NTU Journal of Engineering and Technology (2025) 4 (2) : 73-79
DOI: https://doi.org/10.56286/ntujet.v4i2

IRAQI Academic Scientific Journals

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

Fuzzy Logic Control Implementation for Grid-Connected Multilevel Inverter Using FPGA-Based CORDIC-PLL Synchronization

Ali Ahmad Thenon[1], Taha Ahmed Hussein[1]
[1]*Department of Electrical Engineering Techniques, Technical Engineering College, Northern Technical University, Mosul, Iraq.*
ali.thenon@ntu.edu.iq, *taha.hussien@ntu.edu.iq*.

Article Informations

Received: 16-10- 2024,
Revised: 13-11- 2024
Accepted: 29-11-2024,
Published online: 23-06-2025

Corresponding author:
Name:Ali Ahmad Thenon
Affiliation :*Northern Technical University*
Email: ali.thenon@ntu.edu.iq

Key Words:
Grid-connected inverter,
fuzzy logic control,
CORDIC-PLL,
multilevel inverter,
FPGA implementation,
Synchronization,
active current control,
reactive current control.

A B S T R A C T

This paper discusses a novel approach to control a grid-connected multilevel inverter using Field Programmable Gate Array (FPGA) implemented Fuzzy controlled Coordinate Rotation Digital Computer Phase-Locked Loop PLL (CORDIC-PLL) system for achieving improved inverter performance in injecting active and reactive power into the grid under changing grid conditions of operation. A seven-level cascaded H-bridge inverter topology is used to reduce total harmonic distortion without the need for large filtering components. The CORDIC-PLL system gives fine phase information for synchronization, while the fuzzy logic controller (FLC) makes adjustment in the output of the inverter by changing amplitude factors of carrier signals and phase angles for power injection control. In this way, experimental results depicted the effectiveness of the proposed system with significant improvements related to power quality and system stability.

1. Introduction

The growing integration of renewable energy sources, such as photovoltaic (PV) systems and wind turbines, to the power grid has brought into perspective the need for efficient and reliable grid-connected inverters [1]. The inverters should provide quality functioning at high powers, in synchronization with the grid, and also be able to inject active and reactive power as and when required [2].

In weak grid conditions, traditional control methods based on Proportional-Integral (PI) controllers and Phase-Locked Loops (PLLs) tend to be unstable and suffer from decreased performance [3, 4]. Fuzzy Logic Control (FLC), because of its robust nature along with the ability to handle the nonlinear system without an accurate mathematical model, has come out as a viable alternative [5, 6]. Realizing algorithms on FPGAs has advantages in speed of operation and parallelism—which are critical for real-time applications in power electronics [7, 8]. The present study puts forward an FLC integrated with an FPGA-based CORDIC-PLL Synchronization System to control a grid-connected seven-level Cascaded H-Bridge Inverter.

Bearing in mind efficient calculation of computing trigonometric functions, the output from the CORDIC algorithm results into precise phase tracking and waveform generation [8]. The FLC controls the output of the inverter by adjusting carrier signal amplitudes and phase angle to control active and reactive current injection into the grid at the required instance. Results of experiments confirm that the proposed approach is quite efficient in improved synchronization, decreasing THD, and enhancing current injection capabilities compared to the traditional way.

2. Literature Review

Grid-connected inverter synchronization is very critical for stable operation and power quality. Traditionally, in several methods, PLLs were used for tracking the phase and frequency of grid voltage [9, 10]. The dynamics of the PLL itself may also impose a negative effect on system stability, particularly under weak grid conditions [3, 4]. Some of the improved PLL designs are worth mentioning, apart from PLL-less control strategies, and feedforward compensation methods have also been done in certain works [11–13].

Such multilevel inverters, including cascaded H-bridge topologies, provide better output waveforms at lower harmonic content, hence suitable for grid-connected applications [1, 14]. Various Sinusoidal Pulse Width Modulation (SPWM) techniques are there to control multilevel inverters, with Phase Opposition Disposition (POD-SPWM) being one among them [15, 16]. These techniques enhance power quality but may be complex at higher inverter levels.

The operation of inverters based on them using Fuzzy Logic Controllers has been found attractive due to their intrinsic nature of handling nonlinearities and uncertainties [5, 6]. FLCs have been implemented in the literature for maximum power point tracking [17], direct power control [18], grid synchronization [19]. Real-time implementation of FLC in FPGA takes the advantage of the parallel processing capability of hardware for real-time control applications [7].

3. Mathematical Formulation

The mathematical foundation of the proposed system involves grid synchronization, active and reactive current injection, adjusting inverter voltage amplitude, and the CORDIC algorithm.
The grid voltage is given by:

$$V_g(t) = V_m \sin(\omega t + \theta_g) \quad (1)$$

The inverter's output voltage is:

$$V_{\text{inv}}(t) = V_{\text{inv}} \sin(\omega t + \theta_{\text{inv}}) \quad (2)$$

Synchronization requires minimizing the phase error:

$$\Delta\theta = \theta_g - \theta_{\text{inv}} \quad (3)$$

The CORDIC-PLL ensures that θ_{inv} tracks θ_g. The FLC adjusts θ_{inv} by applying $\Delta\theta$ to control active current injection.
The instantaneous current injected into the grid can be represented as:

$$I_{\text{inv}}(t) = I_{\text{inv}} \sin(\omega t + \theta_I) \quad (4)$$

The active and reactive components of the current are:

$$I_{\text{active}} = I_{\text{inv}} \cos(\Delta\theta) \quad (5)$$
$$I_{\text{reactive}} = I_{\text{inv}} \sin(\Delta\theta) \quad (6)$$

Since the grid voltage V_g is constant, the inverter controls the current I_{inv} by adjusting the phase $\Delta\theta$ and the inverter output voltage V_{inv}.
For active current control (changing I_{active}), the FLC adjusts $\Delta\theta$ (advancing or retarding the phase) while

keeping $V_{\text{inv}} = V_g$. For reactive current control (changing I_{reactive}), the FLC adjusts V_{inv} (modifying the amplitude) by adjusting the amplitude of the carrier signals, while maintaining $\Delta\theta = 0$.

The amplitude of the inverter output voltage V_{inv} can be adjusted by modifying the amplitude of the carrier signals in the POD-SPWM modulation. This changes the modulation index m_a, affecting the output voltage amplitude [15]:

$$V_{\text{inv}} = m_a V_{\text{DC}} \tag{7}$$

where V_{DC} is the DC bus voltage, and m_a is the modulation index defined in (8)[20].

$$m_a = \frac{V_{\text{ref}}}{V_{\text{carrier}}} \tag{8}$$

By increasing V_{carrier}, m_a decreases, reducing V_{inv}, and vice versa.

The CORDIC algorithm computes trigonometric functions using iterative rotations. Using the equations (9-11) [8]:

$$x_{i+1} = x_i - y_i d_i 2^{-i} \tag{9}$$
$$y_{i+1} = y_i + x_i d_i 2^{-i} \tag{10}$$
$$z_{i+1} = z_i - d_i \arctan(2^{-i}) \tag{11}$$

The CORDIC evaluate the sine and cosine in steps (i). Where x representing the $\cos(\theta)$ and y value represent the $\sin(\theta)$ and the initial z or z_0 is the angle in radian and d_i representing the direction of the rotation following this equation $d_i = \text{sign}(z_i)$.
The final y will represent the approximate value of $\sin(\theta)$.

4. Proposed Experimental Setup

The proposed system consists of grid-connected 7-level Cascaded H-Bridge inverter controlled by FPGA-based CORDIC-PLL Synchronization System and FLC. The experimental setup is shown in Figure 1.

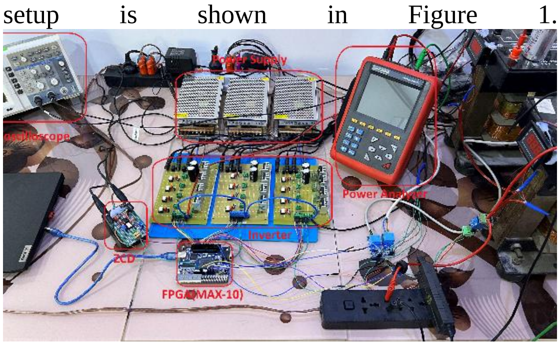

Fig. 1. Experimental setup of the proposed fuzzy logic-controlled grid-connected inverter.

The phase information for grid synchronization is attained by the CORDIC-PLL implemented in an FPGA. This system enables the inverter's output voltage to be compared with the grid voltage $V\_g\ (t)$ via a phase detector. The output of the phase detector is the input to the CORDIC algorithms that implement the digital control of the oscillator frequency and phase. Real-time waveform generation can thus be achieved using the CORDIC algorithm [8].

The FLC changes the inverter output by adjusting the amplitude of the carrier signals and the phase angle θ(t) for active and reactive current injection. Measured current I_meas and measured voltage V_meas from sensors are read by this fuzzy logic controller to determine the required adjustments. Such a control strategy allows dynamic adjustments without the need for an accurate mathematical model of the system. [5]
The inverter package comprises three H-bridges connected in series resulting in seven voltage levels. The topology reduces THD in the output waveform, improving power quality and reducing the requirement for large filters. As a result [14, 15].

5. Control Strategy

The PLL tracks the grid voltage's phase θ_g and outputs a phase $\theta(t)$ for the inverter. The CORDIC algorithm uses this phase to compute the reference sinusoidal waveform:

$$V_{\text{ref}}(t) = V_{\text{ref}} \sin(\theta(t)) \tag{12}$$

This waveform is synchronized with the grid and serves as the reference for the inverter's output. The FLC modifies θ(t) to advance or retard the inverter's output phase, controlling active current injection.
In the Phase Opposition Disposition SPWM technique, the reference waveform is compared with multiple carrier signals (triangular waveforms) with frequency of 1300hz to obtain the PWM signals for the inverter switches. The modulo of inverter output voltage can be controlled by varying amplitude of the carrier signals. If we increase the amplitude of the carrier signals, output voltage from the inverter decreases; on the contrary, lowering the carrier signal amplitude increases the output voltage modulation. It is because of this kind of modulation that multilevel inverters are capable of producing low harmonic-content high-quality output waveforms [15]. The FLC has two main control objectives:

1. Active Current Control: Adjust the inverter's phase $\theta(t)$ to regulate active current injection while maintaining the voltage amplitude equal to the grid voltage.

2. Reactive Current Control: Adjust the inverter's voltage amplitude by modifying the amplitude of the carrier signals to regulate reactive current injection

while maintaining zero phase difference with the grid.

The FLC reads the measured current I_{meas} and measured voltage V_{meas} from sensors. The errors are calculated as:

- Current Error (e): Difference between the reference current (I_{ref}) and the measured current (I_{meas})

$$e_I = I_{\text{ref}} - I_{\text{meas}} \qquad (13)$$

- Change of Current Error (Δe):

Difference between the current error at the present and previous time steps

$$\Delta e_I = e_I(t) - e_I(t-1) \qquad (14)$$

Where I_{ref} is the reference current (either active or reactive component, depending on the control objective).

The outputs from the FLC are $\Delta\theta$ and $\Delta V_{\text{carrier}}$, which are used to adjust the phase and amplitude of the reference waveform and carrier signals:

$$\theta_{\text{new}}(t) = \theta(t) + \Delta\theta \qquad (15)$$

$$V_{\text{carrier,new}}(t) = V_{\text{carrier}} + \Delta V_{\text{carrier}} \qquad (16)$$

By increasing the amplitude of the carrier signals (V_{carrier}), the modulation index decreases, lowering the inverter's output voltage. Conversely, decreasing V_{carrier} increases the modulation index and the output voltage. These adjustments ensure that the inverter injects the desired amounts of active and reactive currents into the grid.

6. Experimental Results

A Zero Crossing Detector (ZCD) with hysteresis was implemented to provide accurate zero-crossing points of the grid voltage, essential for PLL synchronization. Figure 2 shows the improved ZCD output signal, indicating precise detection of zero-crossing points.

The performance of the synchronization system is being illustrated in Figure 3, Key outcomes include accuracy of synchronization, and it shows the output voltage waveform of the presented inverter.

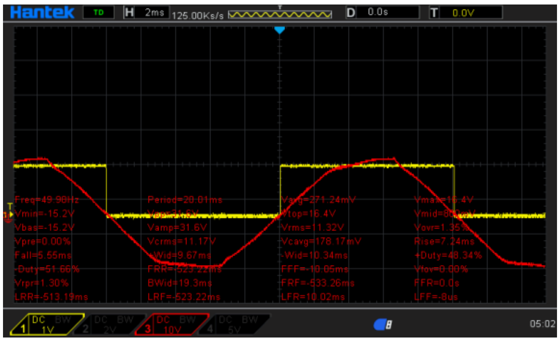

Fig. 2. ZCD output signal after implementing hysteresis.

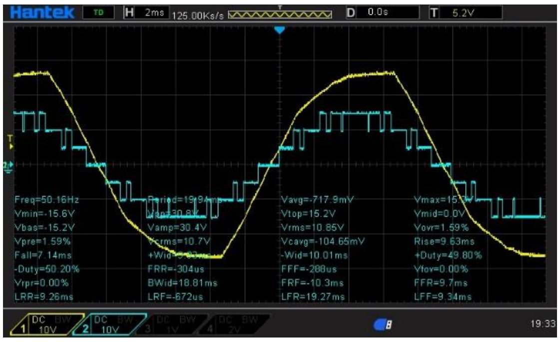

Fig. 3. Inverter output synchronized with the grid.

The FLC automatically adjusted the inverter's phase $\theta(t)$ to inject desired active current levels while maintaining the voltage amplitude equal to the grid voltage. Figure 4 shows the voltage and current waveforms during the injection of 1 A active current. The current waveform is in phase with the voltage waveform, indicating effective active power transfer.

Fig. 4. Waveform of active current injection at 1 A using fuzzy logic control.

Figure 5 displays the power analyzer measurements, showing an active power of approximately 221 W, negligible reactive power, and a power factor close to unity, this figure illustrate that the control unit (FLC) did its intended job of maintaining a value close to the desired of 1 A active.

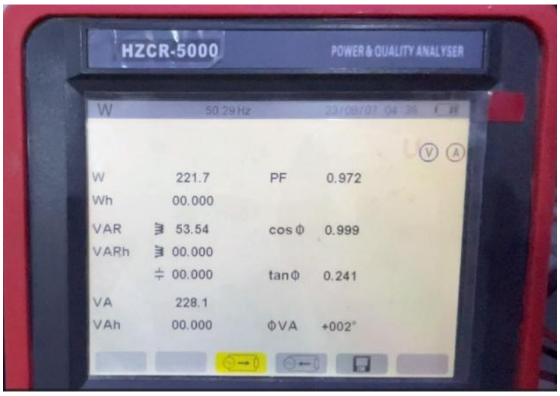

Fig. 5. Power analyzer measurements during 1 A active current injection.

Fig. 6. Waveform of active current injection at 1.5 A using fuzzy logic control.

Similarly, for an active current injection at 1.5 A, Figure 6 illustrates the waveforms. The synchronization between voltage and current remains consistent.

Figure 7 shows the power analyzer readings, confirming an increase in active power proportional to the injected current, power parameters reading prove that the measured active power 323.3W is close to the desired value of 1.5 A, and the measured real power and apparent power are approximately identical that means all the power being injected is active power.

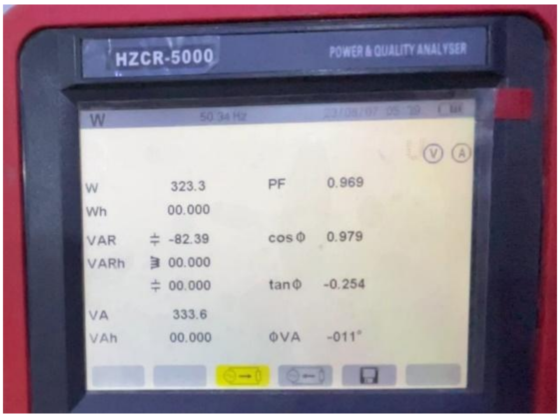

Fig. 7. Power analyzer measurements during 1.5 A active current injection.

For reactive current injection at 1 A, the FLC adjusted the amplitude of the carrier signals to change the inverter output voltage V_{inv}, injecting reactive current while maintaining zero phase difference with the grid.

Figure 8 presents the waveforms during the injection of 1 A reactive current. The current waveform lags the voltage waveform by less than 90 degrees, characteristic of reactive power transfer.

Fig. 8. Waveform of reactive current injection at 1 A using fuzzy logic control.

Figure 9 provides the power analyzer measurements, indicating significant more reactive power than active power, and a power factor reflecting the reactive nature of the current, these numbers ($\cos(\theta)$, $\tan(\theta)$) indicate a strong reactive power flow to the grid.

Fig. 9. Power analyzer measurements during 1 A reactive current injection.

7. Discussion

The validity of the proposed fuzzy logic control scheme for the grid-connected inverter system is confirmed from the experimental results. The CORDIC-PLL on FPGA-based implementation achieved perfect synchronization with the grid, and FLC controlled active and reactive current injection in a very effective way by changing output of the inverter through phase angle and magnitude. The FLC changed the phase $\theta(t)$ for active current control while maintaining the voltage amplitude equal to the grid voltage. This fact is evidenced by the waveforms and power analyzer measurements where the current is in phase with the voltage and the power factor is close to unity. In the reactive current control, the FLC modified the carrier signal amplitudes, thereby changing the inverter output voltage V_inv, keeping, however, the zero phase difference. A rise in carrier amplitude lowers inverter output voltage whereas lowering amplitude increases it to raise the output voltage. Thereby the current waveform leads or lags the voltage waveform by 90 or less degrees, and the power analyzer readings prove reactive power being injected.

The approach would offer improved stability and reduced harmonic distortion with enhanced adaptability to grid fluctuations. The THD in the output waveform is drastically reduced by the multilevel inverter topology, which means better power quality without large filters.

8. Conclusion

A fuzzy logic-controlled grid-connected inverter system implemented with an FPGA-based CORDIC-PLL synchronization technique has been presented in this paper. Integration of FLC with precise phase tracking allows efficient regulation of active and reactive current injection into the grid by adjusting the inverter's output through phase and amplitude modifications. Experimental results showed robust performance based on precise synchronization, effective current injection, and improved power quality provided by multilevel inverter topology.

The importance of this work is the ability to facilitate renewable energy incorporation and smart grid applications by presenting an inverter control strategy that is reliable and effective. The FLC makes it possible to handle system nonlinearities and uncertainties so that the system can adapt to changes in the grid conditions. The hardware implemented system using FPGA would provide real-time execution which is very much important for high performance-based applications in power electronics.

Future work in this research will be to optimize the rule base of the fuzzy logic controller for higher control accuracy (also done to a great extent in this work) and to develop adaptive and predictive control strategies for better responsiveness. More work is also needed to scale the system up for higher power applications. Integration with energy storage systems and a detailed study of its performance under grid faults and disturbances will help draw confidence in deploying them in practice. All these shall be immensely useful.

References

[1] M. K. Jarjes and T. A. Hussein, "Comparative study of SPWM and SVPWM techniques for the control of three-phase grid connected inverter," Przegląd Elektrotechniczny, vol. 99, no. 5, 2023.

[2] T. A. Hussein, "Multilevel level single phase inverter implementation for reduced harmonic contents," Int. J. Power Electron. Drive Syst., vol. 12, no. 1, pp. 314–324, 2021.

[3] D. Zhu, S. Zhou, X. Zou, and Y. Kang, "Improved design of PLL controller for LCL-type grid-connected converter in weak grid," IEEE Trans. Power Electron., vol. 35, no. 5, pp. 4715–4727, 2019.

[4] X. He and H. Geng, "PLL synchronization stability of grid-connected multiconverter systems," IEEE Trans. Ind. Appl., vol. 58, no. 1, pp. 830–842, 2021.

[5] M. A. Hannan, Z. A. Ghani, A. Mohamed, and M. N. Uddin, "Real-time testing of a fuzzy-logic-controller-based grid-connected photovoltaic inverter system," IEEE Trans. Ind. Appl., vol. 51, no. 6, pp. 4775–4784, 2015.

[6] H. F. Farahani and F. Rashidi, "Direct power control of a grid-connected photovoltaic system using a fuzzy-logic based controller," Simulation, vol. 93, no. 3, pp. 213–223, 2017.

[7] Y. Luo, M. A. Awal, W. Yu, and I. Husain, "FPGA implementation for rapid prototyping of high performance voltage source inverters," CPSS Trans. Power Electron. Appl., vol. 6, no. 4, pp. 320–331, 2021.

[8] M. Yin and Y. Jiang, "Enhanced signal processing through FPGA-based digital down conversion via the CORDIC algorithm," J. Ind. Intell., vol. 2, no. 1, pp. 14–30, 2024.

[9] K. M. S. Y. Konara, M. L. Kolhe, and W. G. C. A. Sankalpa, "Grid synchronization of DC energy storage using Voltage Source Inverter with ZCD and PLL techniques," in Proc. 2015 IEEE 10th Int. Conf. Ind. Inf. Syst. (ICIIS), Dec. 2015, pp. 458–462.

[10] S. Golestan, J. M. Guerrero, and J. C. Vasquez, "Single-phase PLLs: A review of recent advances," IEEE Trans. Power Electronics, vol. 32, no. 12, pp. 9013–9030, 2017.

[11] X. Zhang, D. Xia, Z. Fu, G. Wang, and D. Xu, "An improved feedforward control method considering PLL dynamics to improve weak grid stability of grid-connected inverters," IEEE Trans. Ind. Appl., vol. 54, no. 5, pp. 5143–5151, 2018.

[12] N. Mohammed, W. Zhou, and B. Bahrani, "Comparison of PLL-based and PLL-less control strategies for grid-following inverters considering time and frequency domain analysis," IEEE Access, vol. 10, pp. 80518–80538, 2022.

[13] Y. F. Wang and Y. W. Li, "Grid synchronization PLL based on cascaded delayed signal cancellation," IEEE Trans. Power Electron., vol. 26, no. 7, pp. 1987–1997, 2010.

[14] H. A. Khalif, J. K. Abed, and A. J. Mahdi, "A comparative Analysis of Multi-Level Inverters Supplied by Photovoltaic Panels based on THD and Filter Size by using POD-SPWM Technique," in IOP Conf. Ser.: Mater. Sci. Eng., vol. 1105, no. 1, p. 012011, Jun. 2021.

[15] K. Chenchireddy and V. Jegathesan, "Multi-Carrier PWM Techniques Applied to Cascaded H-Bridge Inverter," in Proc. 2022 Int. Conf. Electron. Renew. Syst. (ICEARS), Mar. 2022, pp. 244–249.

[16] A. M. Soomro, A. P. Memon, S. Khokhar, J. A. Ansari, and L. Memon, "Design and Analysis of 11-level Cascaded H-Bridge Multilevel Inverter using Various SPWM Controlling Techniques Considering Current and Voltage Harmonic," Balochistan J. Eng. Appl. Sci. (BJEAS), 2022.

[17] N. Priyadarshi, S. Padmanaban, M. S. Bhaskar, F. Blaabjerg, and A. Sharma, "Fuzzy SVPWM-based inverter control realisation of grid integrated

photovoltaic-wind system with fuzzy particle swarm optimisation maximum power point tracking algorithm for a grid-connected PV/wind power generation system: hardware implementation," IET Electr. Power Appl., vol. 12, no. 7, pp. 962–971, 2018.

[18] M. Jamma, A. Bennassar, M. Barara, and M. Akherraz, "Advanced direct power control for grid-connected distribution generation system based on fuzzy logic and artificial neural networks techniques," Int. J. Power Electron. Drive Syst., vol. 8, no. 3, p. 979, 2017.

[19] S. Ahmad, S. Mekhilef, H. Mokhlis, M. Karimi, A. Pourdaryaei, T. Ahmed, U. K. Jhuma, and S. Afzal, "Fuzzy logic-based direct power control method for PV inverter of grid-tied AC microgrid without phase-locked loop," Electronics, vol. 10, no. 24, p. 3095, 2021. [Online]. Available: https://doi.org/10.3390/electronics10243095

[20] E. H. E. Aboadla, S. Khan, M. H. Habaebi, T. Gunawan, B. A. Hamidah, and M. B. Yaacob, "Effect of modulation index of pulse width modulation inverter on Total Harmonic Distortion for Sinusoidal," in Proc. 2016 Int. Conf. Intell. Syst. Eng. (ICISE), Jan. 2016, pp. 192–196.