for harmonic compensation in the presence of NLL.

The proposed strategy can be adapted for single-phase and three-phase power systems. APF can be used with renewable energy sources in the application of AC MG. The proposed scheme can be implemented in control engineering to adaptive tune the controller parameters with optimization to determine system dynamics.

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