J. Inst. Eng. India Ser. B (April 2022) 103(2):461–468
https://doi.org/10.1007/s40031-021-00661-y

ORIGINAL CONTRIBUTION

# Harmonic Mitigation in Grid-Connected Distributed Energy Systems using PI and Fuzzy Logic Controller

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Received: 16 March 2021 / Accepted: 28 July 2021 / Published online: 30 August 2021


**Abstract** In recent years, the distributed generation systems have been established swiftly with the benefits of zero pollution. But, the harmonics increase due to various loads connected to the distribution system and cause disturbances in the power lines. To overcome such issues, this paper proposes a grid interfacing control using Fuzzy logic-based PI controller. The main intention of the proposed approach is to mitigate the harmonics in an electric grid using fuzzy logic-based PI controller. In addition to this, the control for interfacing inverter is done utilizing the hysteresis current controller. The simulation results are performed to show the performance of the compensating device to reduce the harmonics. In order to evaluate and determine the total harmonic distortion, the fast Fourier transform has been carried out for certain waveforms. Therefore, from the analysis, it is proven that the power quality is enhanced by fuzzy logic-based PI controller when compared with the ordinary PI controller.

**Keywords** Fuzzy logic · PI controller · Power quality · Shunt active power filter

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## Introduction

The environmental problems are increasing prominently all over the world due to the depletion of fossil fuels and fossil energy [1]. The rise in the fossil fuel cost and the climatic changes affects the efficiency of the system. Distributed Generation is dependent on sustainable power sources that play a significant role in fulfilling the present rising need for energy [2]. Generally, the distributed energy generation generally includes the integration of both wind and sun-based energy. In Centralized power generation frameworks, fuel consumption has prompted Carbon di-oxide ($CO_2$) emissions [3]. On the other hand, the introduction of electric vehicles significantly minimizes the usage of fossil fuel energy. The increased penetration of both distributed generation and electric vehicles creates major consequences during network operation [4].

The electric vehicle charging behavior at a large scale sharply enhances the peak load. In addition to this, the DGS can efficiently mitigate the power supply pressure caused due to certain reasons, namely intermittence; power transferred back as well as high power generation. The power transferred back results in an increase in transmission power loss and over-voltage. In order to maximize the distributed generation, it is necessary to minimize the investment revenue and availability of DGS. Generally, the distributed generation utilizes either grid or stands alone that are connected to a modular small electrical device that is situated near the consumption point [5–14].

Also, the ESS is categorized into two based on installation: distributed energy storage system (DESS) as well as centralized energy storage system (CESS). The DESS is installed on the consumer side; in addition to this, the network losses (the processor associated with the *distributed system* fails to perform the execution) that occur during power transmission are minimized significantly in DESS [15]. In this paper, the control for interfacing inverter is done utilizing the hysteresis current controller. Also, the signal quality is determined by the total harmonic distortion that involves designing and obtaining less percentage of total harmonic distortion.

The major contribution of the paper is obtained as follows.

- Mitigating the harmonics in an electric grid using fuzzy logic-based PI controller.
- Utilizing the hysteresis current controller for the control of interfacing inverter, thereby minimizing the power quality issues.
- Determining the signal quality using the total harmonic distortion, thus evaluate the efficiency of the distributed generation system.

## Related Literature Works-A Review

Abbas et al. [16] proposed optimal harmonic mitigation in the distributed generation system containing inverter-based distributed generators using a water cycle algorithm. The main intention of this approach was to minimize the power loss and total harmonic distortion. The performance measures employed in this approach were magnitude, harmonic order as well as phase angle. In addition to this, the voltage profile was very high, but due to over-voltage and over-current the efficiency was decreased significantly.

The harmonic mitigation and power injection technique, using an artificial neural network for solar-fed distributed generation system, was developed by Raj Kumar et al. [17]. The significant role of this approach was adding the active power filter for mitigating the harmonics. Time, total harmonic distortion and magnitude were the simulation metrics employed for evaluation. The efficiency was high with low real power generation.

Rohouma et al. [18] demonstrated D-STATCOM for harmonic mitigation in a low-voltage distribution network containing high penetration of nonlinear loads. The main intention of this approach was to ensure the quality of power. The performance measures, namely power, time, current, magnitude, and voltage, are evaluated to determine the effectiveness. The experimental evaluations were carried out, and the analysis revealed that the loss was minimum when compared with various other approaches. However, this approach failed to determine the voltage regulation.

An artificial neural network based on an active power filter containing immunity in distributed generation system was established by Kadem et al. [19]. This approach was employed to enhance the penetration power of distributed generation. Voltage, current, frequency, total harmonic distortions were the metrics employed for evaluation. The experimental analysis has proven that the performances were very high when compared with the existing techniques. But the time required for the operation was high.

Kolli et al. [20] developed a novel phase let-based approach for islanding detection in inverter-based distributed generation systems. This approach was intended to minimize the power quality issues. Frequency, gain, magnitude, trip signal, and time were the measures employed in this approach. This approach was more reliable with high accuracy rate. However, the implementation complexity was high when compared with other approaches.

## System Design

Figure 1 illustrates the system architecture comprising a renewable energy source (RES) linked and connected to the four-leg inverter via dc link. In distributed generation system, the voltage source inverter (VSI) plays a vital role since the RES are interfaced into the grid for effective power generation. The following section deliberates the mathematical expression based on two significant operation modes, namely the power control operation and dc-link voltage as well as grid interfacing inverter control [21].

### Process 1: Power Control and dc-link Voltage

In general, the power generated is inconsistent because the renewable energy obtained is alternating and discontinuous in nature. Here, the dc-link is capable of transferring the variable and inconsistent power from RES to the power grid. Therefore, the electric current provided at a particular voltage in the dc-link is represented in Eq. (1).

$$i_{\mathrm{dc}}^{1} = \frac{\mathrm{P}_{R}}{v_{\mathrm{dc}}} \tag{1}$$

From the above equation, the current injected and the voltage level is represented by $i_{\mathrm{dc}}^{1}$ and $v_{\mathrm{dc}}$, respectively. The generation of power from renewable energy sources is denoted by $\mathrm{P}_{R}$, respectively. Similarly, the flow of current on the adjacent side of the dc-link is formulated as,

$$i_{\mathrm{dc}}^{2} = \frac{\mathrm{P_I}}{v_{\mathrm{dc}}} = \frac{\mathrm{P_A} + \mathrm{P_L}}{v_{\mathrm{dc}}} \tag{2}$$

From Eq. (2),$\mathrm{P_I}$,$\mathrm{P_A}$, $\mathrm{P_L}$signifies the inverter power, active power, and inverter losses. When the inverter loss is negligible, then

$$\mathrm{P}_{R} = \mathrm{P}_{A} \tag{3}$$

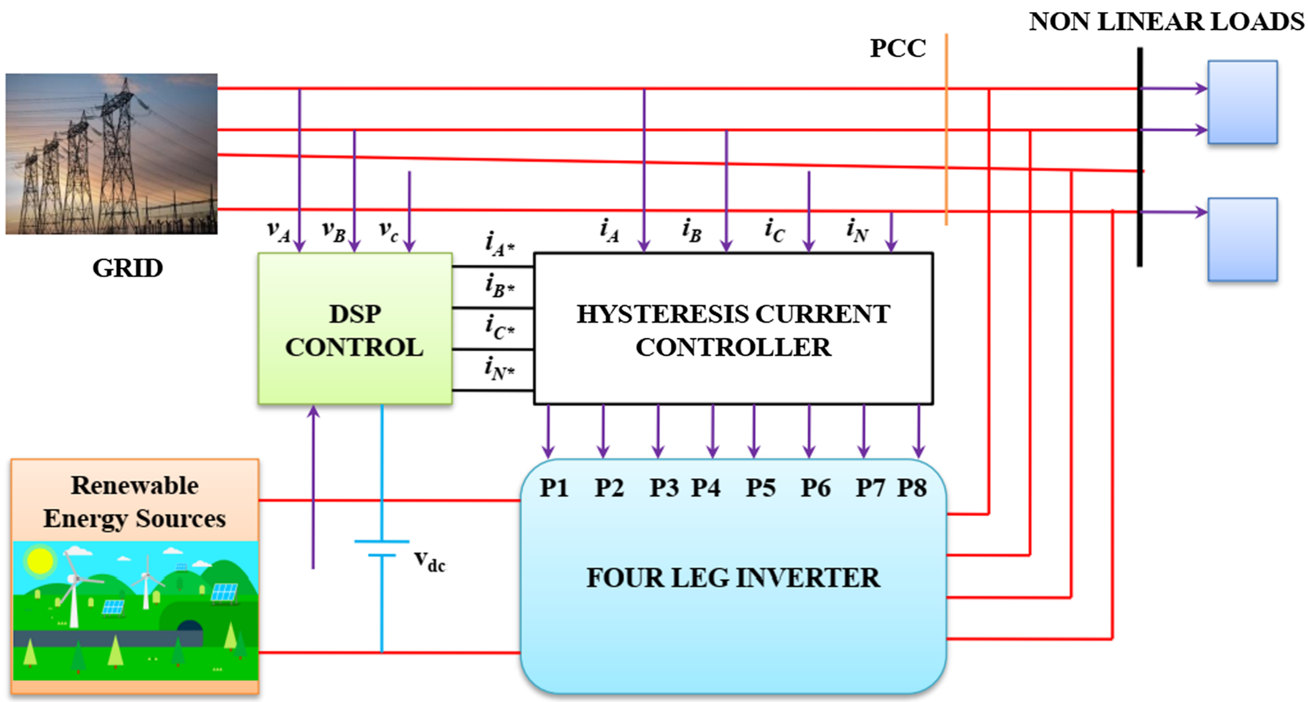



**Fig. 1** RES based DG system

### Process 2: Grid Interfacing Inverter Control Using Hysteresis Current Controller

The loads containing the neutral current are compensated by employing the four-leg inverter [22]. During power generation, the power control center is regulated based on three various cases that are represented as follows.

$$\begin{aligned} &\text{Case 1}: \ P_R = 0 \\ &\text{Case 2}: \ P_R < P_{TL} \\ &\text{Case 3}: \ P_R > P_{TL} \end{aligned} \tag{4}$$

From Eq. (4), $P_{TL}$ signifies the total load power. In addition to this, the load and inverter injected power are appeared as a balanced load to the electric grid due to the variations in the duty cycle [23].

## Proposed Methodology

Figure 2 provides the proposed circuit diagram for the grid interfacing inverter control using fuzzy logic-based PI controller. The proposed architecture comprises of fuzzy PI controller, phase-locked loop, unit vector template, reference grid current, and references neutral current. The following section describes the detailed description and the mathematical expressions based on fuzzy PI controller. The main intention of the proposed approach is to mitigate the harmonics in an electric grid using fuzzy logic-based PI controller.

### Fuzzy Logic-based PI Controller

The fuzzy logic controller is capable of controlling the dc voltage more effectively. Here two various signals, namely the error signal and change in error signal, are provided as an input to the fuzzy logic controller. The fuzzy logic controller is utilized widely because of its low cost, highly robust, reliable and more effective.

The mathematical expression based on the input signals (error signal and the change in error signal) with respect to the *Jth* sampling period is defined in the following equations [8].

$$\alpha(J) = \frac{P(J) - P(J-1)}{v_{dc}(J) - v_{dc}(J-1)} \tag{7}$$

$$\beta(J) = \alpha(J) - \alpha(J-1) \tag{8}$$

From Eq. (7) and (8), $\alpha(J)$ and $\beta(J)$ error signal and the change in error signal with respect to *Jth* sampling period, respectively. Then the instantaneous power and the dc-link voltage are represented by $P(J)$ and $v_{dc}(J)$. Table 1 represents the corresponding fuzzy rules for the power controller. The top row and the left column of the matrix signify the fuzzy set variables. The membership functions of the output variables are represented in the body of matrix. There must be 49 possible fuzzy rules in the matrix.

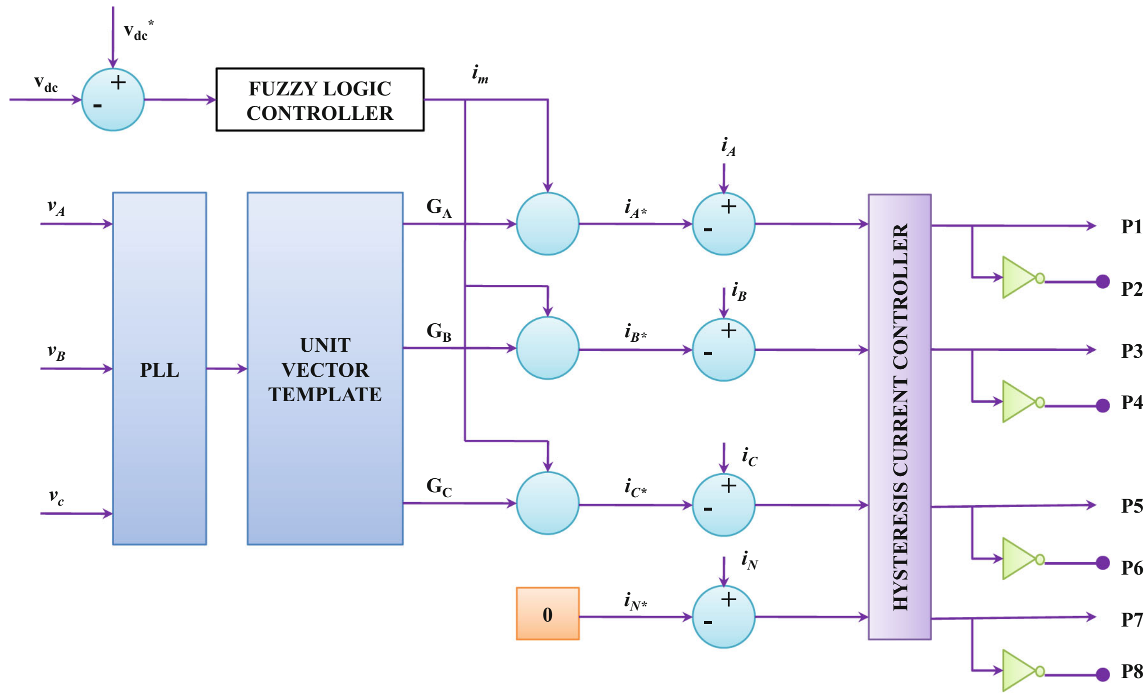



**Fig. 2** Circuit representation of grid interfacing control using Fuzzy PI controller

**Table 1** Fuzzy rule generation

| β\ α | NL | NM | NS | Z | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | NL | NL | NL | NL | NM | NS | Z |
| NM | NL | NL | NL | NM | NS | Z | PS |
| NS | NL | NL | NM | NS | Z | PS | PM |
| Z | NL | NM | NS | Z | PS | PM | PL |
| PS | NM | NS | Z | PS | PM | PL | PL |
| PM | NS | Z | PS | PM | PL | PL | PL |
| PL | NL | NM | NM | Z | PS | PM | PL |

**Table 2** Parameter specification

| Parameters | Ranges |
|---|---|
| Dc bus capacitor | 10 mF |
| Grid frequency | 50 Hz |
| Grid voltage | 110 V |
| Switching frequency | 10 kHz |
| DC bus PI controller | 0.25, 10 |
| Current PI controller | 120, 0.25 |
| Hysteresis band | 0.25 |

Here, NL, NM, NS, Z, PS, PM, and PL signifies negative low, negative medium, negative small, zero, positive small, positive medium as well as positive low, respectively. Thus, by employing fuzzy logic-based PI controller, the harmonics are mitigated in an effective manner. The steps involved in the design of fuzzy logic controller are discussed as follows [24].

### Step 1: Model Characteristic Determination

Determining the model characteristic is considered the most significant process in which the fuzzy logic controller fits into the system that assists the designer in determining the ranges of both inputs and outputs.

### Step 2: Fuzzification Interface

During fuzzification processes, the fuzzifier interprets the crisp value as the fuzzy set for achieving both the high value and low value (i.e., 0 and 1) representing the membership function.

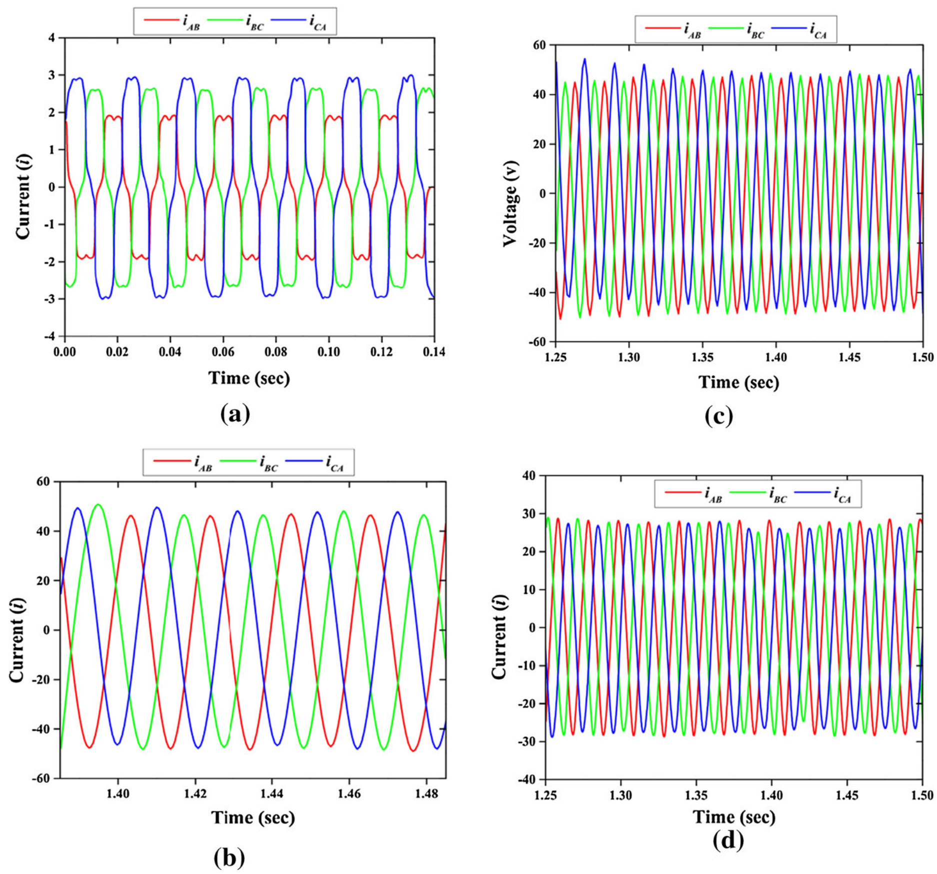



**Fig. 3** **a** Grid current before connecting shunt active power filter **b** Grid current after connecting shunt active power filter **c** Output voltage of grid interfacing inverter **d** Output current of grid interfacing inverter

### Step 3: Decision-Making Logic

The decision-making logic engages in writing the fuzzy rules (i.e., if-then rules); where "if" signifies the condition and "then" signifies the execution.

- If $\alpha > 0$then $\gamma$ increases gradually
- If $\alpha < 0$ then $\gamma$ decreases gradually
- If $\alpha = 0$ *and* $\beta = 0$then $\gamma$ remains unchanged

The output of the membership function is represented by $\gamma$, respectively.

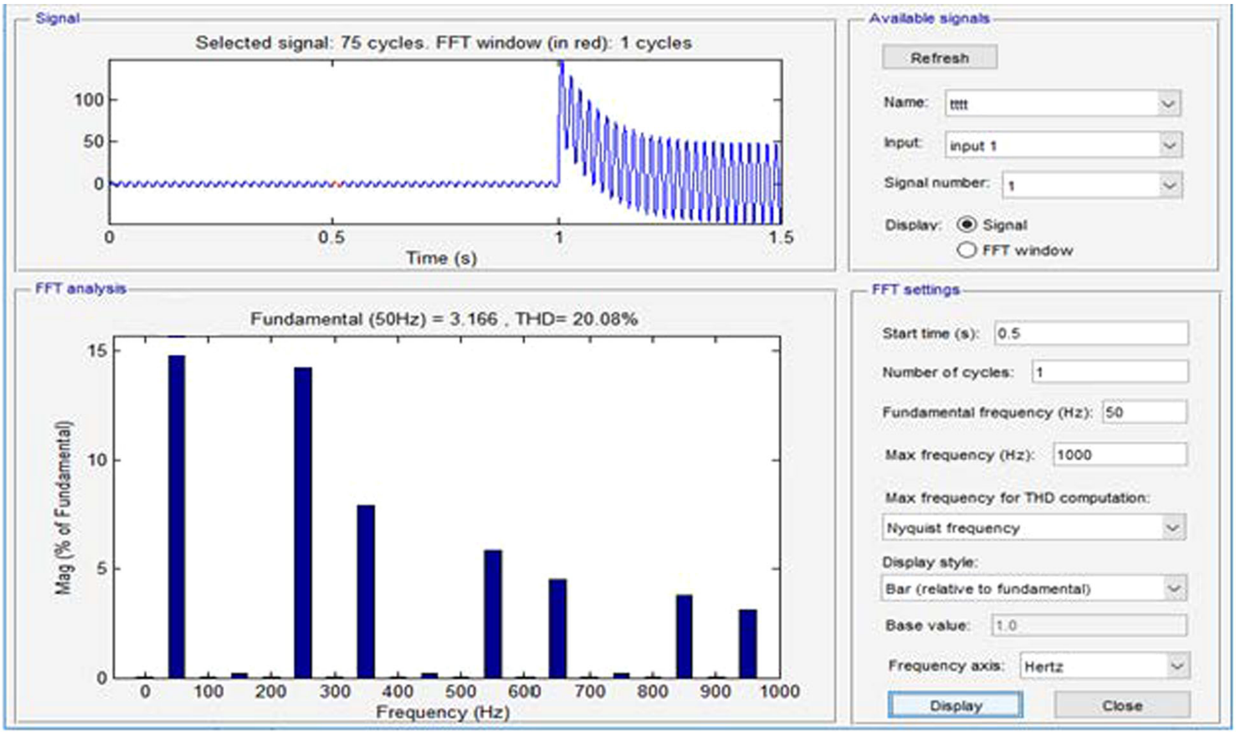
### Step 4: Defuzzification Interface

Defuzzification is the final process involved in the fuzzy logic controller. The defuzzification process is performed using diverse techniques, namely mean of maximum technique (MOM), center of area technique (COA) [25]. But COA technique is employed widely due to the generation of distribution of central area. Here, a triangular membership function is employed containing the normalized domain value of about (− 0.75 to 0.75).

## Results and Discussion

The proposed approach has been implemented under MATLAB or Simulink platform. Here, the fuzzy logic-based PI controller is employed for the grid-connected photovoltaic system. The parameter settings employed for the simulation are discussed in Table 2. Various parameters like DC bus capacitor, Grid frequency, Grid voltage, switching frequency, DC bus PI controller, Current PI controller, and Hysteresis band and their respective values are discussed. The parameters and their respective values are selected in such a way to obtain optimal values and to minimize harmonic mitigation.

The performances of the fuzzy logic-based PI controller are evaluated using the simulation under diverse operating conditions based on the PV module. This section contains the simulation results carried out to show the performance of the compensating device to reduce the harmonics. The non-sinusoidal nature of the grid current because of the nonlinear load connected at the load side is shown in Fig. 3a. The output of grid current after the inverter being connected is represented in the following figure. Here the neutral current is minimized to zero and the current is made


Signal
Selected signal: 75 cycles. FFT window (in red): 1 cycles
Time (s)
FFT analysis
Fundamental (50Hz) = 3.166 , THD= 20.08%
Mag (% of Fundamental)
Frequency (Hz)
Available signals
Refresh
Name:
Input:
input 1
Signal number:
Display:
Signal
FFT window
FFT settings
Start time (s):
0.5
Number of cycles:
Fundamental frequency (Hz):
Max frequency (Hz):
Max frequency for THD computation:
Nyquist frequency
Display style:
Bar (relative to fundamental)
Base value:
Frequency axis:
Hertz
Display
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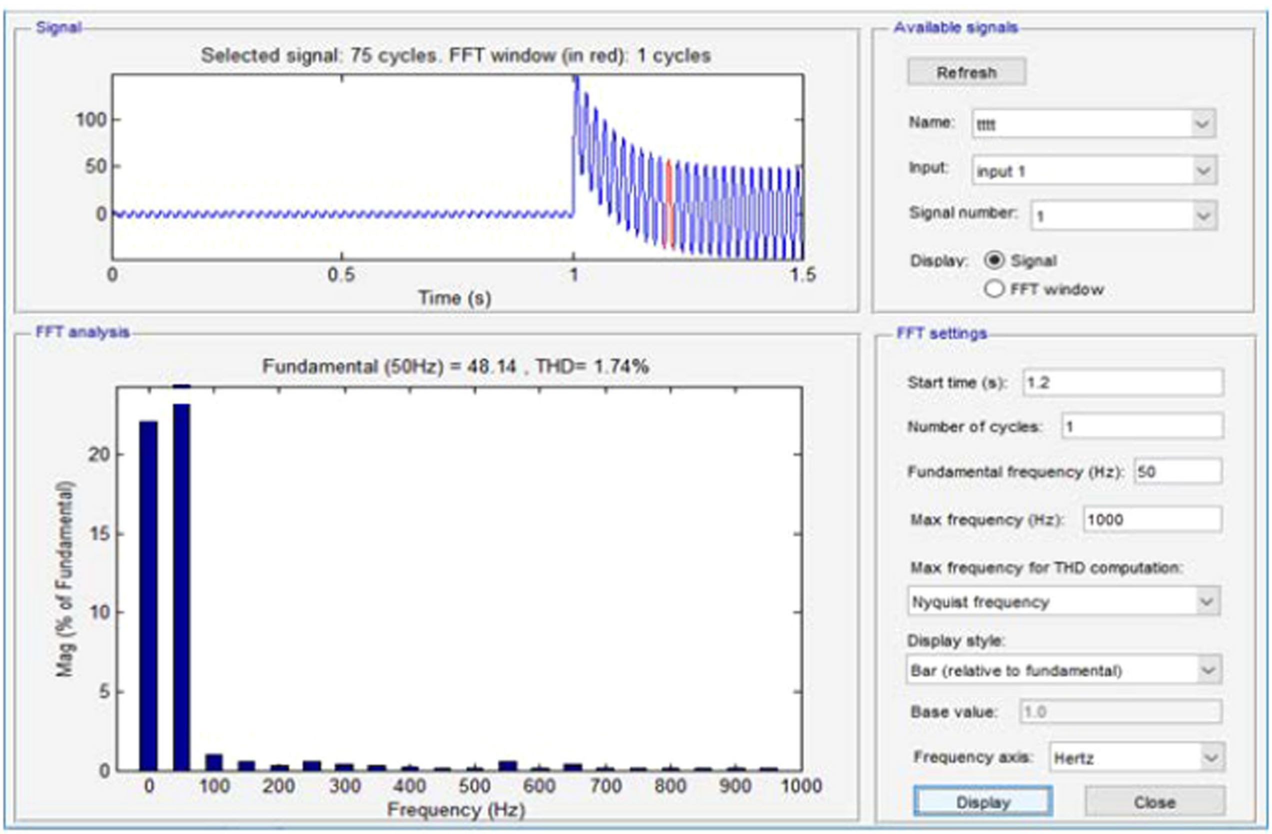
**(a)**


Signal
Selected signal: 75 cycles. FFT window (in red): 1 cycles
Time (s)
FFT analysis
Fundamental (50Hz) = 48.14 , THD= 1.74%
Mag (% of Fundamental)
Frequency (Hz)
Available signals
Refresh
Name:
Input:
input 1
Signal number:
Display:
Signal
FFT window
FFT settings
Start time (s):
1.2
Number of cycles:
Fundamental frequency (Hz):
Max frequency (Hz):
Max frequency for THD computation:
Nyquist frequency
Display style:
Bar (relative to fundamental)
Base value:
Frequency axis:
Hertz
Display
Close

**(b)**

◀**Fig. 4** FFT Analysis **a** without compensating device **b** control of dc-link voltage using PI controller **c** Control of dc-link voltage using fuzzy logic controller

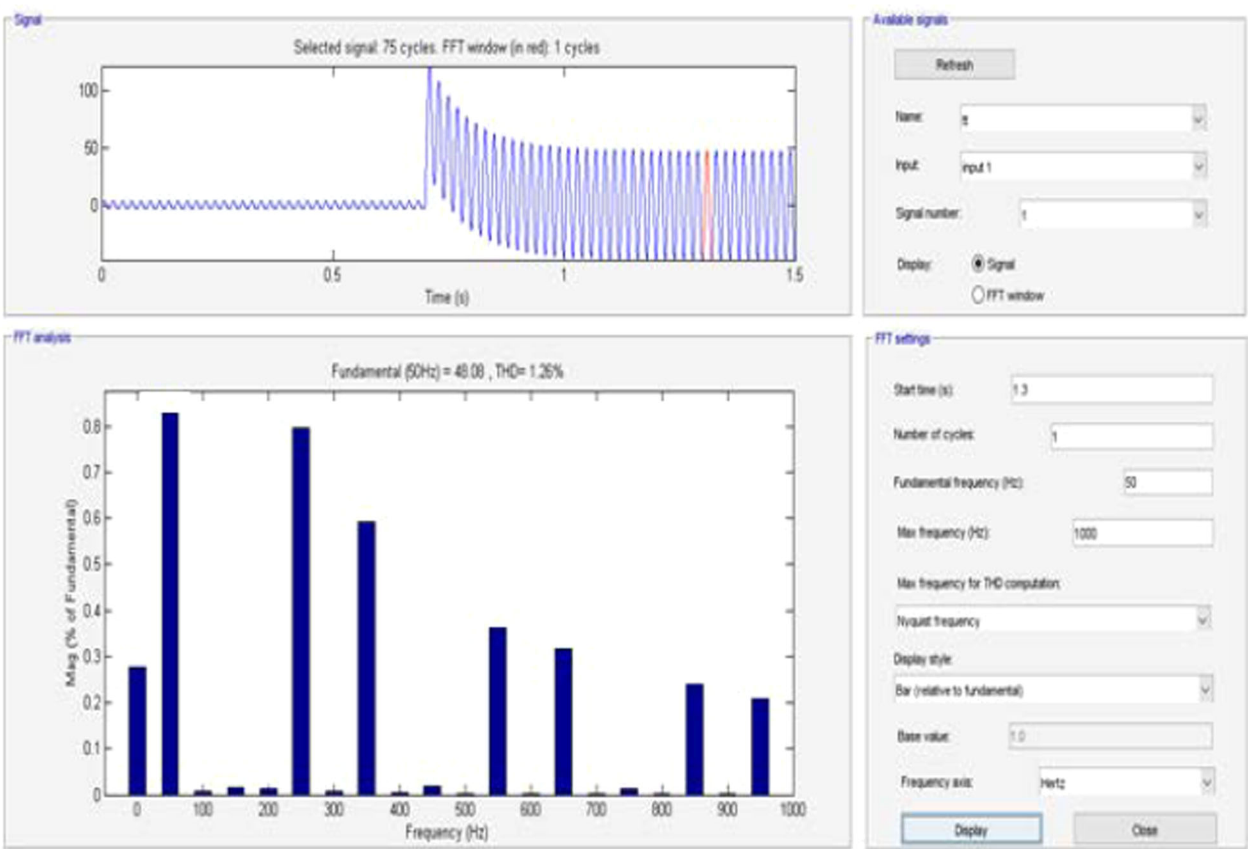
sinusoidal. The non-sinusoidal nature of the current has been eliminated by connecting the shunt active power filter to the grid. Therefore, the output grid current waveform with respect to time is mentioned in Fig. 3b.

Figure 3c represents the output voltage of a grid interfacing inverter. The graph is plotted for the output voltage with respect to time, where the *x*-axis and *y*-axis signify the time and voltage, respectively. Similarly, Fig. 3d describes the output current of a grid interfacing inverter. Here, the graph is plotted for output current versus time. When the inverter starts injecting current to the grid, the nonlinear load appears as a balanced linear load. In order to evaluate and determine the total harmonic distortion, the fast Fourier transform have been carried out for the waveforms mentioned in Fig. 3a–d.

Figure 4a–c signifies the total harmonic distortion for three different cases, namely (a) Fast Fourier transform without compensating device (b) FFT Analysis (control of dc-link Voltage using PI Controller) and (c) FFT Analysis (Control of dc-link voltage using Fuzzy Logic Controller).

## Conclusion

This paper proposed a Harmonic Mitigation in Grid-Connected Distributed Energy Systems Using PI and Fuzzy Logic Controller. Here, the proposed approach is employed to mitigate the harmonics in an electric grid using fuzzy logic-based PI controller. In distributed generation system, the voltage source inverter (VSI) plays a vital role since the RES are interfaced into the grid for effective power generation. In addition to this, Hysteresis current controller (HCC) is employed to control the voltage source inverter for remunerating the current harmonics. Finally, the performances of the fuzzy logic-based PI controller are evaluated using the simulation under diverse operating




**(c)**

**Fig. 4** continued

conditions based on the PV module. From the analysis, it is noted that the total harmonic distortion has been brought from 20.08% down to 1.74% by utilizing PI controller. Also, the fast Fourier transform analysis shows that the total harmonic distortion with respect to Fuzzy Logic Controller is 1.26%. In the future, a novel approach must be designed for mitigating the fluctuations of voltage and frequency in an electric grid system.

**Funding** None.

**Compliance with Ethical Statement**

**Conflict of interest** The authors declares they have no conflict of interest.

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