DYNAMIC HARMONIC ANALYSIS OF AI-BASED CURRENT CONTROL IN A SINGLE-PHASE TWO-STAGE GRID-CONNECTED PV SYSTEM

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Abstract

This paper presents a dynamic harmonic analysis of an Artificial Intelligence (AI)-based current control strategy for a two-stage single-phase grid-connected photovoltaic (PV) system. The proposed system consists of a PV array, DC–DC boost converter, DC-link capacitor, voltage source inverter (VSI), and utility grid interface. A Fuzzy Logic Controller (FLC) is implemented for inverter current regulation and compared with a conventional Proportional-Resonant (PR) controller under identical operating conditions. Harmonic analysis is performed using MATLAB/Simulink and FFT evaluation under both steady-state and dynamic irradiance conditions. Simulation results show that the proposed AI-based controller reduces steady-state grid current THD from 4.28% to 4.16%, corresponding to a harmonic reduction of approximately 2.8%. Dynamic analysis under severe irradiance variation (1000–400–1000 W/m²) demonstrates improved harmonic recovery performance, where recovery-stage THD is reduced by approximately 7.84% (8.55% to 7.88%), while stabilization-stage THD is reduced by approximately 17.92% (5.47% to 4.49%). The proposed controller also exhibits improved transient stability and reduced overshoot while maintaining stable grid synchronization and unity power factor operation. The results confirm that AI-based current control enhances harmonic suppression and grid-side power quality while satisfying IEEE-519 standards.

Keywords— Photovoltaic systems, fuzzy logic control, grid-connected inverter, harmonic distortion, power quality.

1. Introduction

The integration of renewable energy sources into power systems has increased significantly due to growing environmental concerns and the demand for sustainable electricity generation. Among various renewable sources, photovoltaic (PV) systems have gained widespread adoption because of their modular structure and declining installation cost [1]. Grid-connected PV systems typically employ voltage source inverters (VSIs) to interface the PV array with the utility grid. However, inverter switching and nonlinear operating conditions may introduce harmonic distortion in the injected current [2]. According to IEEE-519 standards, the total harmonic distortion (THD) of current injected into the grid should remain below 5% to maintain acceptable power quality levels [3]. Conventional control techniques such as proportional-integral (PI) and proportional-resonant (PR) controllers are widely used for inverter current regulation. PR controllers provide accurate sinusoidal reference tracking in single-phase systems and eliminate steady-state error at the fundamental frequency [4]. However, their performance may degrade under nonlinear disturbances such as sudden irradiance variations. Artificial intelligence techniques such as fuzzy logic control (FLC) have been widely investigated to improve the robustness and adaptability of power electronic converters. Fuzzy controllers can handle nonlinear system dynamics without requiring an accurate mathematical model [5]. Several studies have demonstrated the potential of fuzzy logic controllers for improving dynamic response and harmonic performance in grid-connected PV inverters [6]–[8].

This paper evaluates the dynamic harmonic performance of an AI-based inverter current controller in a two-stage grid-connected PV system. The major contributions of this work include:

1. Implementation of a fuzzy logic inverter current controller.
2. Comparative harmonic analysis with a conventional PR controller.
3. Dynamic harmonic performance evaluation under severe irradiance disturbances.

2. System Description

The proposed system consists of a two-stage single-phase grid-connected PV architecture including a photovoltaic array, DC–DC boost converter, DC-link capacitor, single-phase voltage source inverter (VSI), output filter, and utility grid.

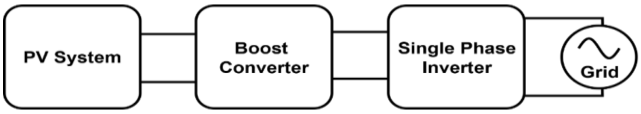

Fig. 1. Two-stage grid-connected photovoltaic system architecture.

The PV array operates under standard test conditions of 1000 W/m² irradiance and 25°C temperature. The boost converter regulates the DC-link voltage, while the VSI converts DC power into synchronized AC power suitable for grid injection. Grid synchronization is achieved using a Second-Order Generalized Integrator Phase-Locked Loop (SOGI-PLL). An L-filter is employed to reduce switching harmonics before current injection into the utility grid.

Typical simulation parameters are summarized in Table I.

Table I. System Parameters

Parameter	Value
Grid Voltage	230 V
Grid Frequency	50 Hz
Switching Frequency	20 kHz
DC-Link Capacitor	240 µF
Filter Inductance	10 mH
Sampling Time	1×10^{-5} s
Irradiance	1000 W/m²
Temperature	25°C

3. Control Strategy

3.1 PR Controller

The proportional-resonant controller is commonly used in single-phase grid-connected converters due to its ability to track sinusoidal references without steady-state error [4]. The transfer function of the PR controller is expressed as

$$G_{PR}(s) = K_p + \frac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2}\#(1)$$

3.2 AI-Based Fuzzy Logic Controller

Fuzzy logic controllers use rule-based decision mechanisms to generate control actions based on linguistic variables [5]. The proposed controller integrates proportional control with fuzzy compensation and is expressed as

$$u(t) = K_p e(t) + K_u FLC(K_e e(t), K_{de}\dot{e}(t))\#(2)$$

4. Simulation Results

4.1 Grid Current Waveform

The steady-state grid current waveform confirms proper synchronization between the inverter current and grid voltage.

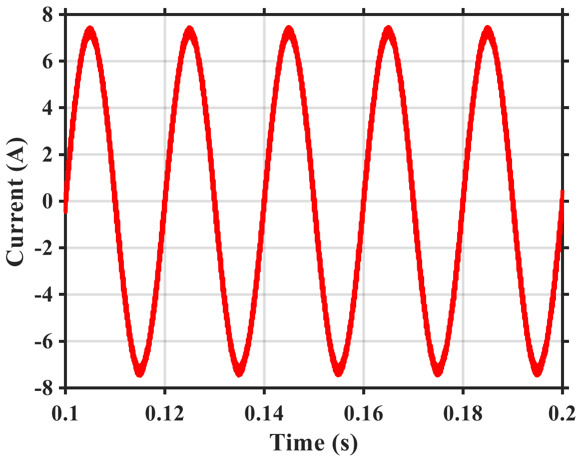

Fig. 2. Grid current waveform using the PR controller under steady-state operation.

The current waveform is nearly sinusoidal, indicating effective current regulation.

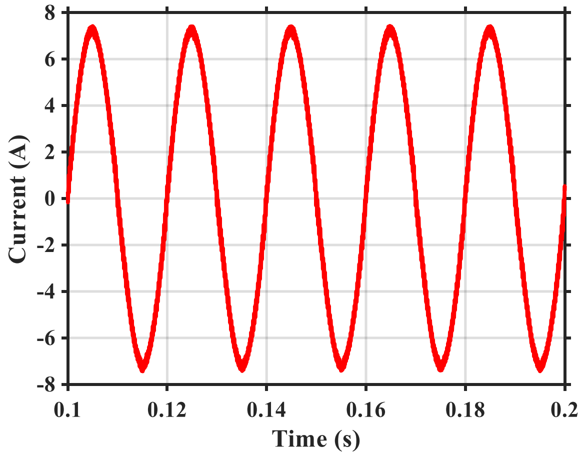

Fig. 3. Grid current waveform using the AI-Based Fuzzy Logic Controller (FLC)

4.2 Steady-State Harmonic Analysis

FFT analysis of the grid current was performed using the MATLAB powergui FFT tool.

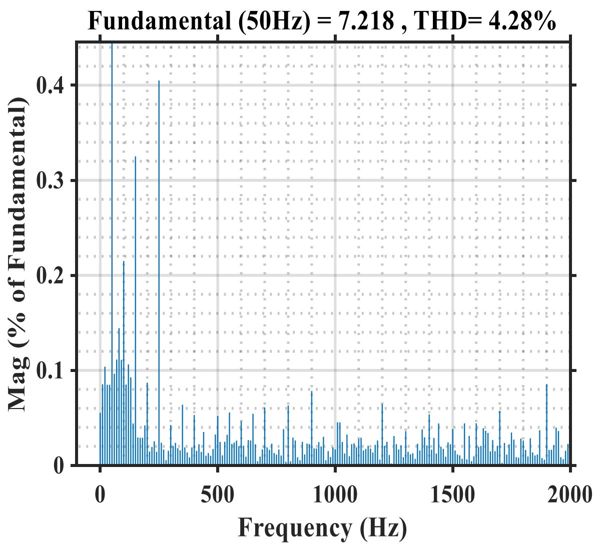

Fig. 4. Harmonic spectrum of grid current using the PR controller.

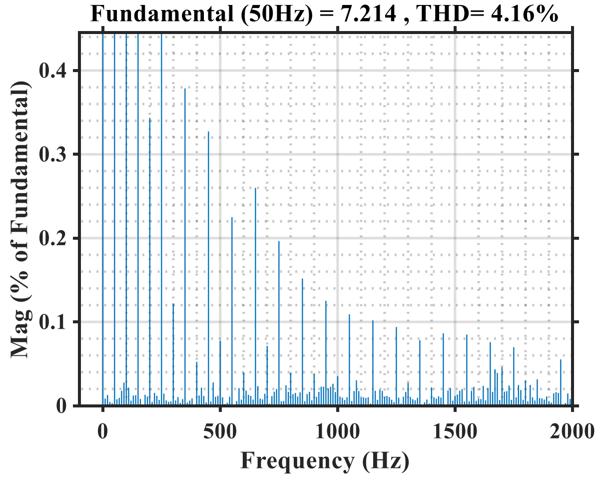

Fig. 5. Harmonic spectrum of grid current using the AI-Based Fuzzy Logic Controller (FLC)

Table II. Steady-State THD Comparison

Controller	Fundamental Current (A)	THD (%)
PR Controller	7.218	4.28
FLC Controller	7.214	4.16

The FLC reduces steady-state THD by approximately 2.8% compared with the conventional PR controller. Both controllers satisfy the IEEE-519 harmonic limit of 5%.

4.3 Dynamic Irradiance Disturbance

To evaluate the dynamic robustness of the controllers, a severe irradiance variation was applied.

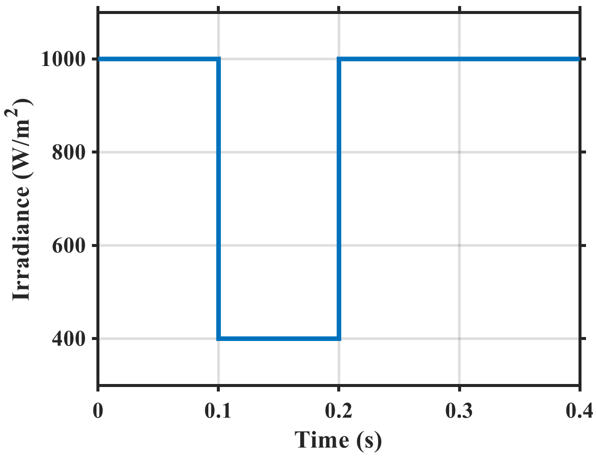

Fig. 6. Irradiance disturbance profile applied for dynamic analysis.

Disturbance profile:

1000 W/m² → 400 W/m² → 1000 W/m²

Such disturbances introduce rapid variations in PV power generation and stress the inverter control system [7].

4.4 Dynamic System Response

The DC-link voltage was selected as the primary stability indicator because it reflects the instantaneous power balance between the PV source and inverter.

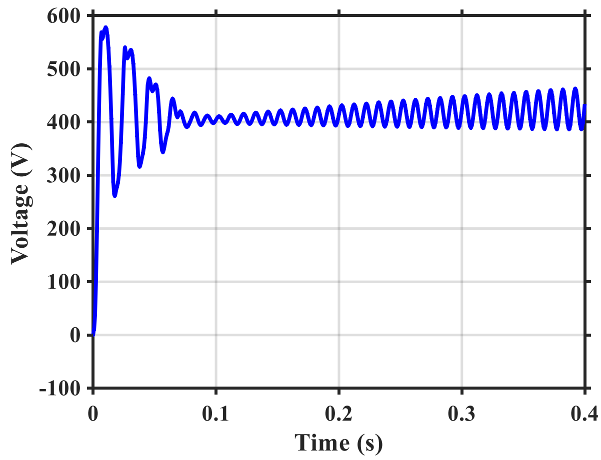

Figure 7. DC-Link Voltage Response – Conventional Controller (P&O + PR)

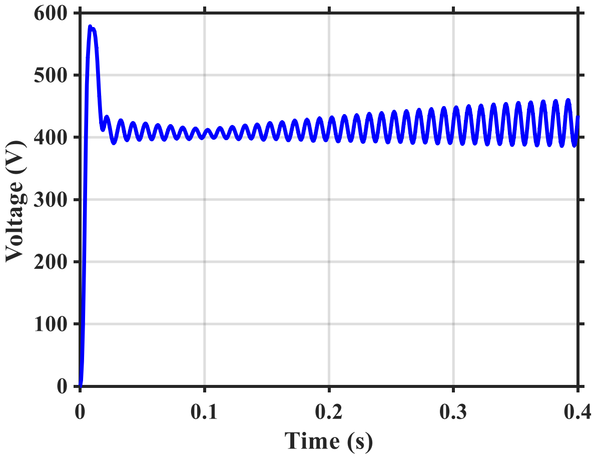

Figure 8. DC-link voltage response using the AI-based control strategy.

The system remains stable with a settling time of approximately 0.099 s.

Table III. Overshoot Comparison

Controller	Overshoot
PR	8.953 %
FLC	8.699 %

The AI-based controller reduces overshoot by approximately 2.83%.

4.5 Dynamic Harmonic Analysis

FFT analysis of the grid current was performed during the disturbance period.

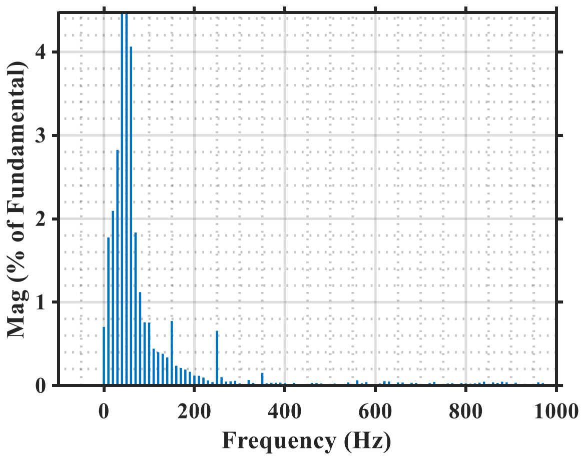

Figure 9. FFT Spectrum After 0.3 s Stabilization – PR Controller (THD = 5.47%)

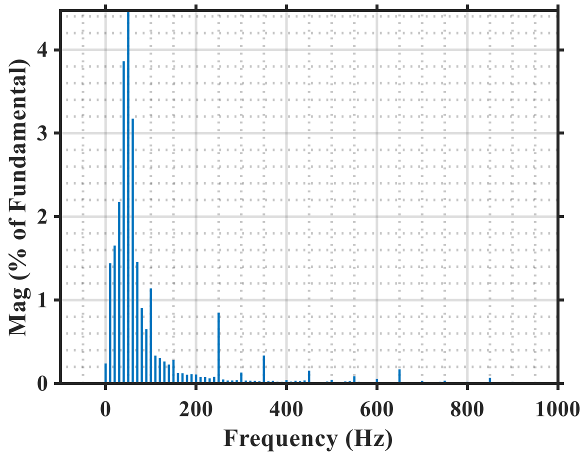

Figure 10. FFT Spectrum After 0.3 s Stabilization – FLC Controller (THD = 4.49%)

Table IV. Dynamic THD Performance

Condition	PR	FLC
After drop	17.50 %	17.10 %
Recovery (0.2 s)	8.55 %	7.88 %
Stabilization (0.3 s)	5.47 %	4.49 %

The dynamic harmonic analysis demonstrates the superior transient performance of the proposed AI-based controller. During the recovery stage, the THD decreases from 8.55% to 7.88%, corresponding to a relative reduction of approximately 7.84%. Similarly, during the stabilization stage, the THD decreases from 5.47% to 4.49%, resulting in a significant harmonic reduction of approximately 17.92% compared with the conventional PR controller. These results indicate faster harmonic recovery and improved grid current quality under severe irradiance disturbances.

5. Conclusion

This paper presented a dynamic harmonic performance evaluation of an AI-based current controller for a grid-connected photovoltaic system. The fuzzy logic controller was compared with a conventional PR controller under both steady-state and dynamic operating conditions. Simulation results show that quantitatively, the proposed controller achieved a steady-state THD reduction of approximately 2.8%, a recovery-stage THD reduction of 7.84%, and a stabilization-stage THD reduction of 17.92% compared with the conventional PR controller. These results confirm the effectiveness of AI-based current control for improving harmonic performance and dynamic robustness in grid-connected photovoltaic systems.

References

[1] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*. Wiley, 2011.

[2] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, 2006.

[3] IEEE Power and Energy Society, *IEEE Standard 519-2014: Recommended Practice for Harmonic Control in Electric Power Systems*, 2014.

[4] D. N. Zmood and D. G. Holmes, "Stationary frame current regulation of PWM inverters with zero steady-state error," *IEEE Trans. Power Electron.*, vol. 18, no. 3, pp. 814–822, 2003.

[5] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, pp. 338–353, 1965.

[6] M. A. Hannan et al., "A review of fuzzy logic based MPPT techniques for photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 749–764, 2017.

[7] J. Carrasco et al., "Power-electronic systems for the grid integration of renewable energy sources," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, 2006.

[8] S. B. Kjaer, J. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Industry Applications*, vol. 41, no. 5, pp. 1292–1306, 2005.

[9] H. Abu-Rub, M. Malinowski, and K. Al-Haddad, *Power Electronics for Renewable Energy Systems*. Wiley, 2014.

[10] J. M. Guerrero et al., "Advanced control architectures for intelligent microgrids," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1254–1262, 2013.

[11] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of single-phase improved power quality AC–DC converters," *IEEE Trans. Ind. Electron.*, vol. 50, no. 5, pp. 962–981, 2003.

[12] M. Liserre, F. Blaabjerg, and S. Hansen, "Design and control of an LCL-filter-based three-phase active rectifier," *IEEE Trans. Ind. Applications*, vol. 41, no. 5, pp. 1281–1291, 2005.