ANFIS controller and DQ frame-based power optimization for grid-tied three phases converter

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Article Info

Article history:

Received Nov 26, 2024
Revised Nov 8, 2025
Accepted Nov 28, 2025

Keywords:

Adaptive control
ANFIS controller
Carbon emission reduction
Grid synchronization
Harmonic suppression

ABSTRACT

The study proposes an effective optimization technique aimed at reducing power loss and improving energy conversion efficiency in a three-phase electrically linked converter by employing an adaptive neuro-fuzzy inference system (ANFIS) controller. The control strategy integrates ANFIS with Fourier direct-quadrature (DQ) cycle translation based on the synchronous reference frame theory (SRFT). This combination significantly enhances converter performance by ensuring precise line synchronization, efficient voltage regulation, and effective harmonic suppression, all while delivering faster dynamic responses. The approach also simplifies the control framework and enables independent regulation of reactive and active power, offering greater operational flexibility. Such converters play a critical role in transforming DC or AC power from the grid or renewable sources into compatible electrical energy suitable for distribution. The proposed ANFIS-based DQ frame control method provides an advanced solution for optimizing the operation of electrically interconnected three-phase power converters. The research demonstrates the method's effectiveness through detailed MATLAB simulations, confirming improved stability, reduced losses, and superior overall system performance.

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1. INTRODUCTION

The rapid growth of renewable energy sources, such as wind power, is a key driver in the global transition toward sustainable energy systems. Among the preferred Techniques for incorporating renewable energy three-phase inductor–capacitor–inducto (LCL) type electrically linked inverters are positioned in the power grid, equivalent to wind turbines. Three-phase LCL type electrically linked inverters are positioned in the power grid, equivalent to wind turbines. These inverters facilitate the conversion of variable renewable energy output into grid-compatible AC power. However, their intrinsic durability at the structure's boundary challenges, necessitating a thorough investigation and resolution of these issues [1]. This work highlights the critical role of energy efficiency and sustainability in various industries, focusing on renewable energy integration. A primary topic of discussion is the implementation of a three-phase grid-connected inverter system designed to comply with industry standards. Using ANFIS controller in combination with a direct-quadrature (DQ) frame transformation, this study proposes a robust control strategy for addressing stability concerns and improving inverter performance.

A synchronous frame of reference is used in [2] to update the controller parameters through a parameter estimation architecture. A three-phase grid-connected inverter with an RL filter is subjected to a deadbeat control in order to confirm the effectiveness of the control come estimate design. A Levenberg-Marquardt reverse propagation approach and dynamic scheduling are used in [3] to create an artificial neural network for controlling inverter-interfaced DERs in a small grid. The work optimizes active and reactive power regulation for a three-phase electrically connected inverter in a microgrid using population-specific extremal optimized approaches (APEO) [4], [5] suggests combining photovoltaic technology and a unified control strategy to create a three-phase electrically linked voltage source conversion. It also suggests using a two-stage power conversion technique to manage a solar PV connected grid system. A novel three-phase electrically connected inverter system is proposed in [6]. The specified arrangement includes two inverters. The primary inverter operates at a modest switching frequency and transmits active electricity to the grid. The supplementary inverter converts a negligible quantity of power to counteract the electrical network current ripple [7]. Compared to earlier voltage lift techniques such as super lift converters and traditional boost converters, ultra-lift converters generate geometrically growing output transfer gains that are exceptionally high. It also provides smaller size and improved efficiency in comparison. Utilizing perpetual conduction mode, ultra-lift converter performance is assessed [8].

In order to achieve low current distortion and fast reaction, the study in [9] offers a functional three-phase four-wire (3Φ4W) electrically linked hybrid-frequency parallel inverter system (HAFIZ) with ripple compensation. This is based on evaluations among different inverter designs in terms of performance, reaction, loudness, disruption of current, and cost. For correlated when combining three-phase, three-wire (3P3W) combination frequency inverter circuits (HbFIS), and combination low- and high-speed changeover are appropriate for heavy power loads appliances, a current ripple compensation methodology is presented in [10]. A better electrically linked management approach based on voltage is recommended in [11], [12], illustrates a basic network current controlling mechanism for network-connected applications and a phase-locked loop (PLL)-based inverter voltage control mechanism for purposeful islanding at the grid-connected three-phase inverter. Based on a direct PQ control methodology, [13] uses model predictive control with finite control sets (FCS-MPC) to regulate the functioning of a three-phase electrically connected string inverter. The three-level converter FCS-MPC represents finite control set model predictive control. that is neutral-point-clamped (NPC) technique uses virtual vectors because of their great power efficiency and good performance in reducing current ripples [14]. SAPFs, or series active power filters, are mainly utilized in low and medium voltage power systems to compensate for voltage aberrations such as flickers, notches, and sags, and to lower harmonics. SAPF can reduce total harmonic distortion (THD) by inserting voltage to reduce distortions in the line [15].

For a two phase electrically linked photovoltaic (PV) inverter, an innovative strong A model reference adaptive PI current controller, or MRAC-PI, is suggested [16]. The topological developments in PV-grid tied inverters are thoroughly reviewed in [17], along with their key benefits, drawbacks, and characteristics. To manage a specified power into the layout and balance the grid currents, a PR controller is utilized [18]. By inserting reimbursement in the fault voltage's recently made remarks, a virtual phase-current regulation (VPCR) mechanism is created [19]. One of the most widely used techniques for the inverter to operate in an electrically linked mode is the PLL [20]. Three methods of control for grid-following inverters (GFLIs) are comprehensively investigated [21]. Babu *et al.* [22], it is addressed how to lessen the harmonics of the primary source current in the electrical mechanism for distribution by using a proportional-integral (PI) processor in conjunction with a chain of H-bridge multilevel inverter (CHBMLI) as DSTATCOM. A simultaneous diagnostic process for electrically linked open-circuit three-level NPC inverter power converter faults and current sensor faults is suggested in [23]. To address the issue of increased circuit loss and complicated methods of control brought on by most clamped resonant DC-link inverters' utilization of independent clamped switching to regulate the clamping process, a unique clamped resonant inverter was provided [24]. To minimize switching losses and improve three-level inverter efficiency at high switching frequencies, an alternative design of the resonant DC link three-level soft-switching inverter is recommended [25].

This work replaces conventional PI controller with ANFIS to enhance adaptability and accuracy in managing power coupling and decoupling in the inverter's DQ coordinate system. The ANFIS controller's intelligent control capabilities allow for efficient and accurate active and reactive power management, enabling improved grid synchronization and harmonic mitigation. In this context, the proposed control structure comprises a private up-to-date cycle with a distant supply cycle with the ANFIS controller governing the system dynamics. Through MATLAB simulation, the study evaluates the control technique's efficiency in ensuring smooth energy transfer from renewable sources to the grid. Key performance metrics, including THD, voltage stability, and power quality, are analyzed to validate the proposed system's effectiveness. The results demonstrate the superior adaptability of the ANFIS-based approach in mitigating grid disturbances, maintaining unity power factor, and ensuring high power quality under varying conditions. The proposed ANFIS-based control scheme addresses the challenges of renewable energy integration, ensuring stability and reliability in modern grid systems. By improving the inverter's ability to react swiftly to grid disturbances and by maintaining high standards of voltage regulation and harmonic suppression, the research supports the transition toward a cleaner and more sustainable energy future.

2. SYNCHRONOUS REFERENCE FRAME THEORY

A tiny power technique's three-phase grid-tied inverter's P-Q regulatory strategy is depicted in Figure 1. The DC voltage provided by the dispersed generating module is indicated in Figure 1, along with the LC filter's comparable resonance and analogous resistor. and represent the ground side's and the low-pass filter's relative capacitors. Grid-side electricity, inverter-side voltages, along with present sensors, reactive as well as active power calculations, ANFIS-based engaged and acute energy buttons, an ANFIS-based energy system, dq/abc and abc/dq alterations, and a forum vector-based pulse widening (SVPWM) are important parts of the command structure. As electricity, its P-Q controlling framework is a control method utilized to manage electricity supply throughout a microgrid, and this is a concentrated group of distributed sustainable energy sources and the central grid of utilities. The management of the active energy (P) and reactive energy (Q) transferred across the microclimate and the national grid is the main objective of the control scheme. The following describes the altered control plan that uses ANFIS in place of conventional PI devices:

- Active power control (P): Active power, also known as real power, refers to the actual energy used to perform work. In the microgrid, the ANFIS-based control mechanism ensures precise and adaptive regulation of active power exchange with the grid of utilities. Whenever a micro-grid needs additional durability (e.g., during a generation deficit), the power converter adjusts its results to import strength that is engaged. Conversely, when the internet of things produces surplus power (e.g., from wind or solar energy), the inverter exports the excess to the utility grid.
- Reactive power control (Q): Adaptive strength is necessary over maintaining grid voltage stability but does not contribute directly to energy consumption. The ANFIS-based control strategy efficiently manages reactive power flow, supplying or absorbing it as needed. In capacitive mode, the inverter supplies reactive power, thereby boosting the microgrid's voltage levels. In inductive mode, the inverter absorbs reactive power, leading to a reduction in voltage levels. This capability ensures stability and smooth operation within the microgrid.

The proposed ANFIS-based P-Q control scheme offers an adaptive, intelligent approach for managing power flows in a grid-linked three-phase inversion, enhancing grid stability, energy efficiency, and overall system reliability.

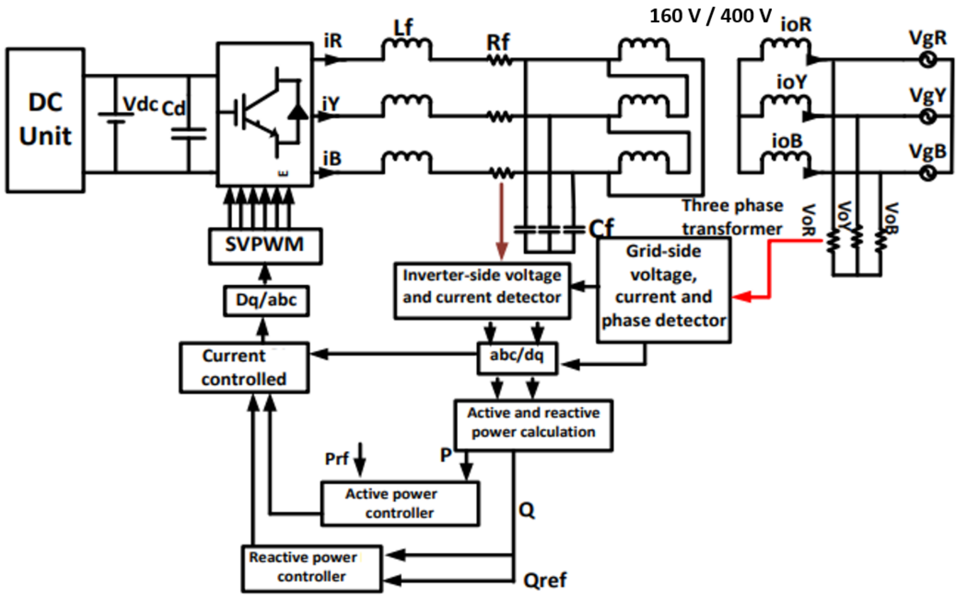


Figure 1. Three-phase grid-tied inverter P-Q control techniques in a microgrid

3. CONFIGURING THE SYSTEM

The schematic diagram for comparative energy retrieval utilizing transient reactive electricity (IRP) assumption employing an ANFIS regulator is shown in Figure 2. The 3-phase power current lines (a, b, and c) in this figure are initially transformed into two-phase currents (α and β) through Clark's transformation. This transformation converts a three-phase system into a two-phase system, enabling effective control and simplification of calculations. The winds of both directions generated and then processed to compute p and q, or both reactive and active power components, ensuring system accuracy and maintaining linearity.

The ANFIS controller replaces the traditional PI controller, providing an adaptive and intelligent response mechanism. It uses the active and reactive power components to control the line currents in the α and β axes. These components are then transformed back into three-phase currents using the reverse Clark's transformation. The transformed three-phase line currents are fed into a hysteresis-based PWM current a ruler, one utilizing the modulation of pulse widths for regulating the values of AC voltages and produces impulses with a regulated period. The controlled line currents are supplied to the voltage source inverter (VSI). Additionally, filters are employed to minimize harmonic distortion, improving power quality. The three-phase voltages are also transformed into two-phase components (α and β) using Clark's transformation for voltage control. These components interact with the power equations, enabling precise regulation of active and reactive power flows. This ANFIS-based approach not only enhances the system's adaptability and response time but also ensures superior harmonic mitigation, making it well-suited for modern grid-connected applications.

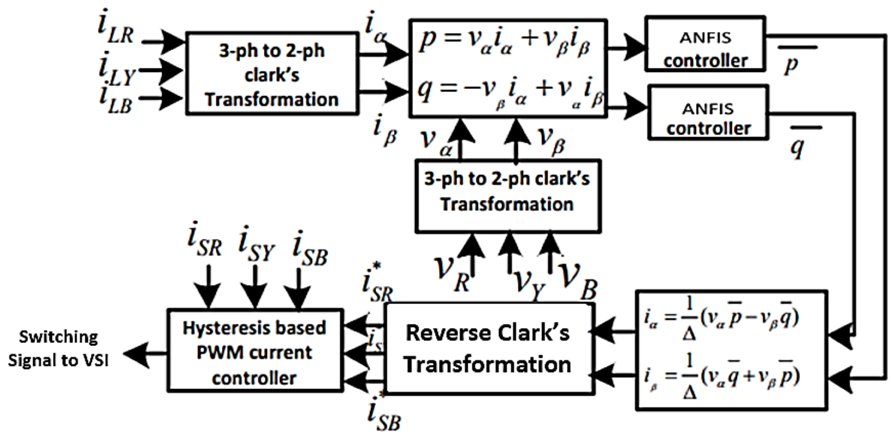


Figure 2. A schematic representation of the ANFIS controller's reference current collection using IRP theory

3.1. ANFIS controller

The ANFIS is a hybrid intelligent control mechanism that integrates the strengths of artificial neural networks (ANNs) and fuzzy logic systems. ANFIS is widely applied in various control systems, including grid inverters, due to its ability to adaptively learn and model complex nonlinear systems. In the context of a grid-connected inverter, ANFIS plays a pivotal role in regulating the flow of energy linking the electricity grid and energy from green sources (such as wind or solar power plants), ensuring precise and efficient control. By integrating ANFIS into grid-connected inverters, systems can achieve superior adaptability, faster response times, and enhanced performance under varying conditions compared to traditional controllers like PI.

3.2. Control algorithms

Since the supply only offers real power, the Department of Statistics distributes responsive to offer dynamic power modification as required by the load. Due to the fact that the initial starting point wattage is equalized, this procedure also makes load balancing easier. The Department of Statistics is triggered by the benchmark source power because the demand power has an elementary frequency part. For accurate and flexible operation, this element is obtained via the aid of an ANFIS processor. In the α-β referent frame, simultaneous reactive and active energy are computed using the momentary reactant power (IRP) concept. For simpler research and control, it entails converting three phases into dual-phase data. Figure 2 uses a distributed ANFIS controller to demonstrate a block illustration for reference potential collection.in conjunction with IRP theory. The controller processes the sensed input voltages. (V_R, V_Y, V_B) and load currents (i_{LR}, i_{LY}, i_{LB}) to produce the momentary action link (i_{SR}, i_{SY}, i_{SB}). After receiving these orders, a hysteresis-based pulse width modulation (PWM) signaler generates the signal paths needed to operate the DSTATCOM. The expression represents the electric voltage network in (1).

$$
\begin{aligned}
v_R &= v_m \sin(\omega t) \\
v_r &= v_m \sin\left(\omega t - \tfrac{2\pi}{3}\right) \\
v_{\boldsymbol{B}} &= v_m \sin\left(\omega t - \tfrac{4\pi}{3}\right)
\end{aligned} \tag{1}
$$

The flows under strain can be seen using (2).

$$i_{LR} = \sum_{i=}^{n} 1\ I_{Lan}\sin\{n(\omega t) - \theta_{an})$$
$$i_{LY} = \sum I_{Lbn}\sin\{n(\omega t - \tfrac{2\pi}{3}) - \theta_{bn}\}$$
$$i_{LB} = \sum I_{Lcn}\sin\{n\omega t - \tfrac{4\pi}{3}) - \theta_{an}\} \quad (2)$$

R-Y-B variables have the R, Y, and B directions fixed in the precise same plane and separated by 2/3. The contemporaneous space vectors, VR and iLR, are located on the "R" axis and exhibit opposite, time-varying intensities. The remaining two phases are no different. It is possible to turn these they into locations using Clark's alteration, as demonstrated in (3) and (4).

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} v_R \\ v_Y \\ v_B \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} i_{LR} \\ i_{LY} \\ i_{LB} \end{bmatrix} \quad (4)$$

At which the geographic location α and β are transverse. Typical authority is described as (5).

$$P = v_a i_a + v_\beta i_\beta \quad (5)$$

Where p is the usual calculation, as indicated in (6).

$$P = v_a i_a + v_b i_b + v_c i_c \quad (6)$$

Likewise, the IRP q is determined by (7).

$$q = -v_\beta i_\alpha + v_\alpha i_\beta \quad (7)$$

True and proactive authority can be expressed as (8).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

To determine the waves, consult (9).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (9)$$

Where is defined as shown in (10).

$$\Delta = v^2{}_\alpha + v^2{}_\beta \quad (10)$$

Both the rhythmic and normal (DC) components of the momentary energetic and receptive duties, p and q, can be distinguished.

$$p = \overline{p} + \tilde{p}$$
$$q = \overline{q} + q \quad (11)$$

The citations of current employing backwards clakr's transition amongst R, Y, and B axes are explained in (12).

$$\begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} = \frac{1}{\Delta} \begin{pmatrix} v_\alpha & -v_\beta \\ v_\beta & -v_\alpha \end{pmatrix} \begin{bmatrix} \overline{p} \\ 0 \end{bmatrix} \quad (12)$$

The R, Y, and B trio of currents are displayed in (13).

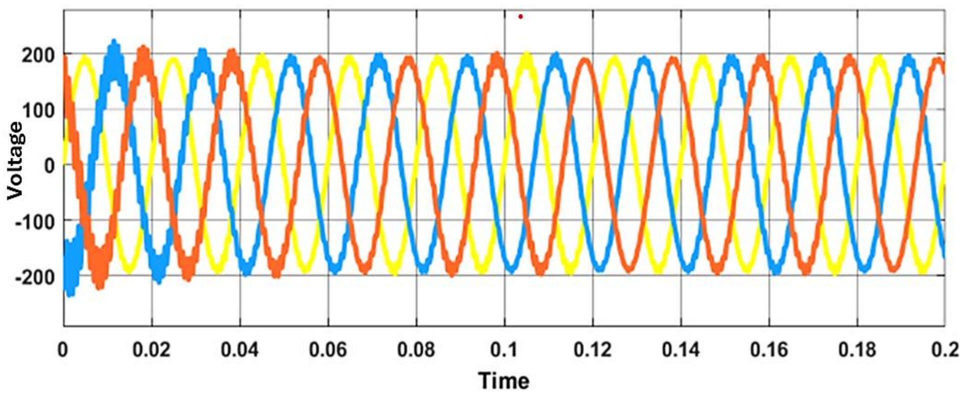
$$\begin{bmatrix} i_{SR}^* \\ i_{SY}^* \\ i_{SB}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} i_0^* \\ i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} \tag{13}$$

4. SIMULATION RESULTS AND DISCUSSION

Figures 3(a) and 3(b) are fed into the power grid using an inverter that handles three phases from clean energy supplies. With a magnitude of 600 V for each of stages R, Y, and B, the inverter transforms DC power into AC power with a highest power source of 600 V. There is a 120-degree phase change throughout the three periods. The supply current is depicted in the graphic as well. Because of the LCL filter and the ANFIS-based control system, the current maintains after initial swings between 0 and 0.01 seconds. Using dynamic and responsive current regulate systems, the supply current is adjusted. Reactive current is set to zero and active power is set to 205 A. The current begins at zero and increases to 205 A. In contrast, while the momentary in use is when the current that responds is zero and the electric current is set to 205 A, the electricity climbs from zero to 205 A. On the other hand, the current begins negatively and increases to an exponent of 150 A when the applied flow is set to 0 and the reactant current is set to 150 A.

Figures 4(a) and 4(b) present the ability to be both active and receptive outputs from the supply. From 0 to approximately 0.02 s, the powers remain constant. After 0.02 s, the waveform becomes sinusoidal, with the reactive power rising and remaining constant. The R and Y phases achieve peak power values due to the ANFIS-based control system. Figures 5(a) and 5(b) illustrate the inverter current and voltage. Considering its magnitude regulated by the proactive and reaction current regulation techniques, the inverter current replicates the supply current. When the control device is turned on, the phases first fluctuate before stabilizing.

(a)



(b)

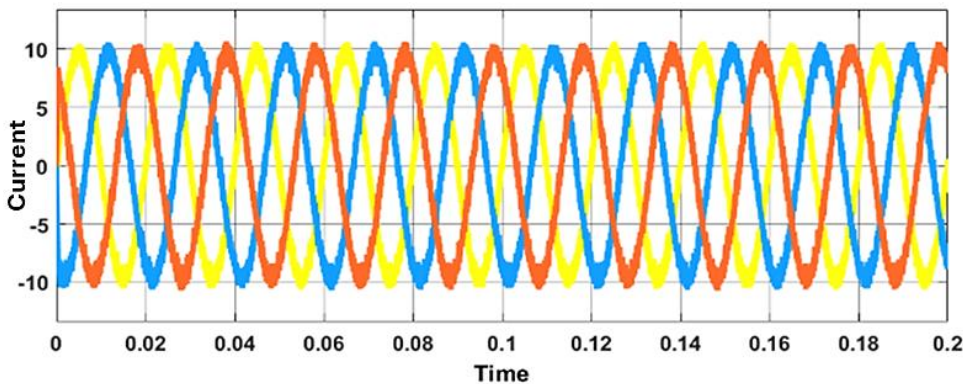


Figure 3. The inverter that handles three phases from clean energy supplies: (a) time-dependent supply voltage and (b) time-dependent supply current

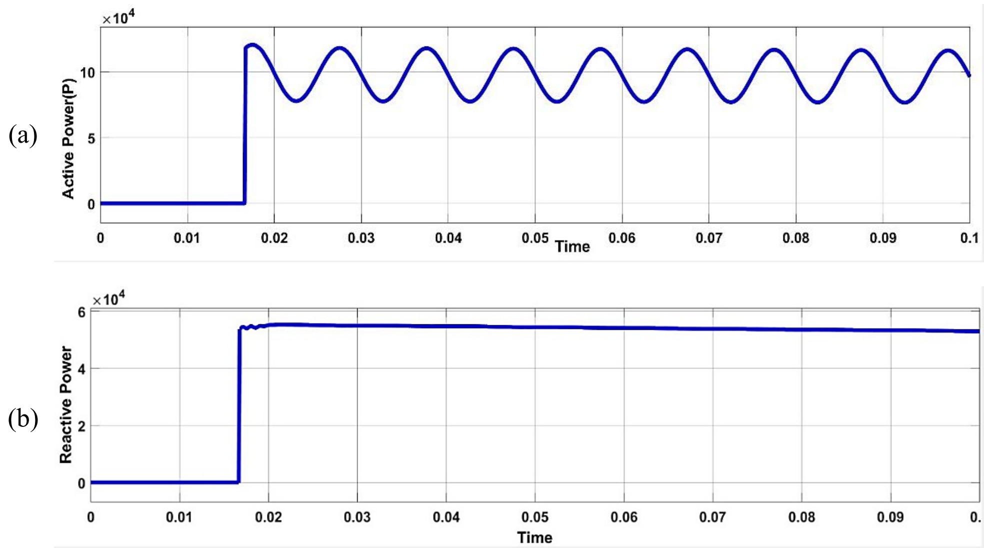


Figure 4. The ability to be both active and receptive outputs from the supply: (a) active power in relation to time and (b) reactive power in relation to time

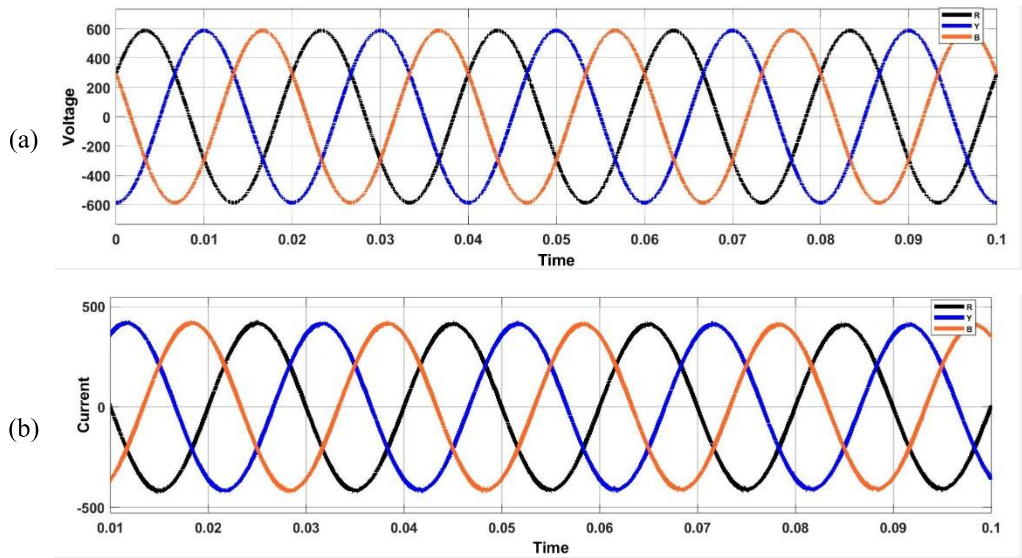


Figure 5. The inverter current and voltage: (a) voltage of 3-phase inverter and (b) current of 3-phase inverter

5. CONCLUSION

To sum up, a smart ANFIS regulator and its DQ building, in conjunction with optimal regulation tactics, provide a dependable and efficient option for contemporary energy grid unification in a three-phase network-connected compressor. Electric systems and alternative power sources, like wind and solar power windmills, can communicate seamlessly thanks to this sophisticated control technology, which allows for exact management of current and voltage patterns. Interactive instantaneous variable change is possible with the ANFIS administrator, improving quick reactions and maintaining constant state functionality. Furthermore, the managing three-phase electricity is made simpler by DQ cycle period, namely promotes effective power flow regulation and grid coordination. In the end, this monitoring approach not only preserves grid stability but also optimizes the production of energy from environmentally friendly sources, offering a viable route for the broad use of renewable energies and promoting ecological sustainability.

FUNDING INFORMATION

This research was funded by Teegala Krishna Reddy Engineering College.

AUTHOR CONTRIBUTIONS STATEMENT

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

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Guguloth Divya	✓	✓	✓	✓	✓		✓			✓	✓		✓	✓
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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

The data that support the findings of this study are available from the corresponding author, [NA], upon reasonable request.

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