Implementation of fuzzy in DQ control of PV based inverter with plug-in electric vehicles

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ABSTRACT

In modern power systems, photovoltaic (PV) generation plays a vital role in sustainable energy supply. PV systems generate DC power, which is converted to AC using built-in converters for grid integration. The quality of power injected into the grid is crucial, especially in the presence of plug-in electric vehicles (PEVs) and non-linear loads, which introduce harmonics and dynamic disturbances. To enhance power quality, advanced control strategies are employed. This paper presents a comparative study of direct-quadrature (DQ) control techniques using traditional proportional-integral (PI) controllers and fuzzy logic controllers (FLCs) in a grid-connected PV system. The DQ control method simplifies the regulation of active and reactive power by transforming three-phase signals into a rotating reference frame. While PI controllers are widely used, they often struggle with non-linearities and load variations. FLCs, on the other hand, offer adaptive control without requiring precise mathematical models, making them more effective under dynamic conditions. The system under study includes PV generation, PEVs, and non-linear loads. Performance metrics such as total harmonic distortion (THD), voltage stability, and power factor are analyzed. Results show that fuzzy controllers significantly improve power quality and system response.

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1. INTRODUCTION

Power quality issues in power system include power factor reduction, insulation failure, line losses, and communication interference problems. Apart from that the device failures like capacitor and insulator failures are evident. Power quality issues are dealt using the custom power devices (CPDs) by introducing control techniques [1], [2]. Introduction of non-linear loads in the power system deteriorates the power quality by disturbing the voltage and the current waveforms. Renewable energy also introduces the power quality issues in the power system due to the power electronics devices and also the intermittent power from the renewable sources [2]. Both shunt and series CPDs can help in compensating the disturbances that get introduced in the power system. Unbalanced current, power factor correction and voltage disturbance are compensated using the distributed FACTS devices like DSTATCOM [3], [4]. Electrical engineers are concerned with designing and modelling an effective control algorithm that takes into consideration the aforementioned issues and topological developments in DSTATCOM [5]-[8]. Numerous control methods have been developed to enhance the effectiveness of the DSTATCOM in balanced, sinusoidal, unbalanced, or distorted AC voltage circumstances [7], [9]-[12] and adaptive control techniques [13]-[19]. Other power control strategies are discussed in [20]-[27].

The performance of the i-cos approach is evaluated under a variety of loading conditions, including non-linear and EV loads. For any power controllers in the power system the voltage and frequency control is primary. Frequency control is made possible using the phase-locked loop (PLL), while voltage control is developed using the voltage regulation controller. Usually, proportional-integral (PI) controllers are used in the voltage and the current control loop used in the controllers. The voltage at the point of common coupling (PCC) is controlled by the proportional-integral (PI) controller. Simultaneously, the voltage across the DC bus capacitor is managed by establishing the reference for the direct axis component within the voltage regulation controller. The results will be analyzed following the substitution of the PI controller with a fuzzy controller.

2. METHOD

The block diagram for the direct-quadrature (DQ) controlled solar integrated electric vehicle in the grid is as given in Figure 1. Photovoltaic (PV) power is integrated to the grid through the grid side inverter. The PV system is integrated with a boost converter, which is controlled through a feed forward loop for maximum power point tracking (MPPT), as illustrated in the diagram. The MPPT control regulates the PV voltage at the maximum power point. The pulses are subsequently outputted. The boost converter subsequently modifies the voltage to align with the required DC link specifications. Subsequently, the DC connection transmits the signal to a DC to AC converter. The grid is subsequently connected to the AC voltage. This system incorporates both linear and non-linear load combinations. The inverter is required to manage power quality challenges arising from the combination of linear and non-linear loads.

The d-q-technique is used in the inveter to perform the active power filter operation. The d-q technique is derived from synchronous machines. The d-q is direct and quadrature axis. The d and q components are perpendicular to each other. The set voltage is compared against the measured voltage. This voltage represents the voltage error. The waceform is processed by the PI controller. The corresponding current is produced in this context. This facilitates the regulation of the DC link within the inverter system. The direct axis current is determined using the formula presented in (1).

$$\left.\begin{aligned} Current^*_{sad} &= Current^*_{spd}.Voltage_{sbd};\\ Current^*_{sbd} &= Current^*_{spd}.Voltage_{sbd}\\ Current^*_{scd} &= Current^*_{spd}.Voltage_{scd} \end{aligned}\right\} \quad (1)$$

Where,

$$\left.\begin{aligned} Voltage_{sad} &= \frac{Voltage_{sa}}{Voltage_{sp}}\\ Voltage_{sbd} &= \frac{Voltage_{sb}}{Voltage_{sp}}\\ Voltage_{scd} &= \frac{Voltage_{sc}}{Voltage_{sp}} \end{aligned}\right\} \quad (2)$$

where $Voltage_{sa}$, $Voltage_{sb}$, and $Voltage_{sc}$ are the instantaneous voltage, and the magnitude is $Voltage_{sp}$.

$$Voltage_{sp} = \left\{\frac{2}{3}\left(Voltage^2_{sa} + Voltage^2_{sb} + Voltage^2_{sc}\right)\right\}^{\frac{1}{2}} \quad (3)$$

For quadrature current reference is calculated as in (4).

$$\left.\begin{aligned} Current^*_{saq} &= Current^*_{spq}.Voltage_{sbq};\\ Current^*_{sbq} &= Current^*_{spq}.Voltage_{sbq}\\ Current^*_{scq} &= Current^*_{spq}.Voltage_{scq} \end{aligned}\right\} \quad (4)$$

Where $Voltage_{saq}$, $Voltage_{sbq}$, and $Voltage_{scq}$ are using the formula stated in (5).

$$\left.\begin{aligned} Voltage_{saq} &= \frac{-Voltage_{sbd}+Voltage_{scd}}{\sqrt{3}} \\ Voltage_{sbq} &= \frac{Voltage_{sad}\sqrt{3}+Voltage_{sbd}-Voltage_{scd}}{2\sqrt{3}} \\ Voltage_{scq} &= \frac{-Voltage_{sad}\sqrt{3}+Voltage_{sbd}-Voltage_{scd}}{2\sqrt{3}} \end{aligned}\right\} \quad (5)$$

The actual control is represented in Figure 1. The sum of direct and quadrature axis control current is given in (6)

$$\left.\begin{aligned} Current^*_{sa} &= Current^*_{sad} + Current^*_{saq}; \\ Current^*_{sb} &= Current^*_{sbd} + Current^*_{sbq}; \\ Current^*_{sc} &= Current^*_{scd} + Current^*_{scq}; \end{aligned}\right\} \quad (6)$$

The current from the (6) is referred with the supply current and the duty cycle is created from that the pulses are generated. This is given to the converter. This controls the power factor and quality of the supply. Figure 2 shows the flow diagram.

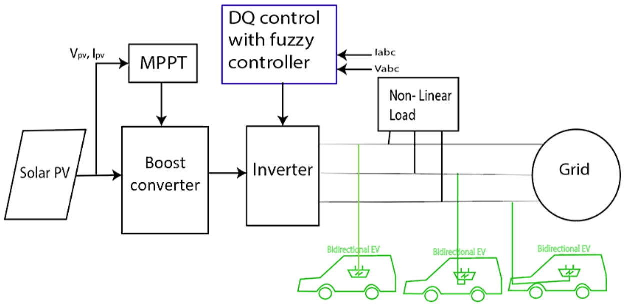

Figure 1. Test setup for testing the proposed controller (derived from [26])

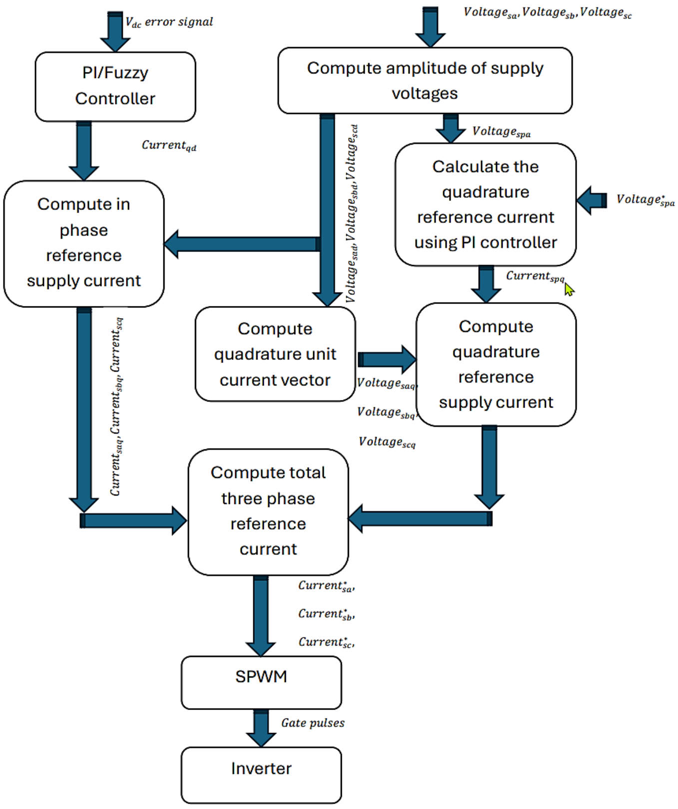

Figure 2. Control block diagram of DQ method (derived from [27])

2.1. PI controller implementation

The 2 µs time step PI controller is here to control the DC link voltage. The discrete PI controller equation specific to the Vdc error is given in (7). The values for KP and KI are tuned using the MATLAB-based arbitrary tuning method.

$$output\ error\ signal = \left(KP + KI\frac{T_s}{z-1}\right) \times Vdc\ error\ signal \quad (7)$$

2.2. Fuzzy logic implementation

The logic of fuzzy control is implemented at the DC link control part of the DQ controller. Here, the rules are formed according to the results achieved. Here, the membership functions are formed like N-negative value, P-positive value, and Z-zero value. Error is the value measured directly from the comparator. The ch-error is the samples of 0.1 ms from the comparator. Table 1 shows the fuzzy rule with a 3×3 inference system.

Table 1. Fuzzy rule with 3×3 inference system

Error/ch-error	N	Z	P
N	N	P	Z
Z	P	N	Z
P	N	Z	P

3. RESULTS AND DISCUSSION

The MATLAB Simulink software was utilized to conduct the simulation studies of the suggested system that is depicted in Figure 1. In Table 2, the simulation specifications are presented for your perusal. The power is being generated by the PV system here. Through the use of the inverter, this DC is converted into AC.

When operating in conventional mode, the inverter is controlled by a DQ controller in conjunction with a PI controller, and by utilizing a DQ controller in conjunction with fuzzy logic in the proposed method. The photovoltaic (PV) power generation is depicted in Figure 3. In this example, the PV power is obtained from an irradiance of 0.4 kW/m^2, then raced to 1 kW/m^2, and then decreased to 0.4 kW/m^2. The power variation is clearly seen with each change in irradiance. Figure 4 is a zoomed-in image of Figure 3, which demonstrates the comparison of PI and DQ in a straightforward and concise manner.

Table 2. Rating of component using in simulation

S.No	Components	Specifications
1	Non-linear load	50-ohm resistor and 2 mH inductor as load connected to rectifier bridge
2	Transformer	1:1 ratio, 100 KVA, 50 Hz
3	Bidirectional EV	40 Ah capacity and 110 V nominal voltage.
4	Grid	Voltage: 440 V, Frequency: 50 Hz
5	Boost converter	Input voltage: 300 V, Output voltage: 700 V
6	Linear load	80 kW
7	PV array	Vmp: 54.7 V, Imp: 5.58 A, Isc: 5.96 A, series panels: 6, Voc: 64.2 V, parallel panels: 48
8	Inverter	3-level

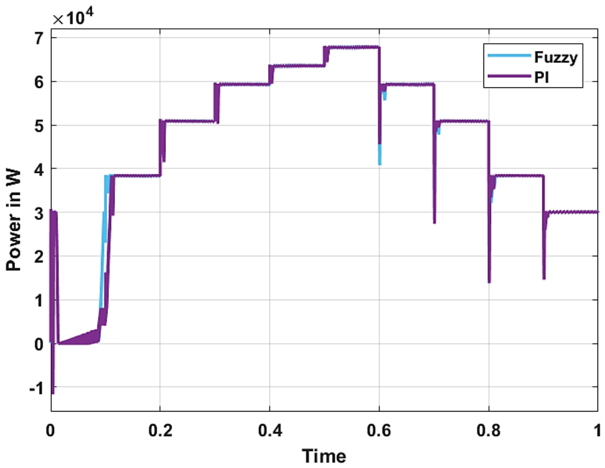

Figure 3. PV power generation

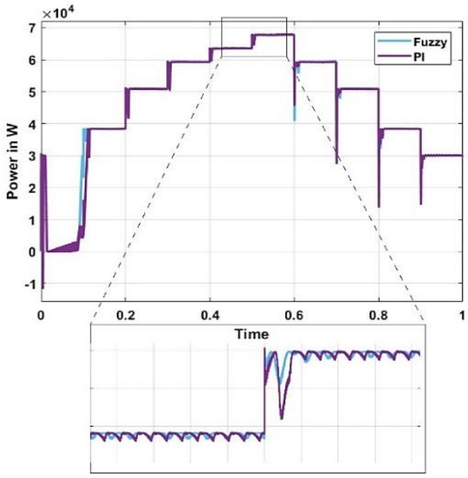

Figure 4. Zoomed view of Figure 3

Taking PI controller for comparison, the fuzzy DQ controller exhibits a lower level of ripples. Figure 5 depicts the power measured at linear load for your reference. This was a representation of the power shift that is taking place in the linear load. The comparison of power at the point of PCC between PI and DQ control and fuzzy control is depicted in Figure 6. The power fed to the grid is represented by the negative power. While the power that is sent to the grid in fuzzy DQ controllers is 65 kW, the power that is sent to the grid in PI control DQ is 60 kW. The power responsiveness is improved by using a fuzzy controller with a DQ system.

Figure 7 shows the battery SOC, current, and voltage. The SOC increases from 0 to 0.3 seconds. It discharges and drops during 0.3 to 0.6 seconds. Then, during 0.6 to 1 seconds, it is charging again. Figure 8 depicts the total harmonic distortion (THD) of the voltage for the PI controller. One last thing to consider is Figure 9, which illustrates the current THD for the PI conventional controller. Figure 10 depicts the THD and voltage of the fuzzy DQ controller. The THD for the fuzzy DQ controller is depicted in Figure 10. When contrasted with the PI controller, the current total harmonic distortion and voltage total harmonic distortion in the fuzzy DQ controller are deemed to be lower, which is shown in Figure 11. From the observation of different simulations, it can be inferred that the fuzzy logic-based implementation is advantageous in THD reduction in the PCC of the power system. Both current and voltage waveform clearly reduces the THD in both waveforms.

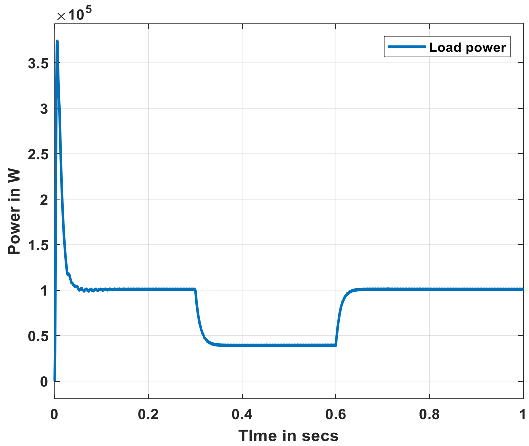

Figure 5. Power measured at linear load

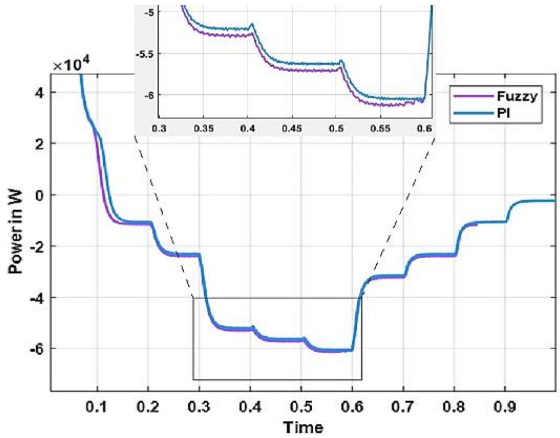

Figure 6. Comparative analysis of fuzzy DQ control and PI control with regard to power at PCC

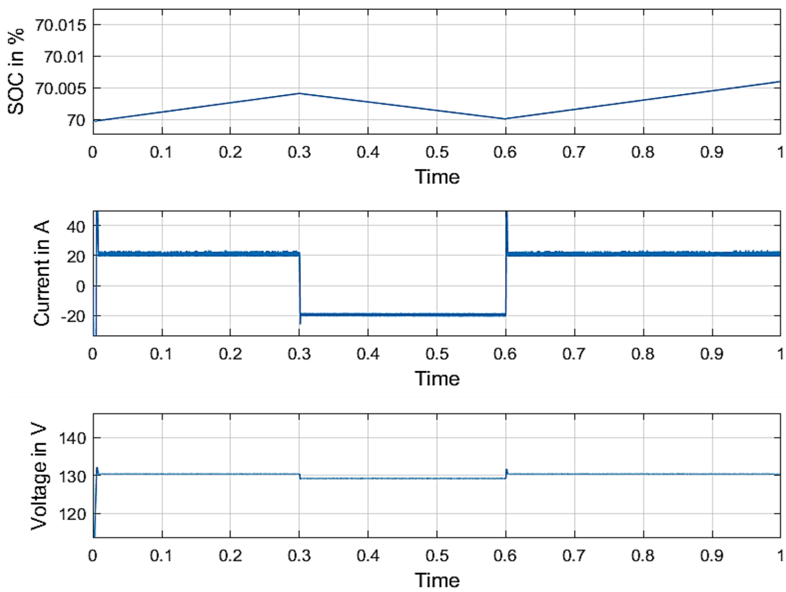

Figure 7. Battery SOC, current, and voltage

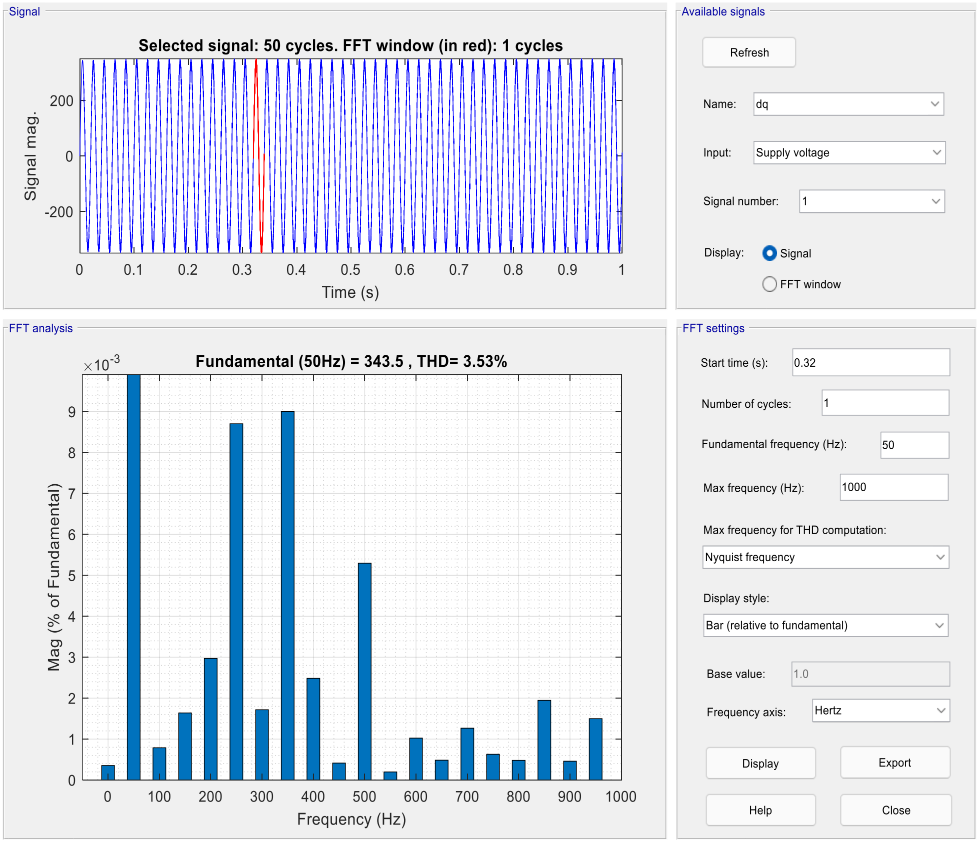

Figure 8. Total harmonic distortion measured for voltage using PI controller

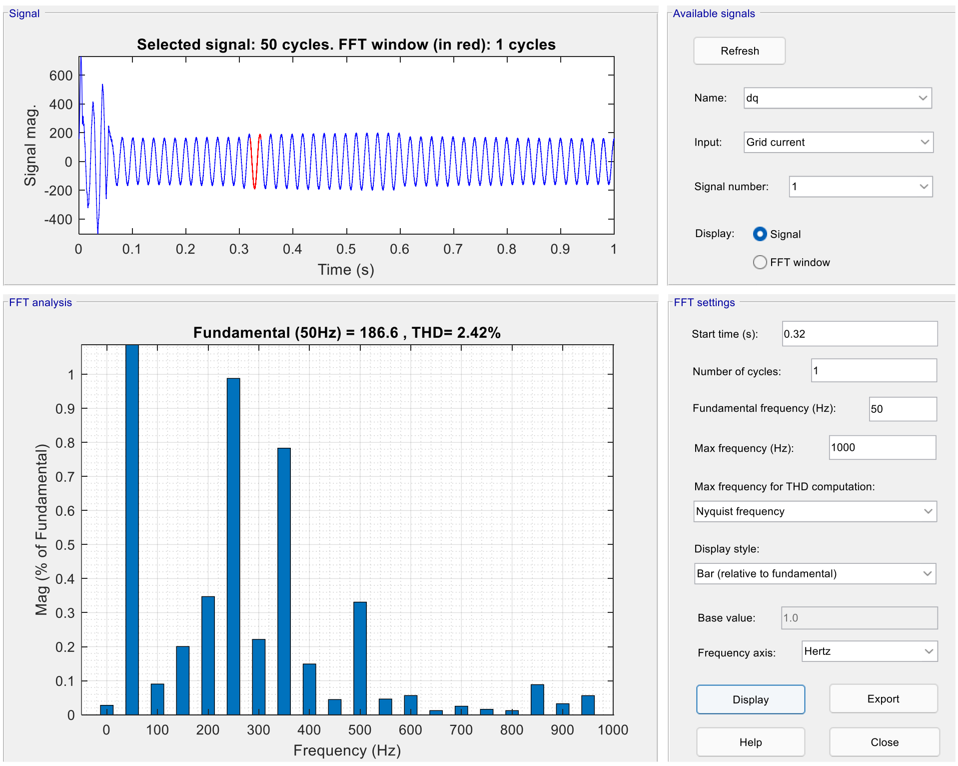

Figure 9. Total harmonic distortion measured for current using PI controller

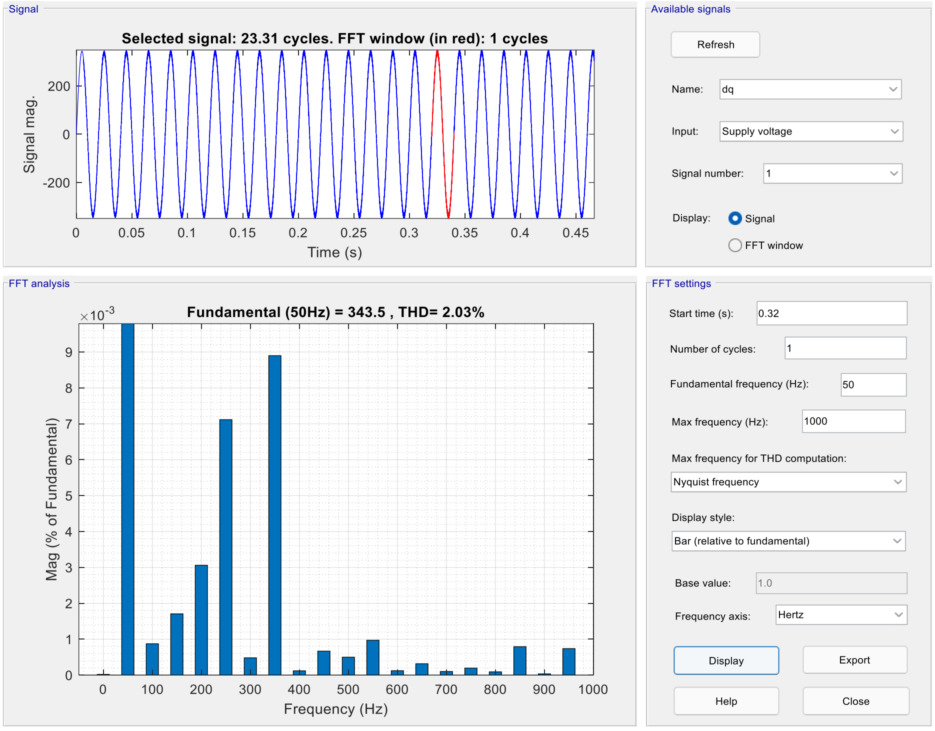

Figure 10. Total harmonic distortion measured for voltage using fuzzy controller

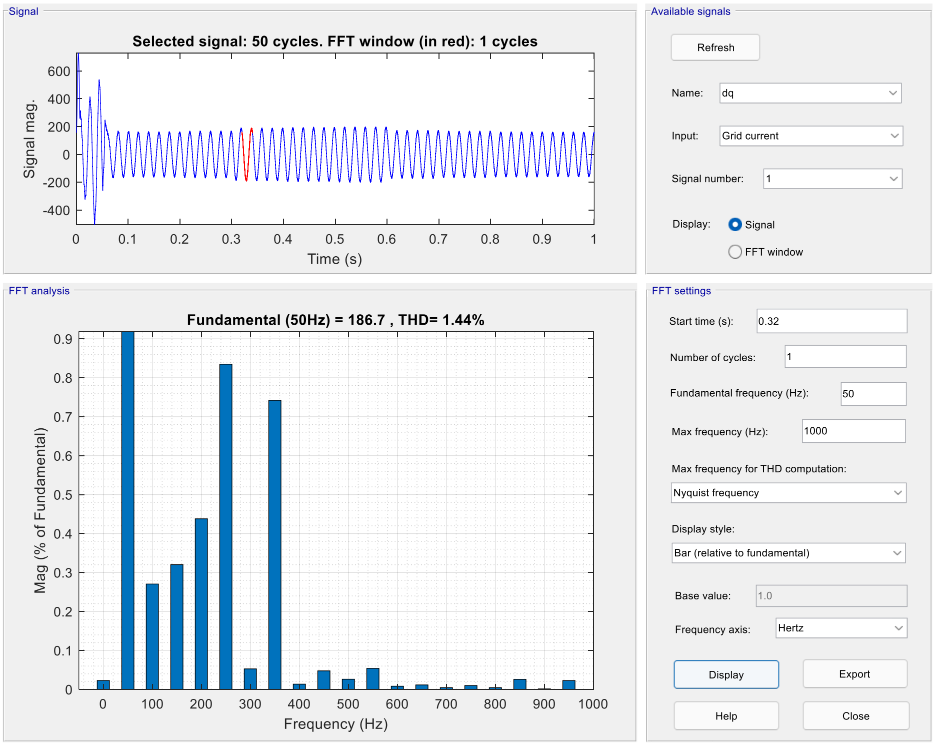

Figure 11. Total harmonic distortion measured for current using fuzzy controller

4. CONCLUSION

This study demonstrates the effectiveness of fuzzy logic controllers over traditional PI controllers within the DQ control framework for grid-connected photovoltaic (PV) systems. In scenarios involving plug-in electric vehicles (PEVs) and non-linear loads, maintaining power quality becomes increasingly challenging due to dynamic and harmonic disturbances. While PI controllers offer simplicity and are widely used, their performance degrades under nonlinear and time-varying conditions. Fuzzy controllers, by contrast, provide adaptive and robust control without requiring an exact mathematical model. Simulation results show that fuzzy logic significantly improves key performance metrics such as total harmonic distortion (THD), voltage stability, and dynamic response. These improvements lead to more reliable and efficient power injection into the grid, even under complex operating conditions. Therefore, fuzzy logic controllers present a superior alternative to PI controllers for enhancing power quality in modern PV systems, especially in environments with high variability and non-linear behavior. Their integration into renewable energy systems supports the development of smarter, more resilient power grids.

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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
Hanumesh	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Arul Ponnusamy	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Dhamodharan Selvaraj	✓		✓	✓			✓			✓	✓	✓	✓	✓
Tanuja Koppa Shankaregowda	✓		✓	✓			✓			✓	✓	✓	✓	✓
Venugopal Narasimhachar					✓				✓					
Ananda Marilingappa Halasiddappa					✓					✓			✓	

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

There is no conflict of interest.

DATA AVAILABILITY

The data used is represented in the paper as a block diagram and Tables 1 and 2.

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