

Intelligent ExDoGBoost-Enabled UPFC System for Power Quality Enhancement in Grid-Connected PV System

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Abstract- With increasing use of Renewable Energy Sources (RES) such as Photovoltaic (PV) systems, power quality has become a major challenge in modern grids. Harmonic distortions, voltage sag/swell, and load demand variations significantly affect stability and efficiency of power delivery. A Unified Power Flow Controller (UPFC) connected to a solar PV system is introduced as a sophisticated control scheme for enhancing power quality. The UPFC consists of a series and shunt converter working together to regulate voltage, manage power flow, and suppress harmonics. To ensure constant DC-link voltage under unpredictable PV conditions, an Extended Double Gain Step-Up Boost Converter (ExDoGBoost) is proposed, enabling high voltage gain and efficient energy conversion. For stable converter operation, a PI controller optimized using the Giant Trevally Optimization Algorithm (GTOA) provides effective DC voltage regulation, while a Decoupled Neural Network (DNN) generates adaptive reference currents to improve responsiveness under dynamic grid conditions. The integration of AI-based control with high-gain conversion significantly enhances the UPFC's ability to mitigate voltage sag/swells, reduce Total Harmonic Distortion (THD) to 1.71%, and support reactive power adjustment. MATLAB simulations validate the proposed system, achieving 96% converter efficiency and appreciable power quality improvement, making it suitable for renewable-integrated distribution networks.

Keywords: Unified power flow controller, ExDoGBoost converter, giant trevally optimization algorithm, decoupled neural network.

1. Introduction

The global demand for electrical energy continues to rise steadily. Although fossil fuels remain abundant, growing environmental concerns are accelerating the transition toward renewable energy sources. Among these, PV technology stands out as a leading form of distributed renewable energy and is projected to become dominant contributor to electricity generation [1]. PV systems are environmentally sustainable, generating power without releasing harmful emissions. As a result, their adoption is expanding rapidly across the globe. A significant portion of PV-generated electricity is now being fed into Low Voltage (LV) distribution networks. However, these networks were originally designed without anticipating widespread PV integration [2]. Most LV systems follow a radial configuration, where electricity flows from medium voltage transformers downstream to end users. High PV penetration disrupts this flow, causing substantial voltage fluctuations that must be carefully managed to stay within acceptable limits. In certain scenarios, when PV output surpasses local demand, the direction of power flow reverse within segments of the network [3]. This reversal, along with changes in voltage profiles, represents major power quality challenges in LV networks with distributed generation. Issues such as voltage imbalance, overvoltage, and phase unbalance become more pronounced and require advanced control strategies to mitigate. To address these challenges, Flexible AC Transmission System (FACTS) devices powered by solid-state electronics offer rapid response capabilities for voltage regulation. Key FACTS technologies include the Static Compensator (STATCOM), Dynamic Voltage Restorer (DVR), and UPFC [4].

Current research in LV networks with PV integration focuses on optimizing voltage control, balancing phases, reducing line losses, correcting voltage profiles, and implementing active filtering. Deployment of FACTS devices is being extensively explored as a solution to these emerging issues. DVR is a series-connected power electronic device designed to safeguard sensitive or critical electrical loads from common supply-side disturbances excluding complete outages [5]. It operates as a Voltage Source Inverter (VSI), with its output linked in series to the distribution feeder. The primary role of DVR is to maintain stable voltage at load terminals, regardless of fluctuations such as voltage sag/swells, distortions, or imbalances in the incoming supply [6]. It achieves this by injecting a compensating voltage with the appropriate magnitude and frequency. While the DVR is capable of adjusting the load voltage to any desired level and phase angle, its performance is constrained by the energy storage capacity available at the DC bus. DSTATCOM is a parallel-connected device designed for voltage regulation in distribution systems [7]. It utilizes a solid-state voltage source inverter and typically relies on energy stored in a DC capacitor to operate. When linked to a specific load, the DSTATCOM inject corrective current to ensure that the overall power demand aligns with utility standards. However, a considerable amount of this current continues to flow through the input terminal, meaning the device does not effectively compensate for zero-sequence components at that point [8].

1.1. Research Gap

Although FACTS controllers are well-established in transmission network control, their deployment in distribution systems remains relatively rare. There is a noticeable lack of comprehensive studies focusing on the use of FACTS devices for voltage regulation in radial distribution networks, particularly those with high levels of PV integration [9]. Current research in exploring the potential of fast-acting power electronic controllers to address voltage-related challenges at the consumer level. Among the FACTS technologies, DSTATCOM is the most straightforward to implement as a shunt-connected device [10]. However, the conventional three-leg DSTATCOM design has limitations, especially in compensating for harmonic and neutral currents, often requiring additional components. These shortcomings are addressed by four-leg DSTATCOM configurations. Meanwhile, the UPFC has demonstrated the ability to perform multiple functions simultaneously, including regulating positive sequence voltage, correcting voltage imbalance, and compensating for both neutral and harmonic currents, as well as improving power factor all without the need for auxiliary devices [11].

1.2. Motivation

As lifestyles transform and traditional energy sources dwindle, alongside shifting supply-demand patterns, importance of integrating RES into conventional power systems continues to grow. This integration is essential to meet rising energy needs in a more sustainable and eco-friendly way [12]. However, incorporating RES like solar PV systems presents notable challenges to maintaining system frequency due to their variable output. This calls for the development of sophisticated control mechanisms to satisfy Load Frequency Control (LFC) requirements. Devices like UPFC play a vital role in absorbing or releasing excess energy. These systems help reduce unnecessary fluctuations in frequency and tie-line power, thereby enhancing stability and responsiveness of overall grid operations [13].

Beyond regulating line power flows, the UPFC also plays a vital role in mitigating power oscillations. Most existing control strategies rely on conventional PI or lead-lag feedback controllers, which offer adequate damping performance near a specific operating point. However, since PI controllers operate with fixed parameters, their effectiveness diminishes when system operating conditions vary [14]. To address this, a sliding-mode control method is introduced as a more robust alternative. Yet, its performance hinges on the system's transfer function an element that is challenging to derive accurately in power systems integrated with UPFC due to their inherent complexity [15]. According to [16], a UPFC equipped with an ANN controller was shown to effectively regulate active power flow within the power system network. However, ANN-based UPFC approach is that the ANN is applied only to the shunt controllers, restricting its ability to fully optimize the dynamic power flow across the entire system. Decoupled neural network based UPFC controller is integrated, for enhancing the performance of the power system by independently managing shunt and series control actions.

1.3. Related Works

The DC link is powered by PV system, the serving as an energy buffer that enables power exchange between the shunt and series converters. The energy attained from the PV system is highly dependent on the environmental conditions, resulting in low and unreliable DC power. The PV power generation is enhanced by employing converters and control approaches explored below. DC-to-DC boost converter plays a crucial role in elevating input voltage to a level suitable for further processing. In solar photovoltaic (SPV) systems, this converter facilitates efficient energy harvesting and precise voltage regulation [17]. The Interleaved Boost Converter (IBC) utilizing an interleaved configuration, the system effectively minimizes conduction losses while significantly reducing Input Current Ripple (ICR) and Output Voltage Ripple (OVR), thereby enhancing the overall power handling capability [18]. The Quadratic Boost Converter (QBC) architecture enables substantial voltage gain even at relatively low duty cycles. This design effectively reduces voltage stress on primary power switch, thereby improving converter's reliability and extending its operational lifespan [19]. Yet, the conventional converters exhibit sensitivity to dynamic load variations and environmental fluctuations, leads to instability or reduced efficiency without robust real-time control mechanisms.

Converter's operation is fine-tuned through control algorithms that dynamically adjust switching duty cycle, thereby achieving desired output voltage and enhancing overall system performance. The converter operations are regulated by a closed loop control mechanism, PI controller where a PI controller optimized using bio-inspired algorithms continuously adjusts the system response to maintain voltage stability and ensure precise regulation of power flow under varying grid and load conditions. The Flower Pollination Algorithm (FPA) is employed to enhance performance of a PI control scheme integrated with a solar PV system. The combined FPA-PI controller, when used alongside a UPFC, capable of generating sufficient electrical energy, significantly improve when the solar PV system supplies power to the system [20]. The Moth Flame Optimization (MFO) algorithm inspired by the natural navigation behaviour of moths, this algorithm mimics their tendency to maintain a fixed angle relative to moonlight during nocturnal flight. This nature-inspired approach enables dynamic adjustment of control parameters, improving system response and stability [21]. However, these existing algorithms are highly dependent on the quality of optimization and system tuning, its effectiveness may diminish under poorly modelled or highly variable thermal-thermal system conditions. The Table 1 reviews PV based UPFC systems.

Table 1. Related works

Author/ Year/ Reference	UPQC System	Converter	Controller	Functionality
Koganti Srilakshmi <i>et al</i> (2024) [22]	Shunt Active Power Filter (SHAPF) integrated with Solar and Energy Storage System (ESS)	Boost converter	Fuzzy Logic Controller (FLC) optimized using Golden Ball Optimization Algorithm (GBOA)	Stabilizes DC-link capacitor voltage, dynamic response with THD reduction from 11.36% to 2.24%; performance highly dependent on accurate tuning of fuzzy membership functions and optimization parameters, which reduce robustness under poor operating conditions
Chilakapati Lenin Babu <i>et al</i> (2025) [23]	Solar-PV coordinated UPQC	DC-DC boost converter	PI controller optimized using Adaptive Leakage Least Mean Square (AL-LMS) algorithm	Improves PQ in grid connected PV system, further research is required to extend the approach with novel converter topologies and advanced optimization techniques for PI regulation
Ramesh Rudraram <i>et al</i> (2023) [24]	PV-integrated UPQC	DC/DC Interleaved Cuk Converter interfaced with common DC-link	d-q theory-based control with PI controller.	System performance under large PV arrays and grid disturbances remains untested.
Mangalapuri Sravani <i>et al</i> (2025) [25]	Grid-PV based UPQC	Boost converter	Deep Reinforcement Learning (DRL)-based PI controller	Provides adaptive DC-link voltage regulation. DRL-PI controller demands high computational resources and stable training environments, which challenge real-time converter control in embedded systems
Alireza Rostamipour <i>et al</i> (2024) [26]	PV based UPQC system	Boost converter	Synchronisation Reference Frame (SRF)	Effectively reduces voltage drop and current harmonics in distribution systems; reliance on SRF requires precise tuning and introduce delays in fast-changing grid conditions.

The proposed intelligent UPFC system in PV based grid system is listed below:

- UPFC effectively controls active and reactive power flow and improves voltage stability and damps power oscillations of the grid-connected PV system.
- Decoupled neural network offers adaptive control through independent management of shunt and series converter operations to achieve dynamic response to grid disturbances with high precision.
- The DC link is energized by the PV system, providing clean and sustainable power supporting efficient power flow control within the UPFC framework.
- ExDoGBoost Converter effectively enhances the low power attained from the PV system, achieving solid performance under diverse system conditions.
- GTOA-PI controller optimizes converter switching by having optimized PI parameters that ensure constant voltage and current output from the PV system to efficiently convert the energy.

1.4. Organization

The rest of the article is organized as follows: Section 2 details proposed modelling PV systems based UPFC system description for LFC. Section 3 covers modelling frameworks for the PV, DC converter, controller, UPFC based system modelling. With Section 4 presenting a comprehensive analysis of the results. The article concludes with final remarks in Section 5.

2. Proposed System Description

The proposed intelligent ExDoGBoost-enabled UPFC system, illustrated in Figure 1, presents an advanced architecture designed to address power quality challenges in grid-connected PV environments through sophisticated power electronic control strategies.

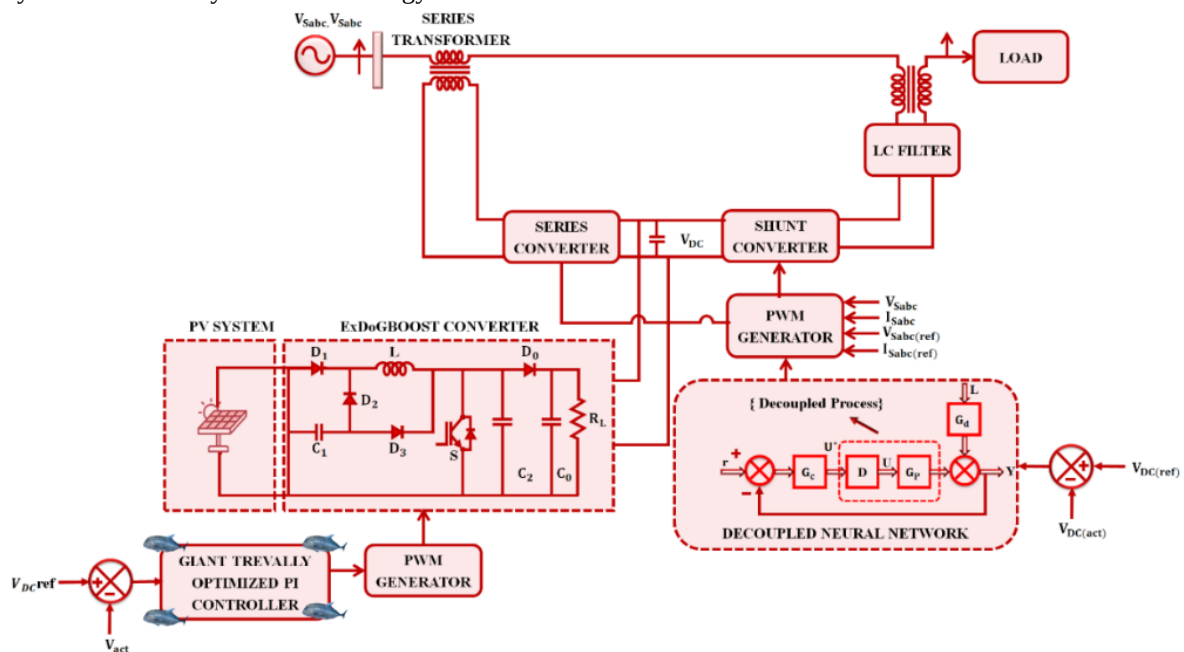


Fig. 1. Proposed UPFC based system.

The PV source serves as the primary renewable energy input; however, due to the intermittent nature of solar irradiance, the output power is inherently variable, leading to voltage and current fluctuations that degrade power quality. To overcome this, the system incorporates an ExDoGBoost, which elevates the low-voltage DC output from the PV array to a higher, grid-compatible level. The converter topology is optimized to achieve high voltage gain at relatively low duty cycles, thereby enhancing conversion efficiency and reducing stress on switching components.

Control of the converter is achieved through a GTOA-based PI controller, a bio-inspired technique that dynamically tunes PI parameters for optimal voltage regulation and maximum power extraction. This controller interfaces with a Pulse Width Modulation (PWM) generator to produce precise switching signals for the converter. The regulated DC output is then fed into the DC bus, maintaining a stable DC-link

voltage essential for consistent system operation. The converter also facilitates seamless bidirectional energy exchange between the series and shunt converters, enabling dynamic voltage regulation and flexible power flow control.

A Decoupled Neural Network (DNN) is employed to manage the real-time behaviour of the UPFC. It receives inputs such as reference and actual DC voltages ($V_{DC(ref)}$) and actual voltage ($V_{DC(act)}$), and generates adaptive reference currents for the shunt converter. The decoupling strategy allows the neural network to independently control the series and shunt components of the UPFC, enhancing the system's responsiveness, accuracy, and adaptability under varying grid conditions. This integrated control framework ensures robust voltage support, harmonic suppression, and improved power quality in renewable-integrated distribution networks.

3. Proposed System Modelling

3.1. UPFC

The UPFC is seen as the most versatile and potent member of the FACTS family and can control voltage, power flow, and system stability in transmission systems. In contrast to traditional FACTS devices that regulate a single variable, the UPFC, Figure 2, offers three degrees of freedom voltage magnitude control, phase angle control, and line impedance control hence regulating both real and reactive power simultaneously.

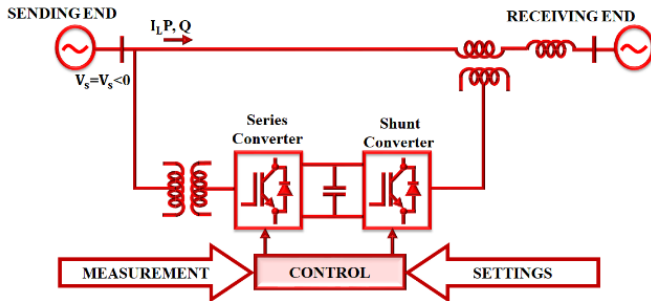


Fig. 2. Fundamental structure of UPFC.

Basic Configuration

Two Voltage Source Converters (VSCs) in UPFC are:

Shunt Converter: Normally connected in shunt to the transmission line via a shunt transformer, maintains bus voltage through controlled injection of reactive current and supplies DC power to the series converter as needed.

Series Converter: In series with transmission line via a series transformer. It introduces a controlled voltage of adjustable magnitude and phase angle into line, thus controlling power transfer.

Two converters are connected via a shared DC link capacitor, which allows active power transfer between them. Energy storage capability of this capacitor is usually small, and therefore the active power supplied by shunt converter should be equal to active power supplied by series converter. Reactive power exchange of each converter is controlled independently, though.

When the DC link switches are not closed, the two converters are independent, the shunt converter acts as a STATCOM and the series converter as an Static Synchronous Series Compensator (SSSC), regulating reactive current and injected series voltage respectively. When they are closed, active power transfer is established, and the UPFC is able to regulate simultaneously both real and reactive power recorded at receiving end of the transmission line. This intensive effort thus quickly stabilizes the system, diminishes the oscillations, and brings back the steady operation. As a result, the UPFC is capable of maintaining stable voltage, improving power factor, and ensuring the grid performance is reliable under the dynamic conditions.

The UPFC principle of operations are explained in Appendix A, as UPFC needs to be controlled by improved control mechanism for ensuring synchronized operation

between them, managing the exchange of active power via the DC link and independently regulating reactive power.

3.2. Decoupled Network

In grid-connected PV systems with a UPFC integrated into them, the control problem is naturally multivariable and very tightly coupled. Injected series voltage, shunt current, and reactive power compensation are not standalone actions, but rather are interdependent to the extent that a control action for regulating one parameter, e.g., bus voltage, tends to affect other performance metrics like harmonic distortion or reactive power balance. This intercoupling makes it difficult to design traditional controllers and leads to suboptimal performance in dynamic operating environments. To address these interactions, a DNN model is proposed, Figure 3. The fundamental rule of this model is to create synthetic manipulated inputs that control the effect on just a single output variable at a time, thus converting the original Multi-Input Multi-Output (MIMO) problem to a sequence of independent Single-Input Single-Output (SISO) subsystems. This enables every control channel, like voltage regulation or current harmonic suppression, to be treated independently without cross-interference.

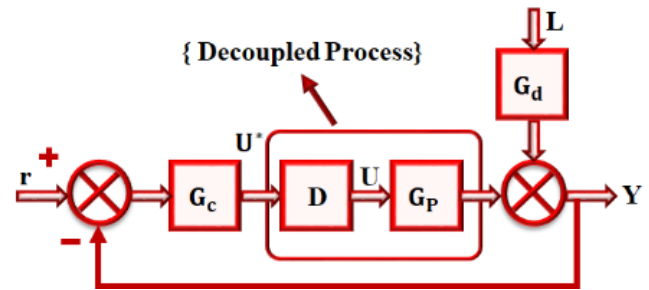


Fig. 3. Decoupled network controller.

The detailed mathematical expressions for decoupled network is given in Appendix B. As the system to energize the DC-link capacitor, a renewable energy input, the photovoltaic (PV) source is integrated.

3.3. PV System Modelling

To energize the DC link, PV module is employed by connecting multiple solar cells, which are basic devices that convert sunlight into electricity without causing pollution. These modules are further arranged in series and parallel configurations to create PV arrays that generate environmentally friendly and sustainable energy. Each solar cell functions as a component within an electrical circuit, comprising a diode and a photocurrent generator responsible for converting light into electrical energy. Additionally, the circuit includes two resistors one in series and one in parallel that represent the Joule heating effect and recombination losses, respectively.

The fundamental circuit layout of a solar panel is illustrated in Figure 4.

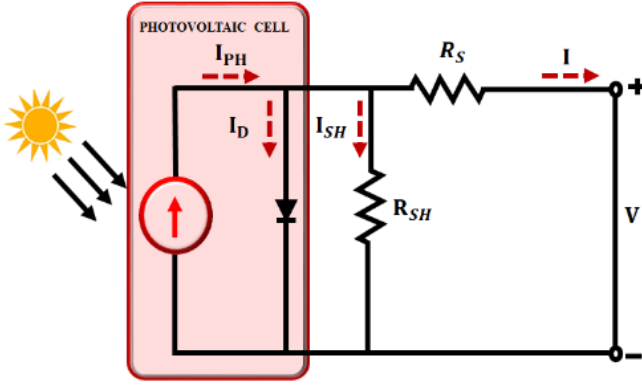


Fig. 4. Solar panel equivalent circuit.

According to Kirchhoff's law, current output of a PV cell is governed by the following expression:

$$I = I_{PH} - I_D - I_{SH} \quad (1)$$

The shunt current is defined as:

$$I_{SH} = \frac{V + R_S I}{R_{SH}} = \frac{V_D}{R_{SH}} \quad (2)$$

Where, (I) denotes output current of PV cell, (I_{PH}) and (I_D) represent the photocurrent and diode current, (I_{SH}) and (R_{SH}) refer to the shunt current and shunt resistance, (V) and (R_S) indicate the terminal voltage and series resistance.

The diode current is described by following equation:

$$I_D = I_S \left(e^{\frac{V_d}{nV_T}} - 1 \right) \quad (3)$$

Here, (I_S) is the reverse saturation current, (n) is the diode ideality factor, (V_T) is the thermal voltage, calculated as:

$$V_T = \frac{N_S k T_C}{q} \quad (4)$$

Where, (k) is Boltzmann constant, (q) is elementary charge, (N_S) is number of series-connected cells.

The reverse saturation current (I_S) is determined using the following relation:

$$I_S = I_{SN} \left(\frac{T_C}{T_{ref}} \right)^3 e^{\left(\frac{E_{go} \left(\frac{1}{T_n} - \frac{1}{T_C} \right)}{nk} \right)} \quad (5)$$

In this formula, eqn (5), (I_{SN}) is reverse saturation current at reference temperature (T_{ref}), (E_{go}) is energy band gap of semiconductor.

The short-circuit current (I_{CC}) and open-circuit voltage (V_{CO}) are used to express (I_{SN}) as:

$$I_{SN} = \frac{I_{CC}}{e^{\left(\frac{V_{CO}}{nV_T} \right)} - 1} \quad (6)$$

The photocurrent (I_{PH}) for any given irradiance (G) and cell temperature (T_C) is calculated by:

$$I_{PH} = \frac{G}{G_{ref}} I_{CC} + k_i (T_C - T_{ref}) \quad (7)$$

Where, (G_{ref}) and (T_{ref}) are the reference irradiance and temperature, (k_i) is the temperature coefficient of current.

Consequently, output current I of PV system is expressed as:

$$I = I_{PH} - I_S \left(e^{\frac{V_d}{nV_T}} - 1 \right) - \frac{V_D}{R_{SH}} \quad (8)$$

PV systems are designed to supply power to electrical loads. However, fluctuations in environmental conditions such as overcast skies or rainfall significantly impact the output voltage. To address this issue, the proposed system incorporates a high-efficiency converter aimed at boosting the output voltage and ensuring stable performance, as elaborated in the following section.

3.4. ExDoGBoost Converter

The proposed ExDoGBoost converter is developed for boosting the PV power with enhanced voltage gain, as depicted in Figure 5. The main concept of the ExDoGBoost converter is to utilize an additional capacitor–diode branch (C_1, D_2, D_3) combined with the boost inductor (L) and diode (D_1) to form an enhanced energy transfer cell, which doubles the voltage boosting capability.

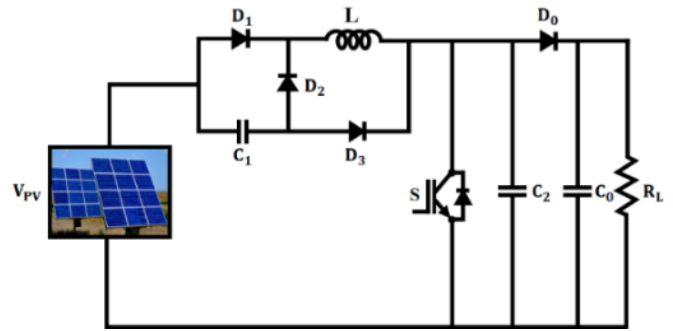


Fig. 5. ExDoGBoost converter.

In this configuration, the boost network is composed of (L, C_1), switch (S), and diodes (D_1) and (D_3). The extended voltage cell consists of capacitor (C_1) and diodes (D_2) and (D_3). During the ON-state of switch (S), the inductor (L_1) stores energy from PV source (V_{PV}), while capacitor (C_1) is charged through (D_2). When switch (S) turns OFF, (L_1) releases its stored energy in series with (C_1), transferring it through (D_0) to charge (C_2) and (C_0), thereby supplying the load (R_L). This coordinated energy transfer charging capacitors in parallel and discharging them in series enables the converter to achieve a significantly higher voltage gain compared to a conventional boost converter, while maintaining continuous input current and reduced voltage stress across the switch and diodes.

Proposed converter operates in two distinct switching modes within each switching -cycle, as illustrated in Figure 6 (a) and Figure 6 (b).

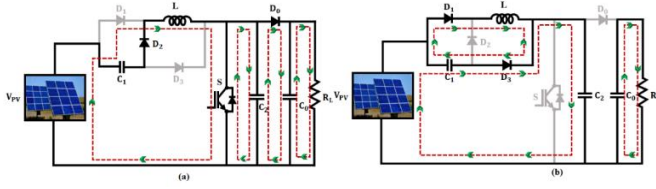


Fig. 6. (a) Mode 1 (b) Mode 2 operation of proposed ExDoGBoost converter.

Operating principle of proposed ExDoGBoost converter.

To simplify analysis, all components in the converter are assumed ideal. Inductor (L), capacitors (C_1, C_2, C_0) diodes (D_0, D_1, D_2, D_3) and load (R_L) are considered linear, time-invariant, and frequency-independent. Converter is analyzed under Continuous Conduction Mode (CCM), where inductor current never falls to zero during switching period T_s .

Mode 1: Switch ON State (S Conducting)

When main switch S is turned ON, diodes (D_1) and (D_3) are reverse-biased, while (D_2) and (D_0) becomes forward-biased, allowing capacitor (C_1) to be charged from the input PV source (V_{PV}). During this mode, Inductor (L) stores energy directly from (V_{PV}), capacitor (C_1) is charged via (D_2). Load (R_L) is supplied by discharge of capacitors (C_2) and (C_0) in parallel.

The inductor voltage during this interval is expressed as:

$$V_{L,ON} = V_{PV} \quad (9)$$

Capacitor (C_1) voltage increases as it charges.

Mode 2: Switch OFF State (S Open)

When switch S is turned OFF, energy stored in inductor (L) is released. Diodes (D_1) and (D_3) conduct, allowing inductor current to flow through (C_1) and in series with (V_{PV}). During this mode, inductor (L) discharges energy, which adds to (V_{PV}) and charges (C_2) and (C_0) through diode (D_0). Capacitor (C_1) discharges through (D_3), boosting the total transferred energy.

The effective series connection of (V_{PV}) and (C_1) produces a higher voltage at the output, providing a double-boost effect.

The inductor voltage during this interval becomes:

$$V_{L,OFF} = V_{PV} + V_{C1} - V_{C2} \quad (10)$$

The load is continuously powered by (C_0) during this phase, ensuring smooth voltage output.

Voltage Gain Derivation:

Applying the volt-second balance on the inductor (L):

$$V_{L,ON} \cdot DT_s + V_{L,OFF} \cdot (1 - D)T_s = 0 \quad (11)$$

Substituting $V_{L,ON}$ and $V_{L,OFF}$ and solving for V_{C1} and V_0 ,

$$V_{C1} = \frac{D}{1-D} V_{PV} \quad (12)$$

$$V_0 = V_{C2} = V_{PV} + V_{C1} = \frac{V_{PV}}{1-D} \quad (13)$$

Thus, the overall voltage gain of the ExDoGBoost converter is:

$$G = \frac{V_0}{V_{PV}} = \frac{1+D}{1-D} \quad (14)$$

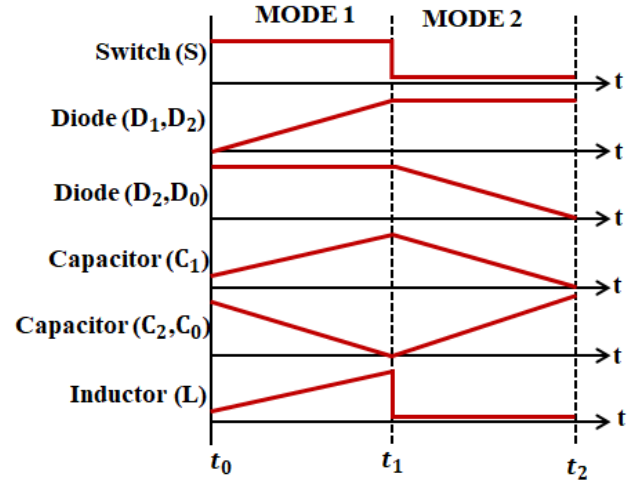


Fig. 7. Timing diagram.

Figure 7 displays the timing diagram, shows that the proposed converter achieves higher step-up capability compared to a conventional boost converter, while maintaining continuous current and reduced switch stress.

3.5. Giant Trevally Optimized PI Controller

For smooth converter operation in the proposed ExDoGBoost-based UPFC system, a PI controller is used for efficient DC voltage control. PI controller, works on the principle of smoothly controlling the system response after a fault or deviation from the reference is detected. The control sequence starts with the calculation of error signal, which is difference between desired set point and system's actual output. The Proportional (P) term is immediate in its action by multiplying the error with a proportional gain (K_p). Thus, it takes a corrective action proportional to the size of the deviation. This ensures an immediate response. The Integral (I) term, however, adds the history of past errors through the process of integration with an integral gain (K_i). This block removes steady-state error by ensuring persistent deviations are increasingly reduced.

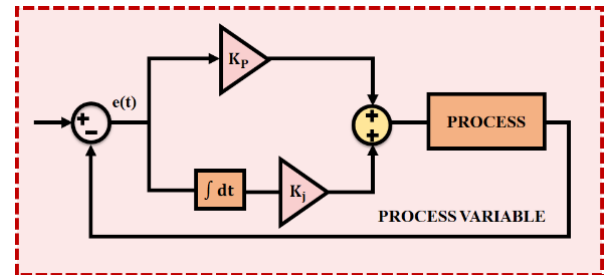


Fig. 8. PI controller circuit diagram.

Through the integration of the proportional and integral actions, the PI controller produces a control output signal that constantly leads the system to the reference value. The

generated control signal is given as a summation of the error and its integral, which guarantees inaccuracies decrease over time and the set point is held consistently. The overall structure is depicted in Figure 8, where the generated control signal is utilized to control the DC-link voltage and stabilize converter operation.

For further improvement in the controller robustness, the PI controller gains (K_p, K_i) are optimized by the GTOA, a population-based metaheuristic motivated by the intelligent and adaptive predatorial tactics of the giant trevally fish (also referred to as giant kingfish). Members of the jack family of predatory sea creatures, giant trevallies dominate their environments through highly adaptive predatorial methods. They are able to hunt singly or as coordinated hunting groups, with the dominant predator within a group typically being the most successful at catching prey.

One outstanding feature of the hunting tactic of giant trevallies is their prowess in jumping out of the water to ambush seabirds, thus showing intelligence, flexibility, and opportunism. This novel tactic has been mathematically formalized into the GTOA for optimization problem solving.

Like other metaheuristic methods, GTOA starts by generating a random population of potential solution candidates known as giant trevallies. Each candidate is a potential solution vector in the search space. The population matrix is written as,

$$X = \begin{bmatrix} X_1 \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix} = \begin{bmatrix} x_{1,1} & \cdots & x_{1,j} & \cdots & x_{1,Dim} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i,1} & \cdots & x_{i,j} & \cdots & x_{i,Dim} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{N,1} & \cdots & x_{N,j} & \cdots & x_{N,Dim} \end{bmatrix} \quad (15)$$

Here, X_i denotes the i^{th} candidate solution, N is the population size, Dim represents the number of decision parameters, and $x_{i,j}$ stands for value of j^{th} variable of i^{th} candidate solution. After initialization, population size and dimensions are fixed throughout optimization.

Every member is initially given a random position within the assigned search space to ensure complete coverage of feasible regions. This random initialization is controlled by:

$$X_{i,j} = Minimum_j + (Maximum_j - Minimum_j) \times R \quad (16)$$

Where, R is a uniformly distributed random number between $[0, 1]$, $Minimum_j, Maximum_j$ are lower and upper limits of the search space in the j^{th} dimension.

The performance of every candidate is assessed based on an objective function, in this study pertaining to reducing voltage deviation and control error. The objective function value vector is presented as:

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix} = \begin{bmatrix} F(X_1) \\ \vdots \\ F(X_i) \\ \vdots \\ F(X_N) \end{bmatrix}_{N \times 1} \quad (17)$$

Where, F_i is the fitness of the i^{th} candidate.

Exploration and Exploitation Phases of GTOA:

Hunting behaviour of the giant trevallies is simulated in three primary steps that are evenly balanced between exploration (global search) and exploitation (local tuning):

- Levy flight search on large scale
- Hunting ground selection
- Jumping exploit attack on prey

The broad-scale searches of trevallies for seabirds during the exploration phase are modelled by Levy flights, which enable large jumps and avoid premature convergence. This is represented as:

$$X(t+1) = Best_p \times R + ((Maximum - Minimum) \times R + Minimum) \times Levy(Dim) \quad (18)$$

Where, $X(t+1)$ is position at iteration $t+1$, $Best_p$ is best position so far, and $Levy(Dim)$ simulates random steps with heavy-tailed step lengths.

The Levy function is given as:

$$Levy(Dim) = step \times \frac{u \times \sigma}{|v|^{1/\beta}} \quad (19)$$

Where, $step = 0.01$, β is the Levy flight index (set to 1.5), and u, v are normally distributed random numbers between 0 and 1. The scaling parameter (σ) is calculated as:

$$\sigma = \left(\frac{\Gamma(1+\beta) \times \sin(\frac{\pi\beta}{2})}{\Gamma(\frac{\beta-1}{2}) \times \beta \times 2^{\frac{\beta-1}{2}}} \right) \quad (20)$$

In the second stage, trevallies choose the most favourable hunting area based on prey concentration. This adaptiveness is modelled mathematically as:

$$X(t+1) = BestP \times A \times R + MeanInfo - X_i(t) \times R \quad (21)$$

Where, A is a parameter (0.3–0.4) that governs position changes, and $MeanInfo$ is the population-average positional information, computed by:

$$MeanInfo = \frac{1}{N} \sum_{i=1}^N X_i(t) \quad (22)$$

Lastly, during exploitation, the attacking mechanism is emulated by simulating trevallies jumping out of the water and catching seabirds. This includes random distortions simulating visual refraction effects encountered during striking, to provide additional variability in the solution space.

Figure 9 visualizes flowchart of GTOA-PI control strategy depicts a biologically inspired method which adjusts the PI controller parameters in real time so as to control the DC, link voltage in the given power system. After measuring the actual DC, link voltage $V_{DC(act)}$ and setting a reference voltage $V_{DC(ref)}$, the error $e(t)$ is calculated as the difference between these two values. If the error goes beyond a predetermined threshold ϵ , the optimization procedure is activated. Starting PI parameters K_p and K_i are considered, and a population of individuals is created according to GTOA rules. The quality of each individual is determined through an objective function that reflects the performance, usually the minimization of voltage deviation and overshoot. At this point, the algorithm moves to the exploration phase, where it performs a global search using Levy flight operations to widen

the search area. If the number of iterations is not yet at the maximum, the process returns to the exploration again. After reaching the iteration limit, the algorithm goes to the exploitation phase, which includes the operations of hunting ground selection and jump attack in these trevally fish hunting behaviour is simulated, and local search is done by the PI parameters adjusting. The candidate solution with the highest fitness is chosen and the optimized K_p and K_i values are used to produce the final PI output. Such an adaptive tuning method ensures excellent voltage regulation, making it very appropriate for real-time power quality improvement in the envisaged smart UPFC system.

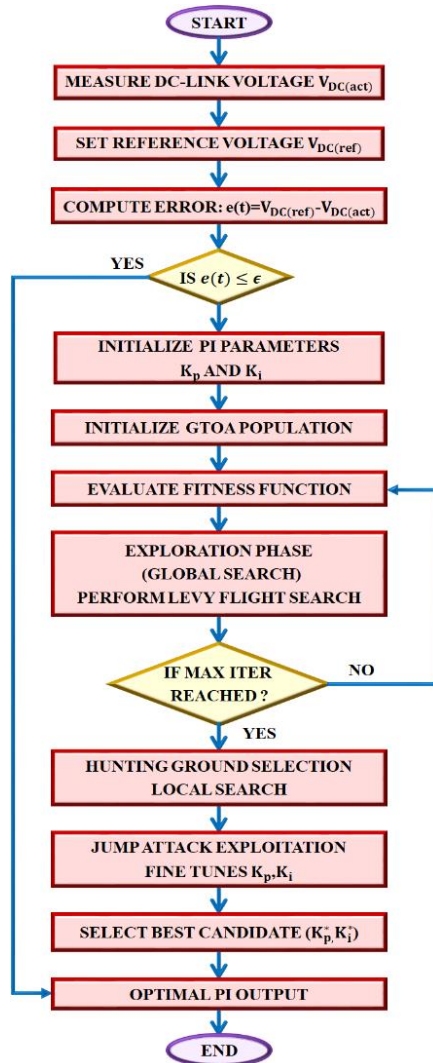


Fig. 9. Flowchart of GTOA-PI control algorithm.

4. Result and Discussion

This section presents a detailed account of the results obtained through MATLAB/Simulink simulation and experimental validation of the proposed framework. A comparative evaluation is also conducted against conventional methods, to demonstrate the superiority of the proposed topology. Furthermore, Table 2 outlines the parameter specifications used in the development and implementation of the system.

Table 2. Parameter specifications

Parameters	Values
PV System	
Open Circuit voltage	37.25V
Short Circuit current	8.95A
Number of cells connected in series	17
Number of cells connected in parallel	5
Rated Power	20kW
ExDoGBoost Converter	
Switching Frequency	10kHz
Inductor (L)	4.7mH
Capacitor (C_1, C_2)	22 μ F
Capacitor C_0	2200 μ F
UPFC	
Turns ratio	1:1
Resistance	0.28 Ω
Leakage Inductance	0.3mH
V_{dc}	600V
Z_{dc}	4700 μ F

Case 1: Constant Condition

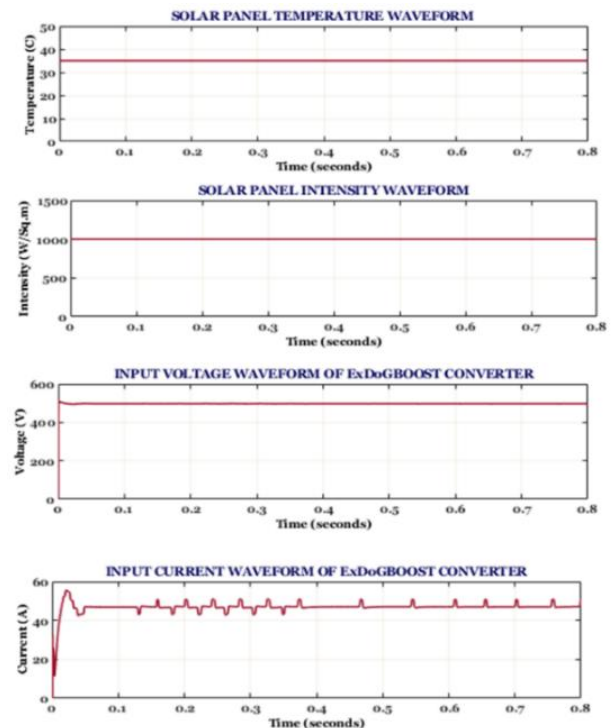


Fig. 10. PV system.

Figure 10 presents PV system response under constant temperature and intensity condition. The PV temperature waveform is constant at around 35°C during the observed time frame. This shows that the solar panel is working under constant ambient conditions without any temperature fluctuations. A constant temperature is good for PV efficiency, as high heat degrades performance. A constant level of irradiance of about 1000 W/m², which is optimum for solar panel performance. With constant irradiance, the solar panel provide a reliable power output, making it easy to design the control strategy for the UPFC system. The input voltage is

held constant at around 500V, which means that the converter is being fed a stable DC supply from the solar panel. This is what happens when temperature and irradiance are also constant, with the panel's output voltage levelling off accordingly. The input current is always approximately 50A, which shows a constant power consumption from the solar panel. This implies that the grid interaction or load demand is balanced and not changing at this time. A fixed current under constant voltage and irradiance conditions verifies that the system is operating in a steady-state mode. This is perfect for testing or baseline analysis, as the engineers can assess the behaviour of the converter without external interference.

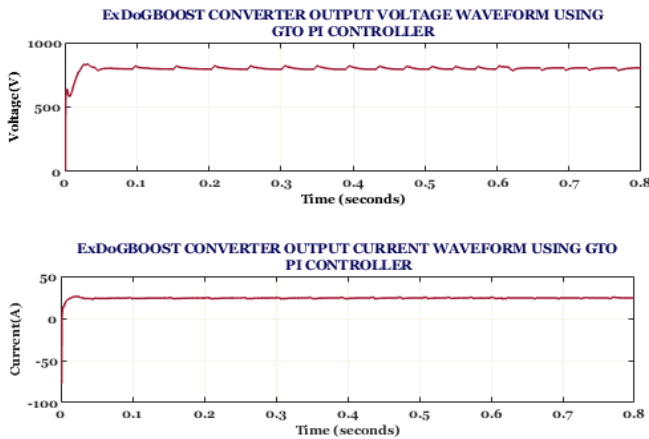


Fig. 11. ExDoGBoost converter.

Figure 11 represents the dynamic behaviour of the ExDoGBoost converter regulated by a GTO PI controller in an intelligent UPFC system for power quality improvement in a grid-connected PV system. The converter voltage graph starts with a short transient period before the output voltage settles to a constant value of 750V. When environmental conditions are kept constant the input to the converter is also constant, and the GTO PI controller rapidly drive the system to its set operating point. The transient describes the initial adjustment of the system, while the rapid settling is a demonstration to the precision and responsiveness of the controller. As with the voltage waveform, the graph of current displays a transient for a very brief moment followed by a stable output current 25A. This action verifies that the input power and load demand are balanced and that the converter is successfully controlling energy flow. The GTO PI controller makes sure the current settles at its desired value quickly and stays steady, which is vital for reliable power supply to the grid.

Case 2: Constant Temperature Varying Intensity Solar Panel Temperature Waveform

Figure 12 displays the PV array temperature, intensity, voltage and current waveform, where both temperature is maintained constant and varying intensity throughout depicted time duration of 0.8s. Temperature is kept constant at about 25°C and the irradiance starts at 800 W/m² and ramps to 1000 W/m² by approximately 0.4 seconds, then remains constant. This represents a real-world condition in which sunlight rises due to cloud movements or environmental variations. The

input voltage of the converter shows that, voltage is constantly maintained at 500V through entire time period with null fluctuations. The input current exhibits oscillating characteristics around 48A, with periodic ripples.

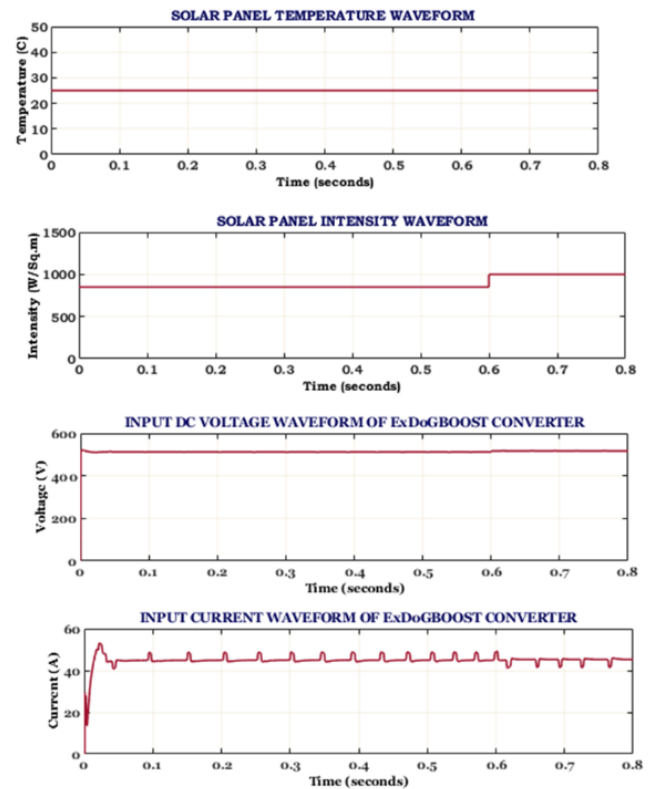


Fig. 12. PV array waveforms.

Figure 13 visualizes the behaviour of the proposed ExDoGBoost converter, controlled using GTO-PI controller, under constant temperature and varying intensity condition, for validating the converter abilities. Output voltage begins around 600V stabilizes and staying across 750V across the entire 0.8-s duration. This stability is impressive considering the fluctuating solar intensity, with temperature kept constant at 25°C, ExDoGBoost converter, driven by the GTO PI controller, effectively controls the output voltage.

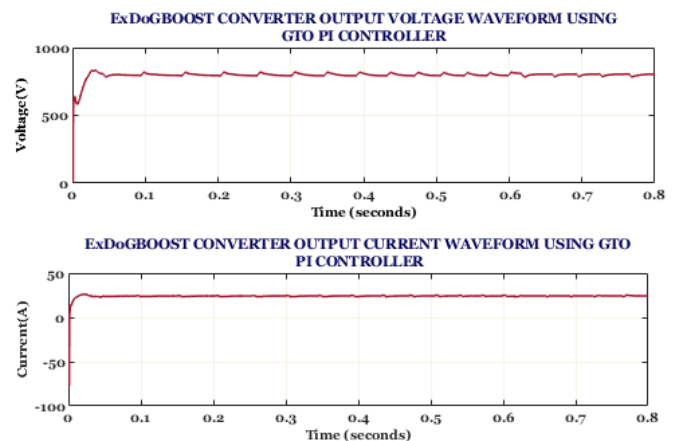


Fig. 13. Proposed ExDoGBoost converter.

The output current stays constant at 25A with minimal ripple, demonstrating the proposed converter's capacity to adjust to rising irradiance and maintain current supply smooth and consistent.

Case 3: Swell +2

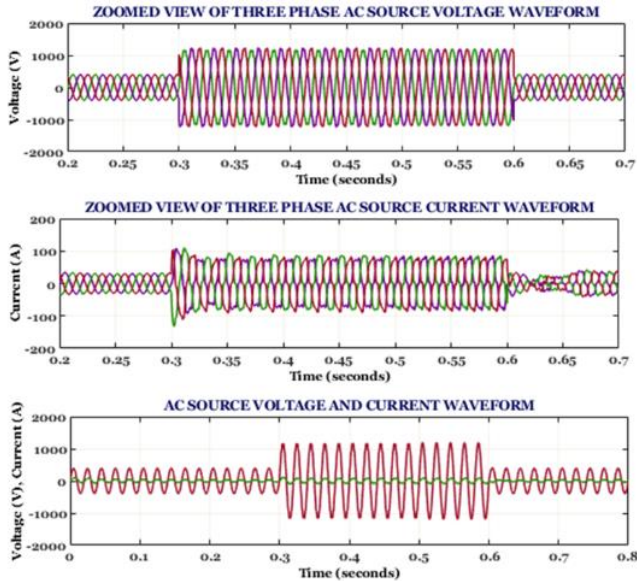


Fig. 14. Three-phase AC waveforms.

Figure 14 illustrates the behaviour of AC source voltage waveform in the swell condition. The three Phase AC source voltage and current with significant sag, which are maintained between $\pm 400V$ and $\pm 45A$ respectively. These distortions occurring is a result of the dynamic response of the converter to varying grid conditions. Nevertheless, the overall waveform is stable, indicating that the system is efficiently regulating power supply. The combined waveform indicates both voltage and current over a wider time period. In spite of the swell situation, voltage and current are closely coordinated and in phase, which is a definite indicator of power factor correction as well as harmonic suppression.

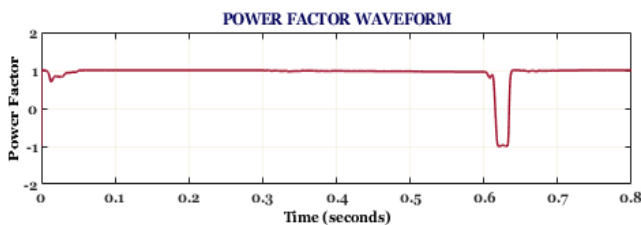


Fig. 15. Power factor.

Figure 15 demonstrates the power factor waveform describing how it behaves in swell, condition. The power factor waveform starts close to unity (1), which means the system is running efficiently with little reactive power. The beginning stability is a result of the UPFC keeping the voltage and current waveforms in synchronization under normal loads. The waveform takes a sharp drop to about -1 around 0.63 seconds, which is an indication of a transient disturbance here, the swell event. The negative indicates that the system temporarily entered a leading power factor condition, perhaps

due to overcompensation or reactive power flow reversal. The quick return of the power factor to close to unity at 0.65 seconds is due to the smarter control approach built into the UPFC.

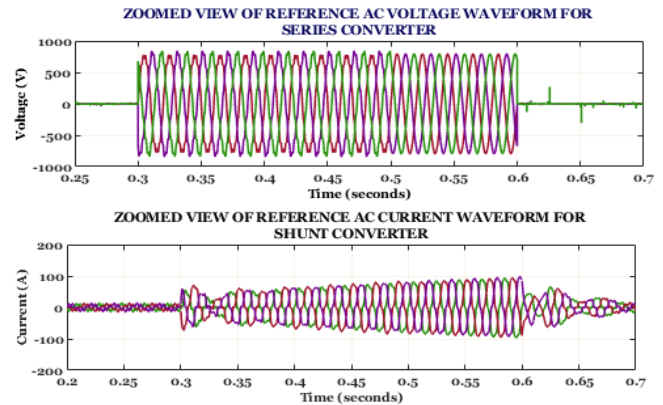


Fig. 16. Series and shunt converter.

Figure 16 indicates the reference AC voltage and current waveform of series and shunt converter under condition of swell. The reference AC voltage waveform of the series converter illustrates a high-frequency sinusoidal signal with amplitude modulation of up to $\pm 750V$, signifying that the series converter is actively injecting compensating voltage to compensate for the sag and stabilize the grid-side voltage. AC reference current waveform of the shunt converter indicates a sinusoidal waveform with amplitude fluctuations within $\pm 20A$, capturing the function of the shunt converter for reactive power assistance and harmonic reduction during sag conditions. These waveforms, illustrate the coordinated functioning of series and shunt converters, demonstrating UPFC system's ability to maintain voltage and current stability, damp disturbances, and improve overall power quality in real time.

Figure 17 shows three-phase load voltage and current waveforms in scenario SAG +2, disturbances in a grid-connected PV setup is exhibited by the system. In the three-phase load voltage waveform, sinusoidal signals with a clear disturbance around 0.3 seconds are shown. This fluctuation is equivalent to the SAG +2 event, in which the grid suffers a momentary reduction in voltage caused by external disturbances like fault conditions or rapid load changes. In spite of the sag, the waveform rapidly settles, reflecting the fact that the UPFC system, actively injecting counteracting voltage to bring load-side voltage back to normal. In three-phase load current waveform, there is a similar transient action in the same time interval. The current waveforms have a short fluctuation before they return to steady-state sinusoidal forms. The intelligent control strategy facilitates to make output change to ensure current stability, keep harmonic distortion suppressed, and assist in the dynamic demand of the load.

Figure 18 exhibits the response of the real and reactive power waveforms under voltage sag +2 condition. In the real power waveform, a steady power output initially attained followed by a sharp dip at about 0.3 seconds corresponding to the initiation of the SAG +2 event. This dip signifies a transient decrease in active power supply as a result of the

voltage dip produced by grid perturbations or load variations. In the reactive power waveform, high-frequency oscillations are observed within the same time frame, the reactive power injection to assist voltage recovery and stabilize the system.

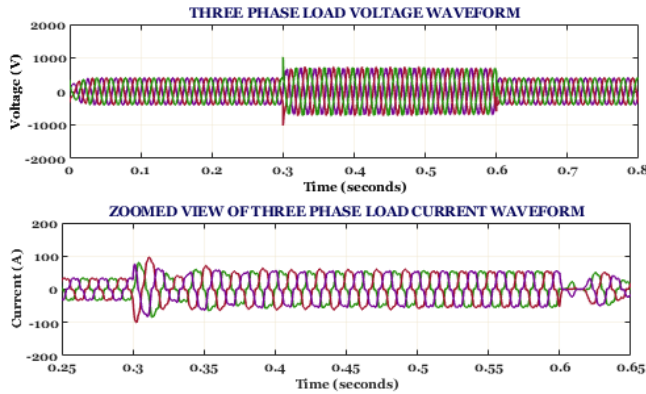


Fig. 17. Three-phase load waveforms.

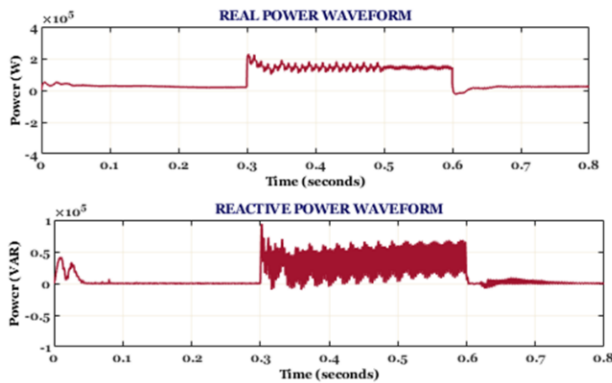


Fig. 18. Real and reactive power.

Case 4: SAG-2

Figure 19 presents the waveform of the dynamic responses of the proposed intelligent UPFC system under a voltage sag condition in a grid-connected PV setup. Three-phase AC source voltage waveform, shows a minor dip in amplitude pointing towards the initiation of the SAG-2 condition. In spite of this perturbation, the waveform is sinusoidal in shape and phase synchrony, which clearly shows the efficiency of the series converter in injecting compensating voltage. The ExDoGBoost Converter provides a stable DC-link voltage so that the series converter, react rapidly and regulate voltages. The PI controller optimized through the GTO algorithm helps improve further voltage regulation, such that there is little deviation from nominal values. The three-phase AC source current waveform demonstrates small amplitude variations across the sag interval, indicating DNN produces adaptive reference currents, enabling the shunt converter to dynamically adjust its output based on grid conditions.

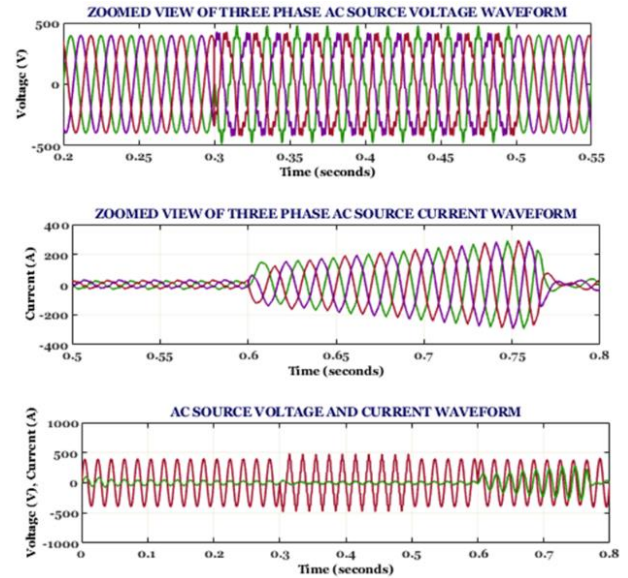


Fig. 19. AC source waveforms.

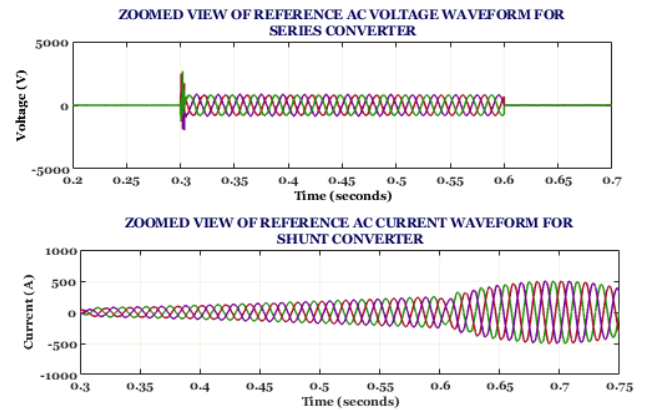


Fig. 20. Series and shunt converter waveforms.

Figure 20 represents the dynamic correction ability of the intelligent ExDoGBoost-enabled UPFC system in a grid-interfaced PV installation. Reference AC voltage waveform of the series converter, exhibits the sinusoidal waveform with high amplitude oscillations for the time period of 0.3 to 0.55 seconds. Reference AC current waveform of the shunt converter shows sinusoidal current starting off with low value and increasing over time and topping off this is in accordance with the response of the system to the SAG-2 condition when the grid voltage falls below nominal levels as a result of some disturbance. The smart control mechanism maintains the voltage waveform as sinusoidal and phase-synchronized, even under the sag occurrence, thus maintaining power supply integrity.

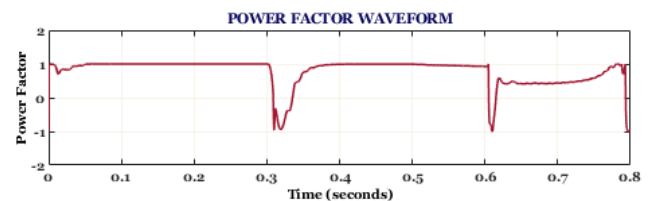


Fig. 21. Power factor.

Figure 21 displays the power factor waveform, an essential measure of the effectiveness with which electrical power is being consumed, and the oscillations under sag conditions indicate the system's capability to absorb and recover under stress. The UPFC system consisting of a series converter, shunt converter, and an ExDoGBoost is to actively control voltage and current, inhibit harmonics, and regulate reactive power. The control scheme is supplemented by a GTOA-based PI controller for DC-link voltage and a DNN for adaptive current output. In the PF waveform, steep changes are noticed and the fluctuations are highest near the sag event, showing the system attempting to compensate for the disparity between real and reactive power. The smart control system, however, learns to adapt very quickly, and the waveform starts stabilizing, showing the UPFC's ability to correct efficient use of power.

Figure 22 illustrates the impact of a voltage sag event on the three-phase electrical load and the corrective response of the Intelligent ExDoGBoost-enabled UPFC system integrated with a grid-connected PV source. In the three-phase load voltage waveform, the sinusoidal signals show clear disturbances around 0.3 and 0.7 seconds. These dips in amplitude are indicative of the SAG-2 condition, where the grid voltage momentarily drops below nominal levels. Despite these transients, the waveform quickly recovers, ensuring that the DC-link voltage remains stable and maintain voltage symmetry across all three phases. The three-phase load current waveform, similar disturbances with fluctuations in amplitude and waveform shape. The DNN generates adaptive reference currents, allowing the shunt converter to adjust its output dynamically in response to changing grid conditions. Waveform's recovery and return to a balanced sinusoidal form confirm the system's ability to suppress current distortion and maintain reliable power delivery.

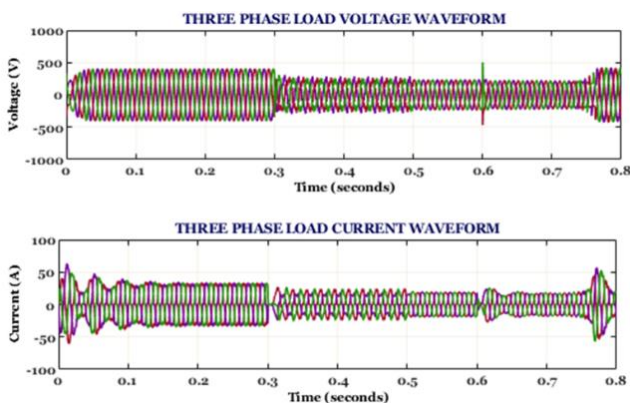


Fig. 22. Three-phase load.

Figure 23 visualizes behavior of real and reactive power waveforms during voltage sag event in a grid-connected PV environment. Voltage sag, typically caused by grid faults or sudden load changes, can significantly disrupt power flow and degrade power quality. The real power waveform, the plot initially shows a stable power output, indicating normal operating conditions. Around 0.3 seconds, a noticeable drop followed by oscillations occurs, marking the onset of the SAG-2 condition. This dip in real power is a direct

consequence of the voltage sag, which temporarily reduces the system's ability to deliver active power. In the reactive power waveform, a similar pattern is observed. The waveform begins with a steady reactive power level, followed by a drop and oscillations around 0.3 seconds. The proposed UPFC system, which integrates a ExDoGBoost, a GTOA-optimized PI controller, and a DNN, is designed to actively regulate voltage and current, suppress transients, and maintain system stability under such conditions.

Figure 24 demonstrates the analysis of harmonic distortion across three different scenarios, each represented by a frequency spectrum bar graph centered on a fundamental frequency of 50 Hz. In all three phases, the THD values are notably low 1.95%, 1.86%, and 1.71% respectively indicating effective suppression of harmonic components in the system. These results reflect the performance of the intelligent ExDoGBoost-enabled UPFC system in maintaining power quality within a grid-connected PV environment. This harmonic analysis validates the system's capability to reduce signal distortion, enhance waveform purity, and ensure stable and efficient power delivery in renewable-integrated networks.

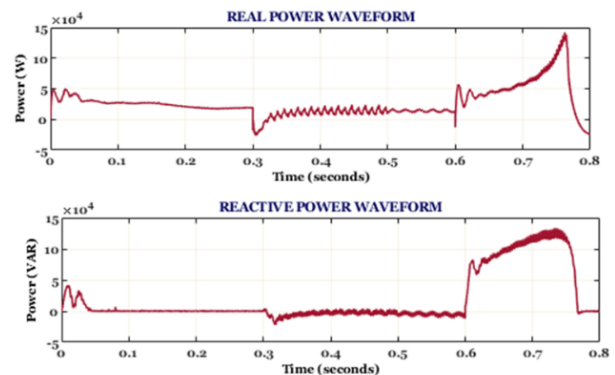


Fig. 23. Real and reactive power.

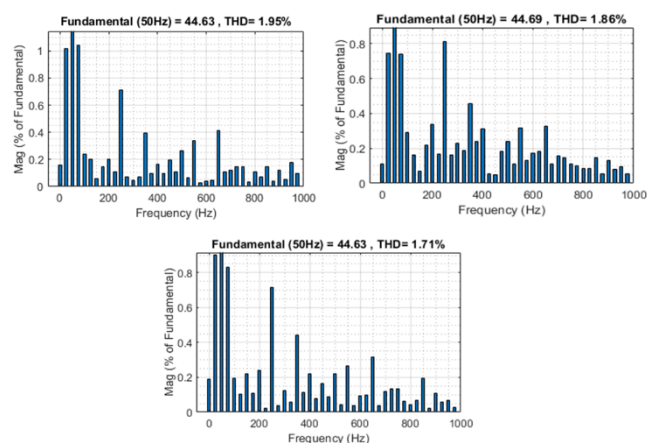


Fig. 24. THD waveforms.

5. Discussion

The simulation results presented in Section 4 vividly illustrate the outstanding functionality of the ExDoGBoost, powered UPFC as a versatile device in the power system. The

proposed system maintain steady voltage and current levels under constant solar conditions, thus acting as a reliable steady, state operation unit. In the face of a changing solar irradiance, the converter is able to keep the DC, link voltage at the desired level and delivers a current free of ripples, thus showing the fast response of the GTO, optimized PI controller. The integration of the series and shunt converters at the point of voltage swell and sag provides timely voltage compensation, reactive power support, and fast recovery of power factor. Furthermore, the low THD values at all phases attest to the effectiveness of the harmonic suppression technique. The simulation results, serve as a proof that the proposed intelligent UPFC is capable of voltage regulation, power factor, and power quality improvement, while being strongly resistant to PV and grid variations.

Figure 25 shows the comparison of the efficiency of various converter topologies, each with their respective efficiency ratings. Of all the converters listed, the proposed converter registers the best efficiency rate at 96%, indicating its superior energy conversion performance. The traditional DC-DC boost converter [27] at 92.40%, followed by the Switched Inductor Boost (S-I B) [28] converter at 94.30%, and

Interleaved Quadratic Boost (IQB) [29] converter reaches an efficiency of 94.80%.

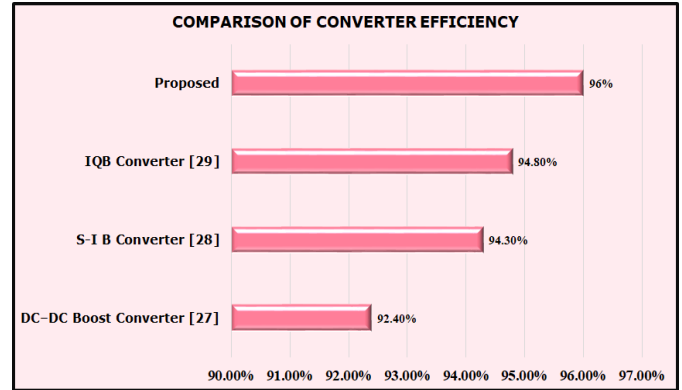


Fig. 25. Comparison of efficiency.

The enhanced performance of proposed converter is realized as a result of incorporating the extended double gain step-up into the boost converter, which ensures minimal power loss and maximum voltage gain under dynamic operating conditions.

Table 3. Comparative study of converter components

Converter Topologies	Switches	Diodes	Capacitor	Inductor	Total No.of components
DC-DC Boost [27]	2	2	5	5	14
IQB [29]	4	2	4	2	12
Proposed	1	4	3	2	10

Table 3 represents the comparison of different converter topologies in terms of number of components. Table compares the performance of DC-DC Boost [27], IQB [29] with proposed ExDoGBoost converter. The proposed converter exhibits high efficiency (96%) with fewer components and

provides high voltage gain with the use of soft-switching for minimizing losses. Such an efficient design performs better than the conventional techniques, highlighting its superiority for enhancing power quality in grid-connected PV based UPFC applications.

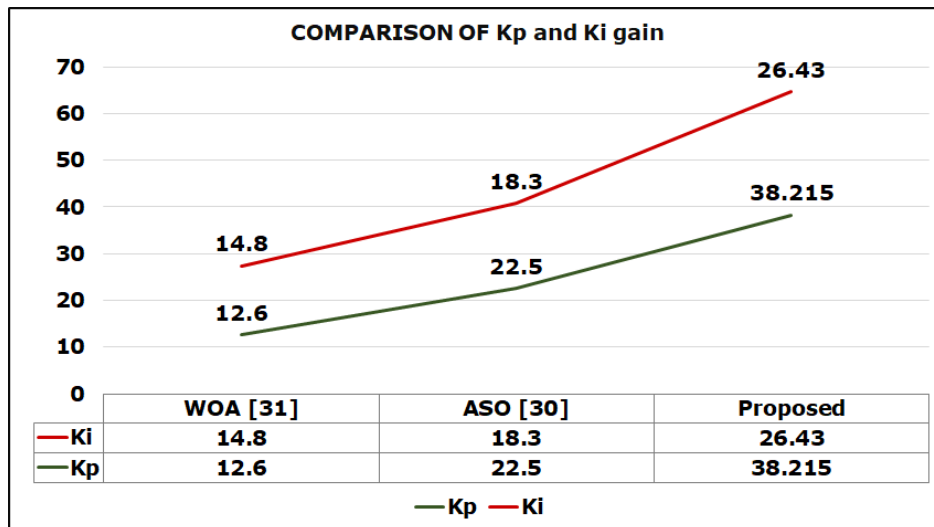


Fig. 26. Comparison of gain parameters.

Figure 26 exhibits the comparison of proportional (K_p) and integral (K_i) gains for different optimization control methods: WOA [26], ASO [25], and the proposed method. As indicated, the proposed method maximizes gain values at $K_p = 38.215$ and $K_i = 26.43$, demonstrating a more sensitive

and well-adjusted control system. Conversely, Atomic Search Optimization (ASO) [30] and Whale Optimization Algorithm (WOA) [31] provides the smallest gains, indicating a reduced response and possibly a less effective dynamic regulation.

Table 4. Comparative analysis of converter topologies

Converter	Voltage gain capability	Main active devices		Passive components		Switching Frequency	Relative efficiency
		Switch	Diode	Inductor	Capacitor		
Conventional boost	Medium	1	1	1	1	10kHz	Moderate
SEPIC converter	Medium-high	1	2	2	2	10kHz	Moderate
Cuk converter	Medium-high	1	1	2	2	10kHz	Moderate
Proposed ExDoGBoost	High	1	3	1	3	10kHz	High

Table 4, the efficiency assessment accounted for conduction, switching, and passive component losses for all converters at 10 kHz. Conventional Boost, SEPIC, and Cuk converters exhibited moderate efficiency levels, which were attributed to higher device stress and passive losses. By contrast, the ExDoGBoost, achieve a higher voltage gain and also reduce the ripple to a minimum. As a result, the ExDoGBoost attain better efficiency and lower losses than the other converters, thereby making it the most appropriate one for dynamic PV, UPFC applications.

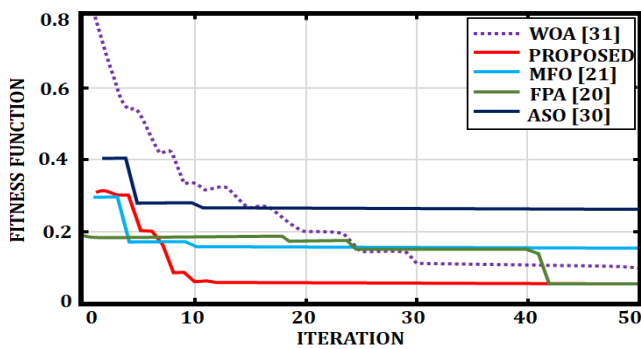


Fig. 27. Comparison of convergence.

Figure 27 displays the convergence characteristics of five optimization algorithms within 50 iterations, by comparing their fitness function values. Proposed The algorithm demonstrates the quickest and most stable convergence, as it achieves the lowest fitness value, which is a clear indication of the best optimization performance. On the other hand, WOA [31], MFO [21], FPA [20], and ASO [30] are showing slower convergence. Thus, it is concluded that the proposed method is very efficient and robust in terms of minimizing the objective function.

Figure 28 presents the dynamic performance of UPFC control methods, Fuzzy Logic Controller (FLC) [32], Fractional-Order Proportional–Integral–Derivative controller (FO-PID) [33], and the proposed DNN method on their settling time. The FLC [32] has the maximum settling time of 2.63 seconds and is indicative of slower system response and lagging stabilization. The FO-PID [33] is much better with a lesser settling time of only 0.64 seconds and is reflective of higher control accuracy and quicker convergence. The Proposed method beats both with an extremely low settling time of only 0.3 seconds. This higher performance is credited to the use of the DNN for adaptive current control in the intelligent UPFC system.

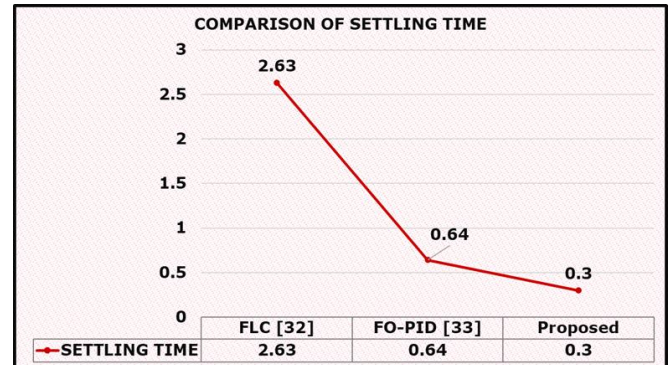


Fig. 28. Comparison of UPFC based controllers.

6. Conclusion

The proposed intelligent ExDoGBoost-enabled UPFC system provides a robust solution for mitigating critical power quality issues such as voltage sag, swell, and harmonic distortion in grid-connected PV environments. By integrating a UPFC architecture with coordinated series and shunt converters, the system achieves dynamic voltage regulation, reactive power compensation, and enhanced power flow management. The inclusion of the ExDoGBoost converter ensures high voltage gain and stable DC-link operation, even under fluctuating solar irradiance, thereby improving efficiency and reducing stress on switching devices. Furthermore, the GTOA-optimized PI controller delivers precise voltage regulation, while the DNN enhances adaptability by generating intelligent reference currents for responsive converter control. Simulation results validate the effectiveness of the proposed system, demonstrating a significant reduction in THD to 1.71%, improved power factor stability, minimized power ripple, and efficient recovery of real and reactive power during transient events. With a converter efficiency of 96% and reduced settling and rise times of 0.3 s, the system proves to be a reliable and scalable solution for renewable-integrated distribution networks. Overall, this research highlights the potential of combining advanced converter topologies with AI-driven control strategies to achieve sustainable, high-quality power delivery, paving the way for future applications in smart grids and large-scale renewable energy integration.

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Author Contributions

J. P. Srividhya: Conceptualization, Methodology, Writing-Original Draft.

D. Meena: Data Curation, Investigation, Validation.

S. Tamil Selvi: Formal Analysis, Visualization, Writing-Review & Editing.

R. Suresh: Supervision, Project Administration, Writing-Review & Editing.

Conflict of Interest

The authors declare no conflict of interest.

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APPENDIX A:

UPQC Principle of Operation

Fundamental working principle of UPFC is to inject a series voltage (V_s) with a certain magnitude and phase angle with respect to sending-end voltage (V_1). The line voltage is thus modified to:

$$V_2 = V_1 + V_s \quad (23)$$

This changes the effective transmission angle (δ), with both transmitted real power and reactive power controllable. The basic equations that determine power flow are:

$$P = \frac{V_s V_r}{X} \sin(\alpha - \beta) \quad (24)$$

$$Q = \frac{V_r}{X} (V_s - V_r) \quad (25)$$

Where, V_s and V_r are sending and receiving end voltages, (X) is reactance of a line, and (α, β) are phase angles.

The transmitted power and reactive power with injected voltage are given by:

$$P = P \left(P - \frac{V_r}{X} \sin \delta \right), Q = Q_r \left(Q - \frac{V_r}{X} (1 - \cos \delta) \right) \quad (26)$$

For general modelling, the injected power and voltage constraints are given by:

$$V_{pq} = \Delta V + V_\sigma + V_q \quad (27)$$

$$Q_r \{Q_r(\delta) - 1\}^2 + \{P_o(\delta)\}^2 = 1 \quad (28)$$

When there is no series injection ($V_{pq} = 0$):

$$P = jQ_r = V_r \left(\frac{V_s - V_r}{jX} \right) \quad (29)$$

With series injection ($V_{pq} \neq 0$):

$$P = jQ_r = V_r \left(\frac{V_s - V_r}{jX} + \frac{V_r V_{pq}}{-jX} \right) \quad (30)$$

Sending and receiving end voltages in phasor form are:

$$V_s = V e^{j\delta/2} = V \left(\cos \frac{\delta}{2} + j \sin \frac{\delta}{2} \right) \quad (31)$$

$$V_r = V e^{-j\delta/2} = V \left(\cos \frac{\delta}{2} - j \sin \frac{\delta}{2} \right) \quad (32)$$

And the injected series voltage in phasor form is:

$$V_{pq} = V_{pq} e^{j(\delta/2 + \rho)} = V_{pq} \left(\cos \left(\frac{\delta}{2} + \rho \right) - j \sin \left(\frac{\delta}{2} + \rho \right) \right) \quad (33)$$

APPENDIX B:

DEEP COUPLED NETWORK

The dynamic relationship between the synthetic input vector $u(s)$, and the system output vector $y(s)$ is expressed as

$$y(s) = G_p(s)D(s) \cdot u(s) \quad (34)$$

Where, $G_p(s)$ is scaled process transfer function matrix of PV-UPFC system and $D(s)$ is the decoupling matrix that projects the original inputs to synthetic inputs. For a two-variable case, the relation can be expressed as:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = G_p(s)D(s) \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \quad (35)$$

Here, $y_1(s)$ and $y_2(s)$ equal to control values like bus voltage amplitude and harmonic distortion factor, whereas $u_1(s)$ and $u_2(s)$ are the control input signals extracted from UPFC converters.

A perfect decoupler is given by:

$$D(s) = \begin{bmatrix} \tilde{g}_{11}(s) & 0 \\ 0 & \tilde{g}_{22}(s) \end{bmatrix} \quad (36)$$

Which shows that every control channel is totally decoupled. In actual grid-connected systems, precise process modelling is difficult because of nonlinearities, parameter uncertainties, and time-varying disturbances. Therefore, a reduced decoupler is employed:

$$D(s) = \begin{bmatrix} 1 & d_{12}(s) \\ d_{21}(s) & 1 \end{bmatrix} \quad (37)$$

By multiplying the process transfer matrix with this reduced decoupler, the resulting decoupled process dynamics are:

$$G_p(s)D(s) = \begin{bmatrix} g_{11}^*(s) & 0 \\ 0 & g_{22}^*(s) \end{bmatrix} \quad (38)$$

Where, the decoupling terms are computed as:

$$d_{12}(s) = \frac{\tilde{g}_{12}(s)}{\tilde{g}_{11}(s)}, d_{21}(s) = \frac{\tilde{g}_{21}(s)}{\tilde{g}_{22}(s)} \quad (39)$$

The compensated diagonal terms are derived as:

$$g_{11}^*(s) = \tilde{g}_{11}(s) - \frac{\tilde{g}_{12}(s)\tilde{g}_{21}(s)}{\tilde{g}_{22}(s)}, g_{22}^*(s) = \tilde{g}_{22}(s) - \frac{\tilde{g}_{21}(s)\tilde{g}_{12}(s)}{\tilde{g}_{11}(s)} \quad (40)$$

The decoupled outputs are subsequently expressed as:

$$y_1(s) = g_{11}^*(s)u_1(s), y_2(s) = g_{22}^*(s)u_2(s) \quad (41)$$

Equation (41) evident that each synthetic input only affects its corresponding output, which forms the basis of the developed DNN strategy. This enables the UPFC to be regulated as a collection of decoupled loops instead of as a highly coupled nonlinear system, greatly easing controller design