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Enhancement of power quality of grid integrated photo voltaic system using active power filter

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ABSTRACT

The world's population's energy needs are growing daily, while at the same time, fossil fuels are being reduced at an alarming rate. Fossil fuel burning also increases pollution and causes global warming. Renewable energies are now being extensively used to generate electricity, so the dependence on fossil fuels is considerably reduced. Among the primary sources of alternative energy used to create power is photovoltaic (PV) technology. A grid-connected PV system is the most widely recommended. When PV is linked to the grid, two main issues are the maximum power that can be taken out of it and the quality of the electricity placed into it. With the help of neural networks, the maximum power point tracking (MPPT) technology has been developed to increase the PV array's power harvesting. An active power filter (APF) had been created and analyzed using Instantaneous Reactive Power Theory, including the Chebyshev II low-pass filter. As required by IEEE 519, the total harmonic distortion (THD) with injected source current has been confirmed well within 5%. These results demonstrate that this method is a simple and efficient way to inject harmonic-free currents into the grid.

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1. INTRODUCTION

The inclusion of renewable energies like solar and wind is increasing daily and rapidly worldwide. It is expected to increase their percentage share in electricity generation from 29% in 2022 to 42% in 2028 [1]. Most parts of India receive about 4 to 7 kWh/m2/day solar radiation and are available almost annually [2].

The Solar cell is used to generate electricity from solar radiation. A single solar cell may develop to about 6 Wh to 10 Wh. This is a minimal amount of energy; hence, a PV module is created by joining solar cells to produce a significant amount of energy. A photovoltaic (PV) array of numerous panels can also produce electrical energy commercially. As PV panels generate DC voltage, an inverter typically supplies AC voltage to the prospective loads [2].

PV panels might be run at maximum power point (MPP) to ensure that we always optimize the PV array's power output. To do this, a DC-DC converter could be utilized, along with an MPPT technique to regulate “the duty cycle inside the DC-DC converter's switch.” The majority of researchers have employed the perturb & observe (P&O) approach for MPP [3]-[7].

Many researchers have also used the incremental conductance (IC) method, which gives slightly better overall efficiency but is slightly more complicated [8]-[11]. Recently, many more maximum power point tracking (MPPT) methods have been developed and used. Neural network (NN) based MPPT is one such method [12]-[15].

As we are extensively using nonlinear devices for controlling many loads, there are issues of harmonic distortion where current and voltage waveforms become non-sinusoidal. Harmonics are undesirable as they adversely affect all the loads connected to such distribution systems. Filters are used to remove these distortions and make the system with minimal and tolerable harmonics. Due to many drawbacks, passive filters are very rarely used. Most commonly, active filters are used.

For obtaining harmonic compensation, many researchers have used different control algorithms. In 1983, Akagi *et al.* [16] introduced an instantaneous reactive power, i.e., P-Q-based algorithm. Ullah *et al.* [17] have shown that the total harmonic distortion (THD) of 28% can be reduced to below 5% using a P-Q-based algorithm. Other researchers have shown similar results [18]-[21]. Amini *et al.* [22] have demonstrated that the source current's THD can be decreased from 20.2% to 4.2% for an R-L load. Rudi and Hashemnia [23] have shown that THD from 29.91% is reduced below 5%, and Manohara *et al.* [24] have used the synchronous reference frame (SRF) method and reduced THD from 26.23% to 5.97%. Gaiceanu *et al.* [25] have reduced the THD of the current from 27.7% to 3.47%.

Barbosa *et al.* [26] have used a P-Q-based controller for grid integration as well as an active power filter (APF) functionality, which also improves the power factor. Iov *et al.* [27] have suggested different control circuits for single-phase and three-phase integration, and the controller has been controlled using a synchronous reference frame control approach based on phase-locked loops (PLLs). Singh *et al.* [28] have used an inverter with a controller having both active power flow to the grid from renewable energy sources (RES) and active power control. They used a 4-leg inverter so that load neutral current does not flow to the source. Azmi *et al.* [29] have investigated the selective harmonic elimination technique for improving THD in grid-connected renewable energy source systems. Yang *et al.* [30] suggested control strategies for efficient power conversion, and one of the suggestions is a PLL-based SRF controller. Sudhakar *et al.* [31] have elaborated on connecting their PV system to the grid. they also suggested the use of PLL for grid synchronization. Sharew *et al.* [32] have done a detailed analysis and suggested that to keep THD below 5%, the maximum PV penetration to the grid could be 48%. Shafiullah *et al.* [33] have discussed many control strategies and highlighted challenges faced by integrating RES into the grid.

The literature review identified three key problems with the grid integration of solar PV systems: the need for an MPPT controller that can maximize electricity generated by the PV panels, harmonics in grid currents, and the challenges of grid integration. Several researchers have employed various MPPT methods to extract maximum power from PV panels. Detailed analysis and simulations have demonstrated that the neural network-based MPPT method is more efficient overall; hence, it is chosen for the system. Harmonics are undesirable and have a significantly adverse effect on all other loads connected to the grid; therefore, they must be minimized using a suitable APF. Additionally, Solar power generated must be properly connected to the grid to ensure proper power sharing between the PV system, other generating units connected to the grid, and the load.

The instantaneous reactive power-based active power filter was designed and developed. Its performance was verified for Butterworth, elliptic, and Chebyshev II filters, and the analysis shows that the Chebyshev II filter performs much better [34]. It has been demonstrated that the use of the Chebyshev II filter gives much better performance of APF. So far, no researcher has used the Chebyshev II filter as a low-pass filter in the APF. This method also provides simple control for grid integration.

A system with PV connected to the grid is designed and analyzed to enhance power quality while supplying PV power to the grid. A neural network-based MPPT system is designed and developed. Instantaneous reactive power theory-based active filtering with the Chebyshev II filter is used for filtering and is synchronized with the grid. Figure 1 depicts the suggested system.

In the method section, we have designed a grid-integrated PV system connected to a nonlinear load to evaluate an active power filter's performance. We have also designed an instantaneous reactive power-based active power filter. We have designed and developed a neural network-based MPPT system, which is simulated in Simulink. Section 3 discusses the findings.

2. METHOD

In this section, there are three subsections. Subsection 2.1. gives details of a system designed, including the APF design. Subsection 2.2. deals with PV system design along with boost controller (BC), subsection 2.3. deals with P-Q theory and grid integration.

2.1. System design

The system consists of a nonlinear load coupled to a three-phase supply via the grid depicted in Figure 1. The decision was made to employ a three-phase balanced system. Table 1 provides the load & three-phase source details.

2.1.1. Active power filter design

Active power filter parameters V_{DC} , C_{DC} & L_f are computed for the APF. Figure 2 displays a basic APF diagram with the parameters. The active power filter is designed using: DC bus voltage, as in (1).

$$V_{DC}=2\sqrt{2}\,\frac{V_{LL}}{\sqrt{3}m} \quad (1)$$

m is modulation index (=1), V_{LL} is AC line-to-line voltage.

$$C_{DC}=\frac{6\,V_{ph}\,I\,\alpha\,t}{[(V_{DC}^2)-(V_{DC1}^2)]} \quad (2)$$

V_{DC1} is the minimum voltage level of the DC bus; α is the overloading factor (1.2); t is time by which the level of DC bus voltage is to be recovered; and I is 5 A.

$$L_f=\frac{\sqrt{3}mV_{DC}}{12\,\alpha f_S I_{crpp}} \quad (3)$$

Where fs is 10 KHz, and Icrpp is 15 % of I = 0.75 A. Based on the above calculations, we get the parameters as shown in Table 2.

C_{DC} is the capacitor attached to the inverter's DC side, and for the APF to work, the voltage required is 190 Volts, so the boost converter is to be designed to produce 190 volts, and the APF will control the voltage to work as an active power filter.

Table 1. System specifications

Sr No	Parameters	Specifications	Sr No	Parameters	Specifications
1	V_{Source}	110 V, AC, 3-phase	3	Load 1	8 Ω, 9 mH
2	Frequency	50 Hz	4	Load 2	8 Ω, 9 mH

Table 2. APF parameters

Parameter	Specification
V_{DC}	190 V
C_{DC}	22 μF
Lf	3.3 mH

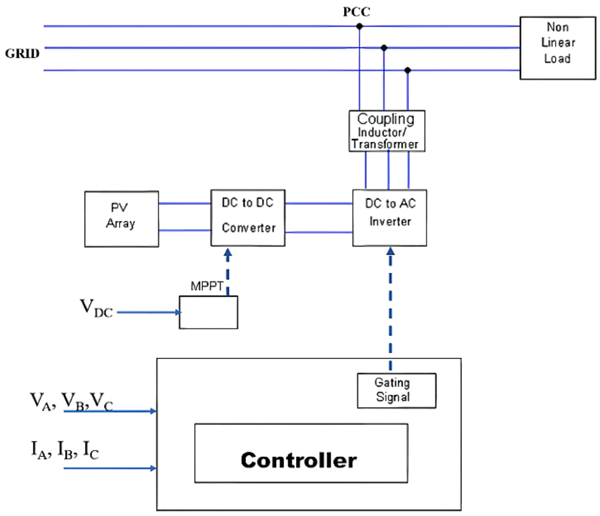

Figure 1. Proposed system

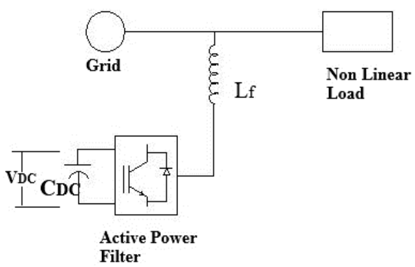

Figure 2. Active power filter

2.2. PV system with boost converter, MPPT, and its design

Figure 3 shows the boost converter attached to the PV array. Based on V_{DC}, the BC is designed, i.e., we require the boost converter output voltage to be 190 V. So, two series connections are made between the solar panels, with the combined panel characteristics given in Table 3. Based on the above, the input voltage is 60-75 V and the output voltage of 190 V, the boost converter is designed as given in Table 4.

2.2.1. Artificial neural network-based MPPT

Nowadays, controllers based on neural networks are designed and used for many applications. Figure 4 shows the basic artificial neural network (ANN) system. A basic neural network system has an I/P layer, a hidden layer, as well as an O/P layer. For the MPPT controller, based on ANN input data, could be temperature, irradiance, PV array current, or PV array voltage. Usually, a single duty cycle signal is generated, which is utilized to modify the BC duty cycle and guarantee that the PV array runs at MPP.

Table 3. PV array specifications

Parameter	Value
Wp	480 W
V_{OC}	74.2 V
I_{SC}	8.58 A
V_{MP}	59.4 V
I_{MP}	8.07 A

Table 4. Boost converter design parameters

Parameter	Formula used	Specifications	Parameter	Formula used	Specifications
V_0	Chosen	190 V	ΔV_0	3 %	5.7 V
I_0	$P\backslash V_0$	2.526 A	L	$V_{imax}D_{min}/\Delta I_0 f_s$	3.3 mH
ΔV_{in}	35-60 V	35-60 V	C_0	$I_0 D/\Delta V_0 f_s$	22 µF
ΔI_0	30 %	0.7569 A	C_{in}	$\Delta I_0 T_s/8\ \Delta V_{in}$	0.33 µF

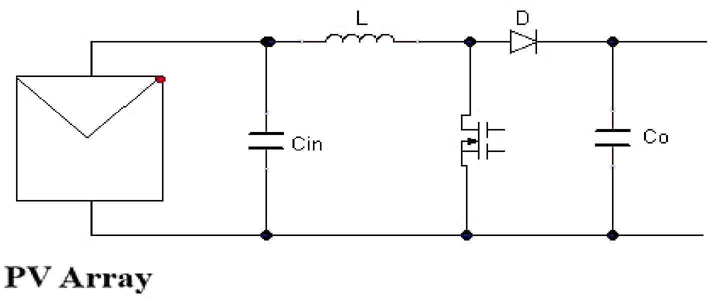

Figure 3. PV with boost converter

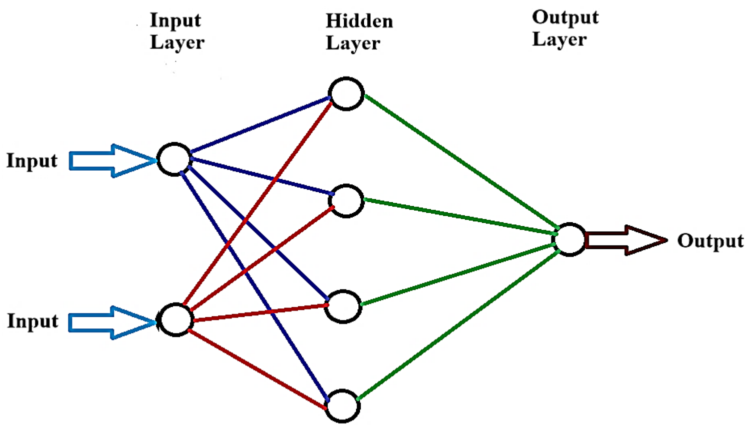

Figure 4. Basic ANN system

Random data is created using a MATLAB application to train the NN. Inputs are irradiance and temperature. Temperatures ranging from 16 to 40 degrees Celsius and irradiance from 0 to 1200 W/m^2 are considered. 2000 random data samples are generated. This data is utilized for testing, with the remaining 15 percent is being used for validation, and the balance 70% for training. To train the data, the Levenberg-Marquardt method is utilized. The voltage at MPP is the result of the NN ("Neural Network"). This NN model is utilized to regulate its BC duty cycle. By comparing the voltage that the PV array generates alongside the voltage of NN, the controller regulates the BC switch's duty cycle. The regression plot in Figure 5 clearly shows that the data is appropriately trained, and we get R = 1.

Neural network-based MPPT will control the gating pulse to the MOSFET of BC, which will maximize the PV array's power to deliver a 190 V output voltage, as this DC side's input, where the capacitor C_{DC} is connected, with respect to the inverter.

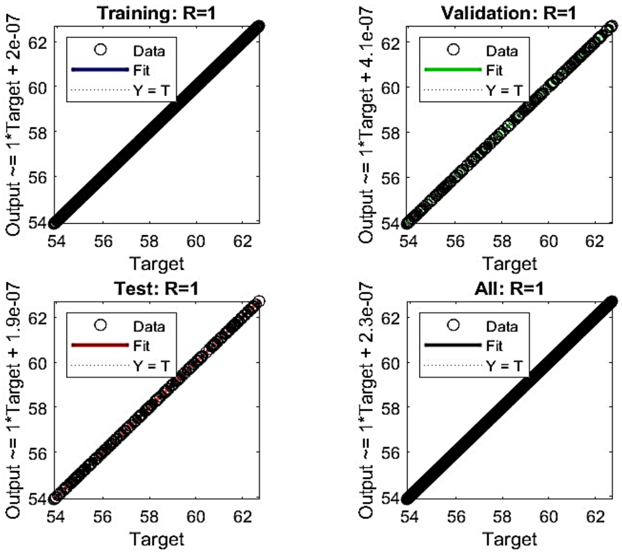

Figure 5. Data training and validation of the neural network system

2.3. APF & grid integration

2.3.1. P-Q theory-based APF

Figure 6 shows an instantaneous reactive power control-based APF controller. This method calculates instantaneous power, both active and reactive, utilizing three-phase currents as well as voltages detected at PCC. PCC senses three-phase voltages and converts them to two-phase orthogonal coordinates, $V\alpha$ & V_β, as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{5}$$

Utilizing a multiplication process, the P-Q theory showed instantaneous reactive as well as active power of voltages and currents in the α-β coordinates.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{6}$$

The (6) instantaneous power p & q, will be (7) and (8).

$$p = P + p\sim \tag{7}$$

$$q = Q + q\sim \tag{8}$$

Currents I_α and I_β could be attained by reversing (6).

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{9}$$

The fundamental component is subtracted to separate harmonic currents, and we can write it as (10).

$$\begin{bmatrix} I_{c\alpha}^* \\ I_{c\beta}^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} P^{\sim} - Ploss \\ -q \end{bmatrix} \tag{10}$$

Reference currents have been used in the equation below to convert α-β to abc coordinates.

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{c\alpha}^* \\ I_{c\beta}^* \end{bmatrix} \tag{11}$$

Based on Figure 6 and (4)-(11), the APF model is developed in Simulink, and the gating pulses generated by APF are given to the inverter switches. The Simulink model of APF and controller are depicted in Figures 7 and 8, respectively.

Figure 7 shows a system in which the APF controller detects grid voltages and currents at PCC, along the non-linear load, which is linked to the grid. The controller, using the P-Q method, generates the pulses and gives them to the inverter switches so that the harmonics of grid currents are reduced.

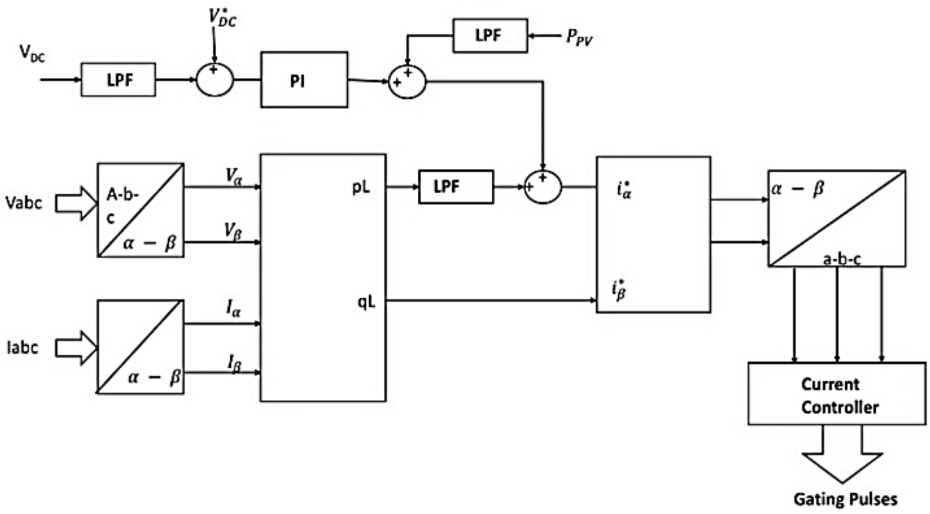

Figure 6. Instantaneous reactive power control

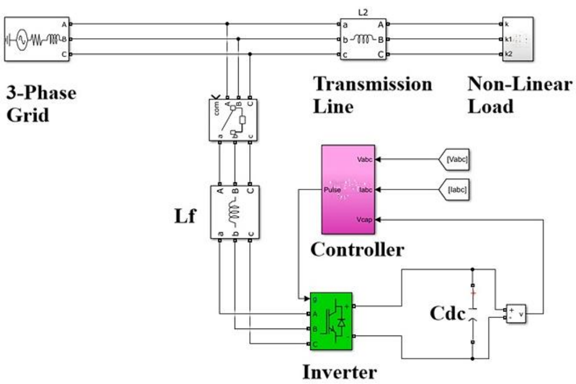

Figure 7. Active power filter model

Figure 8 displays the APF controller's Simulink model. It senses grid voltages and grid currents. It converts it into instantaneous real and reactive power as per (6), and from the real power, the fundamental frequency component is extracted by a Chebyshev II filter. The remaining signal is given to the PQ-to abc block, which, as per (10) and (11), produces a signal, and finally, pulses generated by the Hysteresis controller are given to the switches of the inverter.

2.3.2. Grid integration

Here, the PV is connected to the grid through the inverter via a boost converter; the DC side will have the capacitor Cdc between the boost converter and the inverter. The grid has the loads connected, including a nonlinear load. Table 1 describes the nonlinear load. Figure 9 depicts the grid integration Simulink model. The controller is similar to that shown in Figure 8, with additional blocks of P_{PV} and a low-pass filter with an adder, as shown in Figure 6.

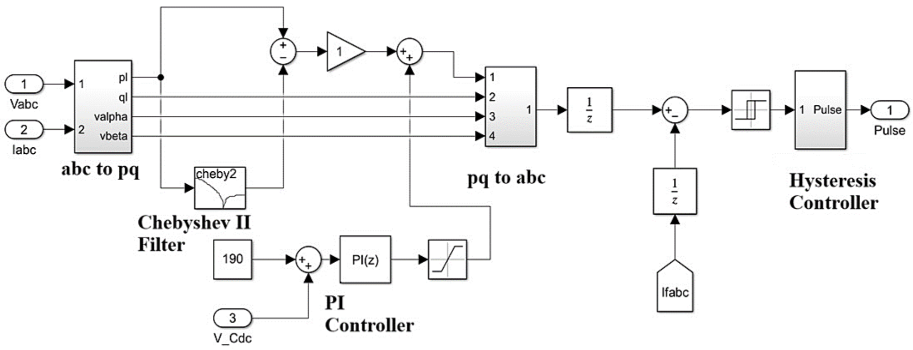

Figure 8. Active power filter controller

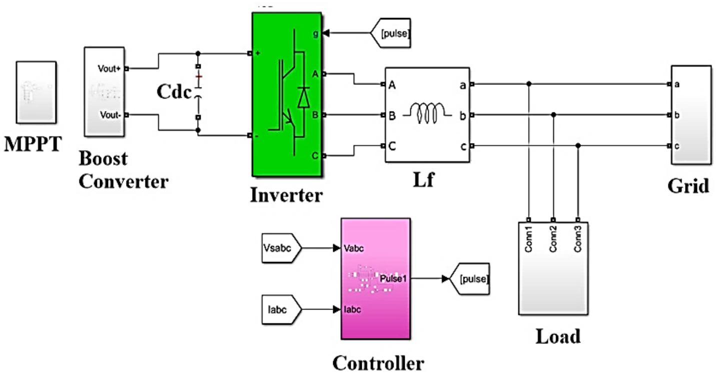

Figure 9. Simulink model for grid integration of PV

3. RESULTS AND DISCUSSION

3.1. MPPT

Neural network MPPT for a 480 Wp PV array with incremental conductance, Perturb & Observe, and neural network MPPT with boost controller were simulated for varied irradiance and fixed load, and the results are shown in Table 5. The simulations were done for 4 seconds.

Figure 10 shows how NN MPPT rapidly approaches and stays around the PV array's maximum power point, which enables it to draw more energy. The NN algorithm extracts more power from the PV array compared to P&O and IC methods, even though the operating point varies near MPP with all three methods, as it remains closer to MPP. The time needed for the NN-based controller to reach the operating point is the quickest. It takes just 0.2 milliseconds, as shown in Figure 10. NN MPPT controller requires measuring only PV array voltage, so it requires only one sensor, whereas both P&O and IC-based controllers require 2 sensors. Hence, the NN-based MPPT algorithm-based controller is better in performance compared to P&O and IC.

3.2. Instantaneous reactive power-based APF

The instantaneous reactive power-based APF was simulated in Simulink to check its performance for a non-linear load, with load I included into the circuit at t = 0.0 seconds, and the second load is added at t = 0.4 seconds to the first load. Figure 11 shows the source current (of one phase) for the duration of the simulations. The controller is connected to the circuit at t = 0.1 seconds, and from Figure 11, we can observe that the current has harmonics. The shape is non-sinusoidal, and from Figure 12, we observe that the THD of the source current is 24.42 %, and once the APF gets connected, the waveform becomes sinusoidal. The THD reduces to 2.05 % when load I is connected to the grid, as seen from Figure 13, and it reduces to 1.34% when both load I and load II are connected, as seen from Figure 14.

We can observe from Figures 12-14 that the THD of 24.42% due to non-linear load is considerably reduced to less than 2.5%, which is lower than the other methods that used a Butterworth filter as a low-pass filter in the APF. From Figure 15, we observe that the controller also improves the power factor of the source current as the current and voltage are in phase after time t = 0.1 seconds, where the controller is connected in the circuit. Figure 16 shows how the Chebyshev filter filters high-frequency signals and extracts only the fundamental frequency signal. This improves the THD of the source current. Also, simulations have shown that the performance is better than a synchronous reference frame-based controller. The comparison with other researchers is shown in Table 6. For simulations, a Non-linear but balanced load is considered, for an unbalanced load synchronous reference frame controller is supposed to give better performance as compared to the P-Q based APF.

Table 5. Power extracted by MPPT methods

MPPT algorithm	Perturb & observe	Incremental conductance	Neural network
Average power extracted from the PV array in watts (variable irradiance)	386.8	387.7	389.0

Table 6. Comparison of THD reduction by APF

Sr No.	Reduction of THD	Year of publishing	Reference
1	28% to 4.5%	2019	[17]
2	20.2% to 4.2%	2024	[22]
3	29.92% to below 5%	2025	[23]
4	26.23% to 5.97%	2025	[24]
5	27.7% to 3.47%	2025	[25]
6	24.42% to 2.05		Proposed scheme

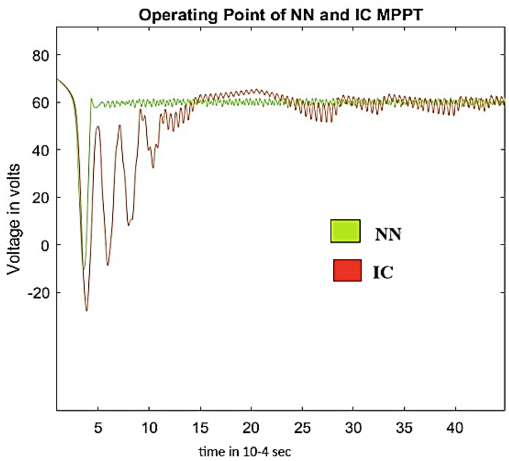

Figure 10. Operating point of NN and IC MPPT

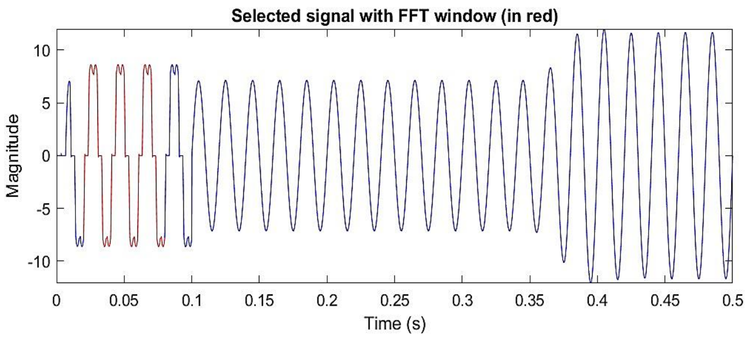

Figure 11. Source current

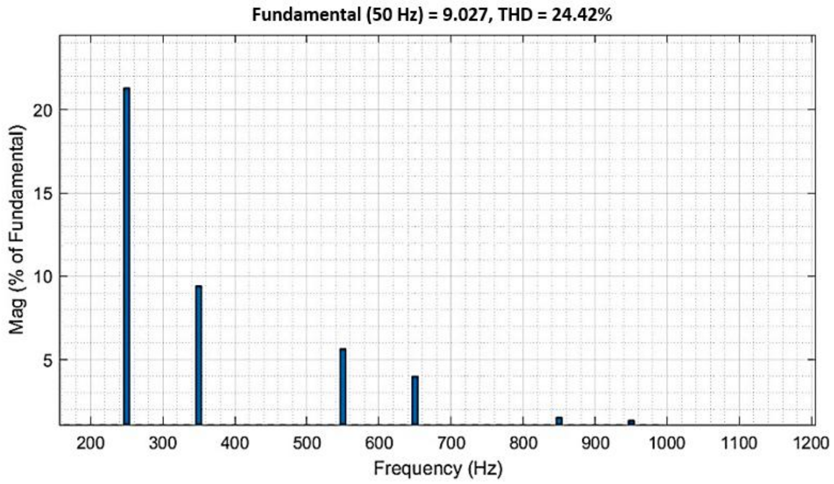

Figure 12. THD of source current when supplying a non-linear load & no APF

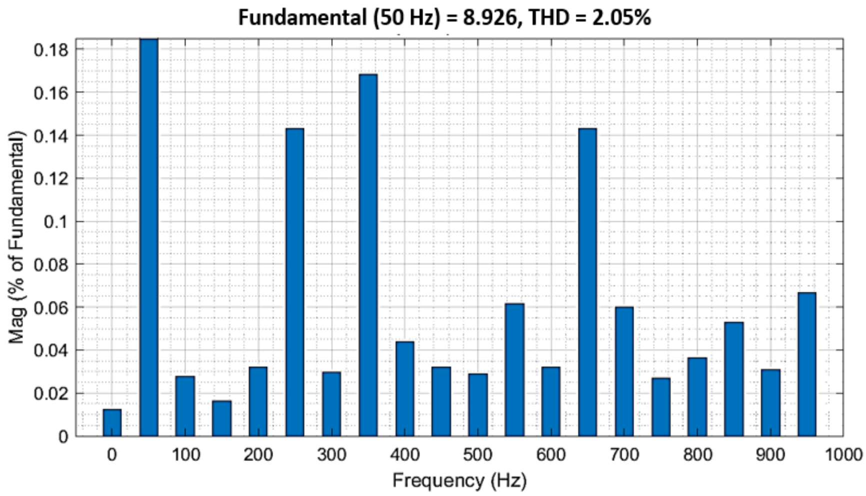

Figure 13. THD with APF and non-linear load

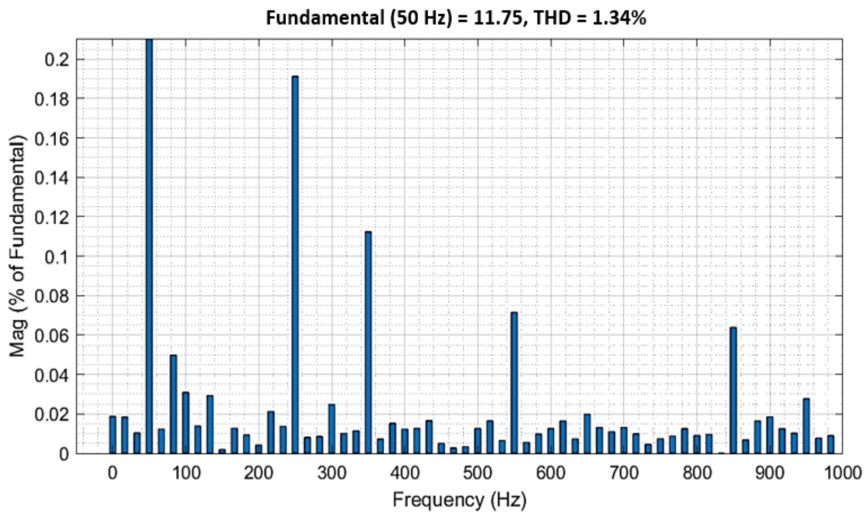

Figure 14. THD with APF and load I plus load II

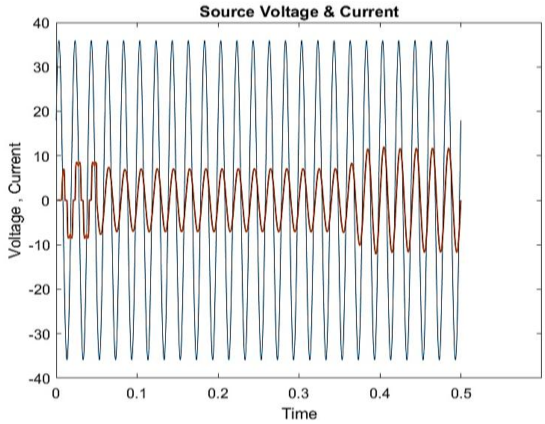

Figure 15. Source voltage and source current

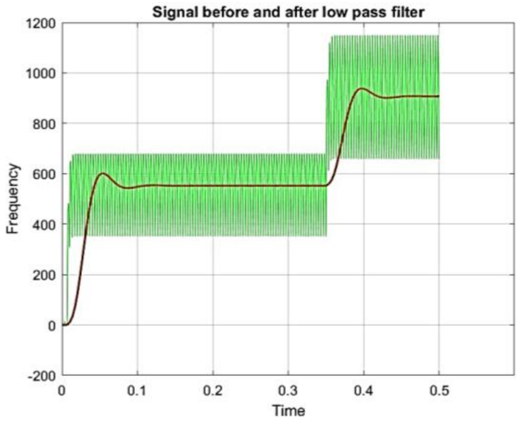

Figure 16. Signal before and after the Chebyshev II filter

3.3. Grid integration

Here it was simulated for 3 conditions: i) PV power is more than the load power; ii) load power is higher than PV power; iii) variation of load when the grid and PV are supplying the power. We observe that PV supplies power to the grid when there is no load. When a load is put in the circuit, the PV and the grid share the load, and when the load increases, the increased load is shared by the grid. Hence, we can say that power flows between the grid and PV as per the requirements, as seen from Figure 17. At the same time, the source current's THD is kept below 5%. As seen from Figure 18, it is 3.15 %. The above simulation results clearly show that the Chebyshev II filter can further enhance power quality.

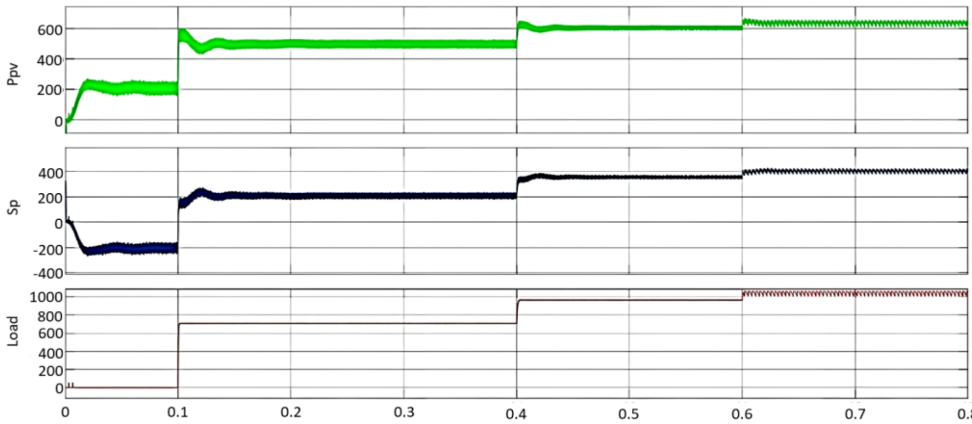

Figure 17. Power transfer between PV, grid, and the load

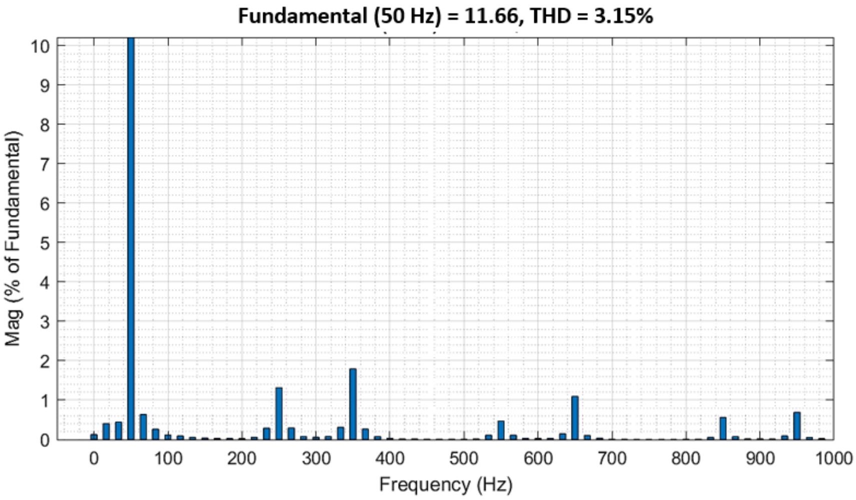

Figure 18. THD of the source current when PV is connected to the grid

4. CONCLUSION

The examination of the suggested system demonstrates that employing neural network-based MPPT may extract more power from the PV array, increasing the overall conversion efficiency. Investigations also show that when using the Chebyshev II filter as the active power filter's low-pass filter, the source currents' current harmonics are successfully decreased, and the sinusoidal waveform of the source current is restored. Also, the harmonics are substantially reduced from THD of 24.42% to THD below 2.5%. Therefore, APF's performance is superior to that of the active filters that were previously created. With respect to the Grid Integration, The THD is also below 4%, and the controller works perfectly. Power is shared among the load, the grid, or the PV array, depending on demand fluctuations.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Praveen Kamat	✓	✓	✓	✓	✓	✓			✓	✓	✓			
Anant Naik	✓		✓	✓			✓			✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability was irrelevant with this research because this investigation didn't generate or analyze any new data.

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