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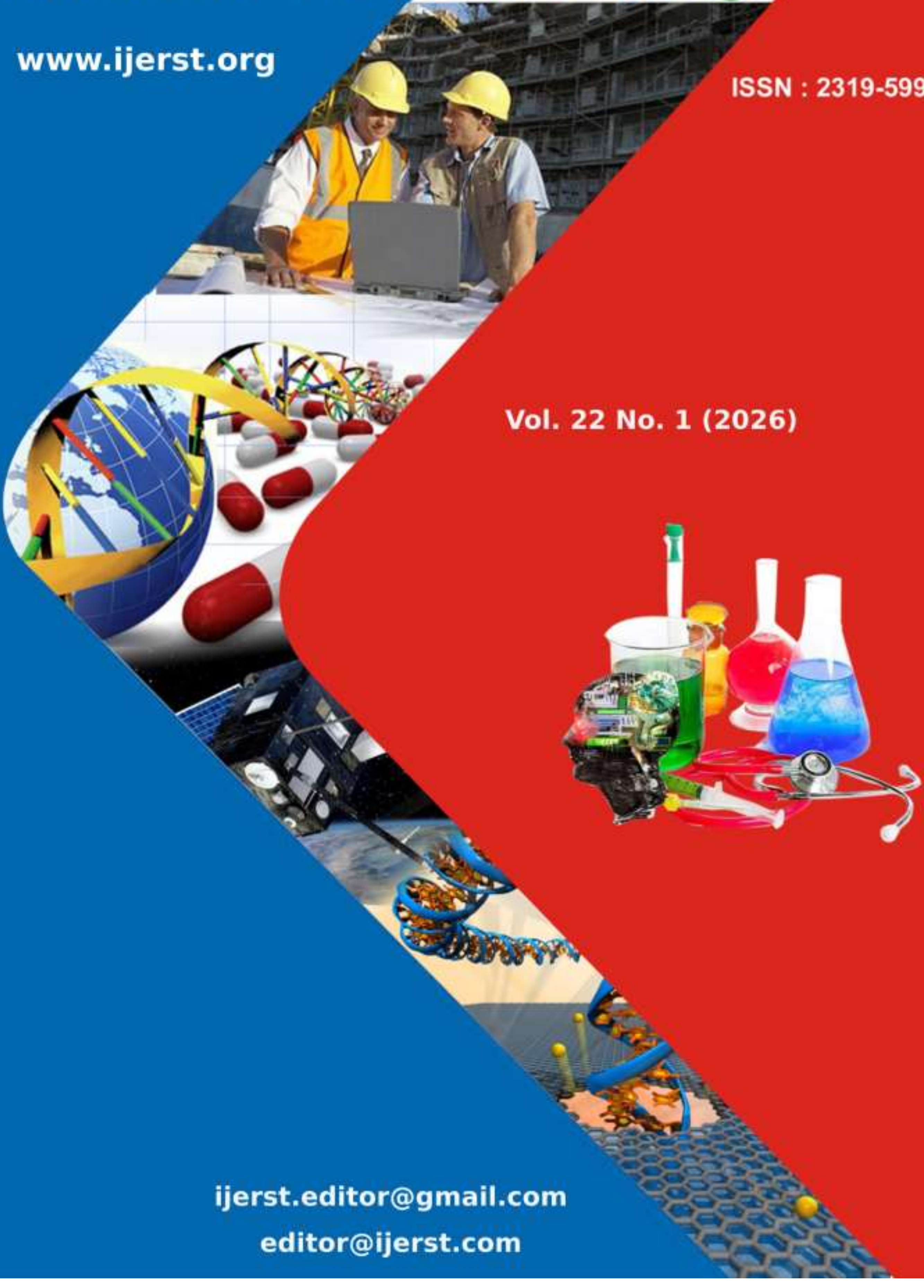

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Research

NEURO-FUZZY CONTROLLED DPFC FOR PERFORMANCE ENHANCEMENT OF GRID-INTERFACED HYBRID SYSTEMS

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ABSTRACT

The increasing penetration of grid-interfaced hybrid renewable energy systems introduces significant challenges related to power quality, voltage regulation, and dynamic stability. Distributed Power Flow Controllers (DPFCs), derived from Unified Power Flow Controller (UPFC) topology, offer flexible power flow control with reduced cost and enhanced reliability. However, conventional PI-based control strategies exhibit poor adaptability under system nonlinearities and varying operating conditions. This paper proposes an **Neuro-Fuzzy Inference System (NEURO FUZZY)–controlled DPFC** to enhance the overall performance of grid-interfaced hybrid energy systems. The proposed controller dynamically regulates series and shunt converter operations to improve voltage stability, power flow control, and harmonic mitigation. Detailed modeling of the hybrid system and DPFC is carried out in MATLAB/Simulink. Simulation results demonstrate superior performance of the proposed NEURO FUZZY-DPFC in terms of reduced Total Harmonic Distortion (THD), improved voltage regulation, faster dynamic response, and enhanced system stability when compared with conventional PI and fuzzy logic controllers.

Keywords—Neuro-Fuzzy Inference System (NEURO FUZZY), Distributed Power Flow Controller (DPFC), Hybrid Renewable Energy System, Power Quality, Grid Interfacing.

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1. INTRODUCTION

The rapid growth of renewable energy integration has led to the widespread deployment of grid-interfaced hybrid energy systems comprising photovoltaic (PV), wind energy conversion systems (WECS), fuel cells, and energy storage units. While hybridization improves reliability and energy availability, it introduces complex control challenges such as voltage fluctuations, harmonic distortion, and power flow instability under variable generation and load conditions.

Flexible AC Transmission System (FACTS) devices have been extensively employed to mitigate these issues. Among them, the Distributed Power Flow Controller (DPFC) has emerged as a promising alternative to the UPFC due to its elimination of a common DC-link and improved modularity. Despite its advantages, the performance of DPFC largely depends on the effectiveness of its control strategy.

Conventional PI controllers suffer from parameter sensitivity and degraded performance under nonlinear and time-varying system dynamics. To overcome these limitations, intelligent control techniques such as fuzzy logic and neural networks have been explored. NEURO FUZZY combines the learning capability of neural networks with the reasoning ability of fuzzy systems, making it suitable for complex power system applications.

This paper presents an **NEURO FUZZY-based control strategy for DPFC** to enhance the performance of grid-interfaced hybrid systems under steady-state and dynamic operating conditions.

2. LITERATURE REVIEW

2.1 Neuro-Fuzzy Inference Systems in Power Systems

Neuro-Fuzzy Inference Systems (NEURO FUZZY) integrate the learning capability of artificial neural networks with the rule-based reasoning of fuzzy systems, providing a powerful technique for modeling and control of nonlinear and time-varying systems. NEURO FUZZY employs a hybrid learning algorithm combining least squares estimation and gradient descent, enabling automatic tuning of fuzzy membership functions and rules from data, which leads to improved adaptability and robustness compared with standalone fuzzy logic or neural-network techniques. Wikipedia

In the context of renewable energy systems, NEURO FUZZY has been successfully applied for MPPT control in grid-integrated photovoltaic and wind systems, showing superior dynamic response and power quality under varying operating conditions. Nature For hybrid energy management too, NEURO FUZZY-based strategies have been explored for efficient power distribution and stability enhancement in systems combining PV, wind, and storage units. journal.esrgroups.org

2.2 Distributed Power Flow Controller (DPFC) Control Strategies

Flexible AC Transmission System (FACTS) devices such as the DPFC have emerged as effective tools for active and reactive power flow control in transmission networks. The DPFC, by virtue of its distributed series converters and a shunt converter, facilitates independent control of voltage magnitude and phase angle along the line without the need for a common DC link. This modular structure enhances reliability and reduces converter stress. Earlier works on DPFC have focused on conventional control schemes such as PI and fuzzy logic controllers to regulate power flow and maintain voltage stability under disturbances and load changes.

Rao *et al.* proposed an NEURO FUZZY-based DPFC scheme in multi-machine power systems, where NEURO FUZZY controllers recognize appropriate parameter settings for different operating points to enhance dynamic performance. The study highlights the potential of NEURO FUZZY to adjust control parameters intelligently across varying system conditions.

2.3 Intelligent Control in Hybrid Systems

For hybrid renewable systems, conventional control strategies often struggle with the nonlinear behaviors of renewable sources and grid interactions. Intelligent controllers such as NEURO FUZZY help in addressing these challenges by adapting in real time to fluctuations in generation and load. For instance, NEURO FUZZY-based power management has been shown to enhance system stability and dynamic response in hybrid microgrids with PV, storage, and wind generation.

Furthermore, NEURO FUZZY-centered controllers have been applied to ancillary control objectives like voltage regulation, harmonic mitigation, and transient stability enhancement. Studies integrating NEURO FUZZY with optimization techniques (e.g., genetic algorithms) further demonstrate enhanced performance in tuning controller parameters for complex energy systems.

2.4 Gap Identification

Despite the success of NEURO FUZZY in various renewable energy control applications, **its integration with DPFC for grid-interfaced hybrid systems remains under-explored**. Most prior works either focus on standalone NEURO FUZZY control for converters or basic fuzzy/PI control for DPFC.

A unified NEURO FUZZY-controlled DPFC framework capable of simultaneously delivering enhanced power flow regulation, voltage stability, and power quality improvement in hybrid systems still requires comprehensive investigation — especially under diverse operating conditions and grid disturbances.

3. GRID-INTERFACED HYBRID SYSTEM CONFIGURATION

The considered hybrid system consists of renewable energy sources such as PV and wind generators connected to the utility grid through power electronic converters. A common DC bus facilitates power exchange, while grid synchronization is achieved using a phase-locked loop (PLL).

The DPFC is installed in the transmission line connecting the hybrid system to the grid. It consists of:

- A **shunt converter** for reactive power support and DC voltage regulation
- Multiple **series converters** distributed along the transmission line for active and reactive power flow control

This distributed structure enhances reliability and reduces converter ratings.

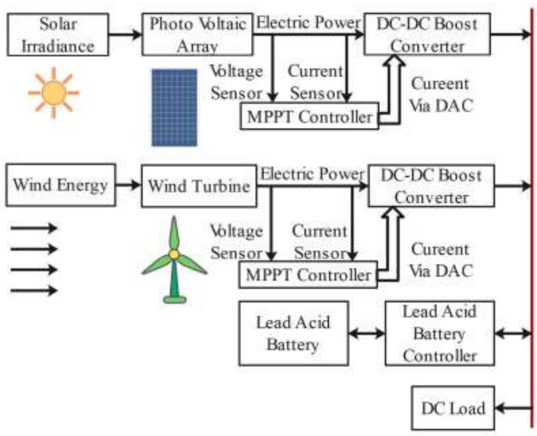

Fig 1. microgrid architecture system

4. MODELLING OF DISTRIBUTED POWER FLOW CONTROLLER

The DPFC operates by exchanging active power through the transmission line using third-harmonic frequency components, eliminating the need for a common DC link. The shunt converter injects reactive power and compensates system losses, while the series converters independently control line voltage magnitude and phase angle.

Mathematical modeling is developed in the synchronous d-q reference frame to regulate:

- Line active and reactive power
- Grid voltage magnitude
- Harmonic distortion

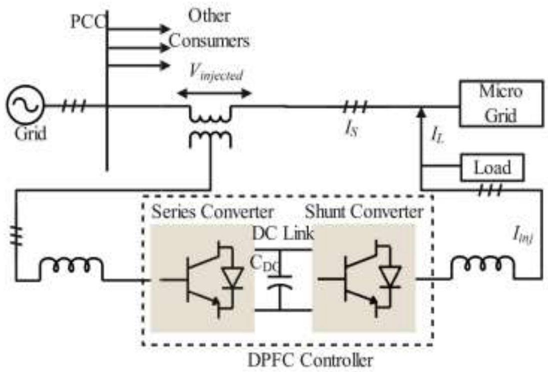

Fig 2. Microgrid based DPFC

5. NEURO FUZZY-BASED CONTROL STRATEGY

An NEURO FUZZY controller is a crucial part of a DPFC system that improves grid-interfaced hybrid system performance. NEURO FUZZY effectively controls the DPFC's operation by combining the advantages of fuzzy logic and neural networks. The NEURO FUZZY controller first transforms input signals into linguistic variables by fuzzifying them. After that, it evaluates fuzzy rules using adaptive neural networks, modifying parameters in response to training data to maximize system performance. After the rule outputs are combined, defuzzification generates clear output signals that direct the DPFC to offer accurate control actions.

The proposed NEURO FUZZY controller replaces the conventional PI controller in both series and shunt control loops of the DPFC.

5.1 NEURO FUZZY Structure

The NEURO FUZZY controller employs:

- Two inputs: error and change in error
- One output: control signal for converter modulation

Gaussian membership functions are used, and the rule base is optimized using a hybrid learning algorithm combining least-squares estimation and gradient descent.

5.2 Control Objectives

The NEURO FUZZY-DPFC aims to:

- Minimize voltage deviations at the point of common coupling (PCC)
- Regulate active and reactive power flow
- Reduce harmonic distortion under nonlinear loads
- Improve transient and steady-state performance

6. GRID-INTERFACED HYBRID SYSTEM MATHEMATICAL MODELLING

Consider a hybrid energy source connected to the grid through a **DPFC** installed in the transmission/distribution line.

6.1 Grid Voltage and Current Model

The three-phase grid voltages are:

$$\begin{aligned} v_a &= V_m \sin(\omega t) \\ v_b &= V_m \sin(\omega t - 2\pi/3) \\ v_c &= V_m \sin(\omega t + 2\pi/3) \end{aligned}$$

Using Park's transformation:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Active and reactive power:

$$\begin{aligned} P &= \frac{3}{2}(v_d i_d + v_q i_q) \\ Q &= \frac{3}{2}(v_q i_d - v_d i_q) \end{aligned}$$

6.2 Distributed Power Flow Controller (DPFC) Modeling

DPFC consists of:

- One **shunt converter**
- Multiple **series converters**
- No common DC link (active power exchanged via line harmonics)

6.2.1 Series Converter Voltage Injection

Injected series voltage:

$$\vec{V}_{se} = V_{se}(\cos\delta + j\sin\delta)$$

Power flow through transmission line:

$$P = \frac{V_s V_r}{X} \sin(\delta + \delta_{se})$$

$$Q = \frac{V_s}{X}(V_s - V_r \cos(\delta + \delta_{se}))$$

Where:

- δ_{se} is controlled by DPFC
- X is line reactance

6.2.2 Shunt Converter Model

Shunt converter controls DC voltage and reactive power:

$$L_{sh}\frac{di_{sh}}{dt} = v_{sh} - v_g - R_{sh} i_{sh}$$

DC-link capacitor dynamics:

$$C_{dc}\frac{dV_{dc}}{dt} = i_{dc}$$

6.3 Control Objective of DPFC

The DPFC regulates:

- Active power P
- Reactive power Q
- Bus voltage magnitude

Error signals:

$$\begin{aligned} e_P &= P_{ref} - P \\ e_Q &= Q_{ref} - Q \end{aligned}$$

6.4 Neuro-Fuzzy Controller Modeling

6.4.1 Neuro-fuzzy Input–Output Structure

Inputs:

$$x_1 = e_P, x_2 = \frac{de_P}{dt}$$

Output:

$$u = \Delta V_{se} \text{or} \Delta\delta_{se}$$

6.4.2 Fuzzy Rule Base (Sugeno Type)

Typical rule:

$$\text{IF } e_P \text{ is } A_i \text{ AND } \dot{e}_P \text{ is } B_i \text{ THEN } f_i = p_i x_1 + q_i x_2 + r_i$$

6.4.3 Neuro-Fuzzy Layer-Wise Mathematical Model

Layer 1 (Fuzzification):

$$O_{1,i} = \mu_{A_i}(x_1), O_{1,j} = \mu_{B_j}(x_2)$$

Gaussian MF:

$$\mu(x) = \exp\left(-\frac{(x-c)^2}{2\sigma^2} \right)$$

Layer 2 (Rule Firing Strength):

$$w_i = \mu_{A_i}(x_1)\mu_{B_i}(x_2)$$

Layer 3 (Normalization):

$$\bar{w}_i = \frac{w_i}{\sum w_i}$$

Layer 4 (Consequent):

$$O_{4,i} = \bar{w}_i(p_i x_1 + q_i x_2 + r_i)$$

Layer 5 (Overall Output):

$$u = \sum_i \bar{w}_i f_i$$

6.5 DPFC Control Law with Neuro-Fuzzy.

The control signal adjusts injected voltage magnitude/angle:

$$\delta_{se}(t) = \int u(t)\, dt$$

or

$$V_{se}^* = V_{se,0} + u$$

6.6 Stability Representation (Closed-Loop Model)

State vector:

$$x = [i_d, i_q, V_{dc}, P, Q]^T$$

State equation:

$$\dot{x} = f(x) + g(x)u_{ANFIS}$$

ANFIS ensures:

$$\lim_{t\to\infty} e_P(t) = 0, \lim_{t\to\infty} e_Q(t) = 0$$

7. SIMULATION RESULTS AND DISCUSSION

The proposed system is simulated in MATLAB/Simulink under various operating scenarios, including load variations, renewable intermittency, and grid disturbances.

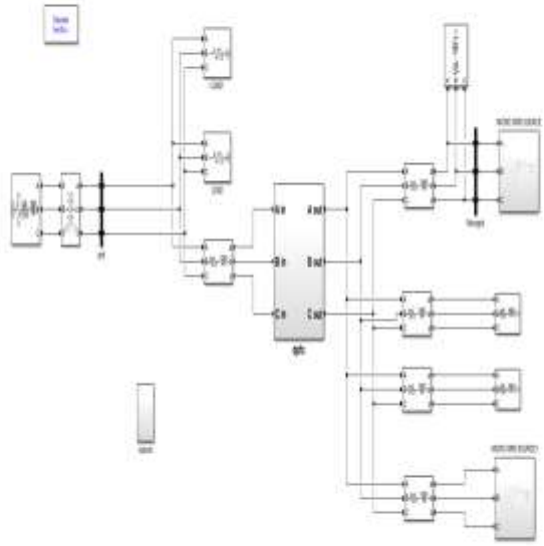

Fig 3. simulation circuit model

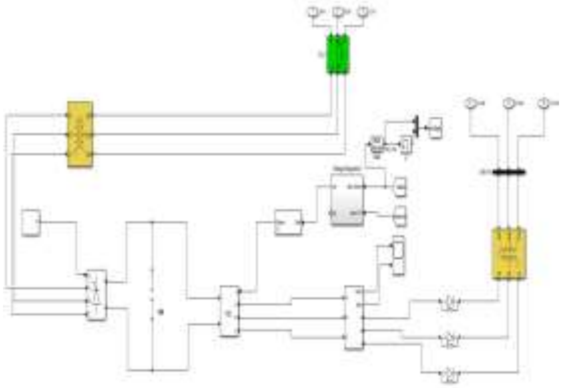

Fig 4. dpfc architecture

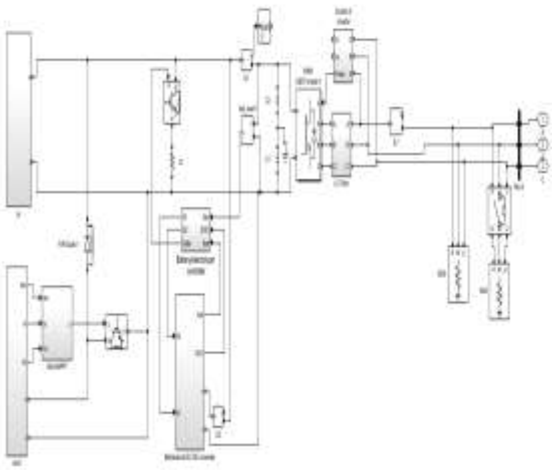

Fig 5. microgrid architecture.

The PI, FLC, and NEURO FUZZY controllers are included in the MATLAB/SIMULINK framework model shown in Figures. The proposed grid-interfaced hybrid system with a DPFC controller was modeled and tested using two different case studies.

CASE-1: USING NEURO FUZZY-DPFC, FLC, AND PI TO IMPROVE POWER QUALITY IN A HYBRID SYSTEM

Here, the proposed system is evaluated using a DPFC-PI, FLC, and NEURO FUZZY; the results are shown in Fig. 6,7.

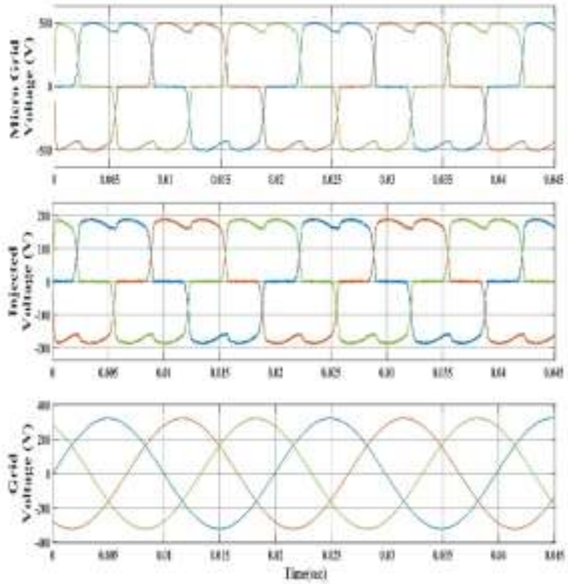

Fig 6. Output waveforms of uncompensated micro grid volatge, injected voltage and compensated grid voltage.

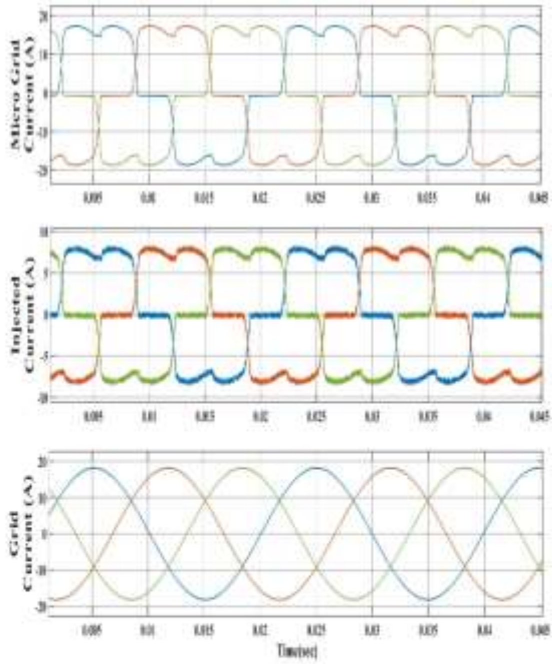

Fig 7. Output waveforms of uncompensated micro grid current, injected current and compensated grid current.

The voltages achieved at the DG side, injection, and grid are described in figures 6 and 7above. In an attempt to lessen the distortions produced, the voltage distortions that impact the suggested grid-connected system are evaluated at the grid side. In addition to the unbalanced current brought on by the unbalanced load, Figure 4 shows the injected current from the DPFC parallel converter at fundamental and third order frequencies. Fig. 4 shows the grid system's rectified current. The proposed system is linked to both linear and unbalanced loads, among other load circumstances. The microgrid current is impacted by the imbalanced conditions brought on by the utilization of nonlinear loads, which are mitigated by the DPFC's shunt converter. A DPFC controller adjusted for the harmonic distortion of the grid current caused by the non-linear and unbalanced loads. The NEURO FUZZY-based system shows less distortion than the PI and FLC.

7.1 Voltage Regulation

CASE 2: USING PI, FLC, AND NEURO FUZZY TO IMPROVE TRANSIENT STABILITY IN A HYBRID SYSTEM

In this case, the proposed hybrid system converter control diagram was tested and the stability of the hybrid system was improved using PI, FLC, and NEURO FUZZY controllers.

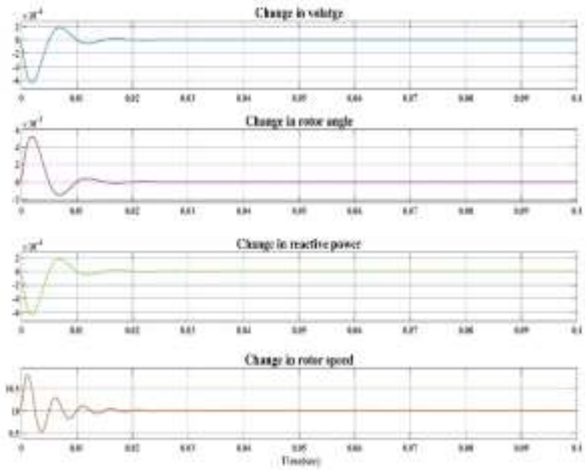

Fig 8. Transient stability in hybrid system using neuro-fuzzy controller.

Stability problems are mostly caused by changes in supply, load, or system factors. By measuring the simulation results shown in the preceding Figures, it was possible to observe the stability of the generators' voltage, rotor speed, reactive power, and angle.The NEURO FUZZY-controlled DPFC maintains PCC voltage within permissible limits, showing faster settling time and lower overshoot compared to PI-controlled DPFC.

7.2 Harmonic Mitigation

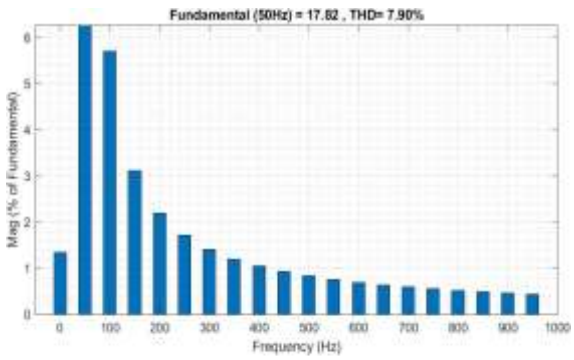

Fig 9. Total harmonic distortion of grid current using PI controller.

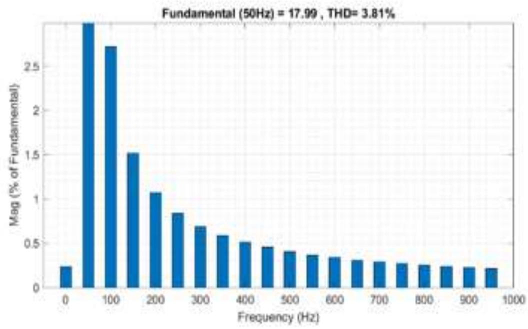

Fig 10. Total harmonics distortion of grid current using fuzzy controller.

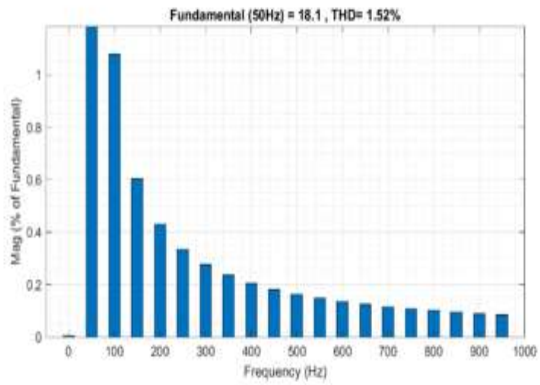

Fig 11. Total harmonics distortion of grid current using neuro-fuzzy controller.

The Total Harmonic Distortion (THD) of grid current is significantly reduced and maintained within IEEE-519 standards.

7.3 Comparative Analysis

Compared with PI and fuzzy logic controllers, the NEURO FUZZY-DPFC demonstrates:

- Improved dynamic response
- Enhanced robustness
- Reduced steady-state error

Type controller	THD %
PI	7.90%
FUZZY	3.81%
NEURO FUZZY	1.52%

The THDs values found in the grid current utilizing various controllers are shown in the above table. When compared to PI and FLC, the NEURO FUZZY-Based system reduces THD more effectively.

8. CONCLUSION

An intelligent NEURO FUZZY-based control strategy for DPFC in grid-interfaced hybrid energy systems has been presented. The proposed approach effectively enhances voltage stability, power flow control, and power quality under diverse operating conditions. Simulation results validate the superiority of the NEURO FUZZY-DPFC over conventional control methods, making it a viable solution for future smart grid and renewable energy integration applications.

Future Scope

- Hardware-in-the-loop (HIL) validation
- Integration with EV charging infrastructure
- Extension to multi-area interconnected power systems

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