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Research Paper

Comparison of PI and PID Controllers for UPQC Integrated Hybrid Renewable Energy System

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Abstract

Unified Power Quality Conditioner (UPQC) plays a key role in improving power quality by alleviating voltage and current troubles in electrical distribution systems. The ability of UPQC to respond effectively to power quality turbulences is essentially determined by its control technique. The proportional-integral (PI) and proportional-integral-derivative (PID) controllers are the two most popular control techniques for UPQC. The primary objective of this article is to present a comparative analysis of UPQC performance using PI and PID controllers. The proposed system integrates a photovoltaic system, wind turbine and battery energy storage with UPQC. The PI and PID controllers are employed to regulate the dynamic response of the system. The comparative analysis of the controllers is done on the basis of qualitative parameters such as current response, voltage stability, fast fourier transform (FFT) analysis, step response and quantitative parameters such as total harmonic distortion, maximum overshoot, settling time, power factor, voltage regulation and DC-link deviation. Qualitatively, PID offers smoother current and voltage responses, stronger damping, better harmonic mitigation, and faster transient recovery. Quantitatively, the PID achieves 48% lower THD, 50% reduction in overshoot, halved settling time, improved power factor (0.99 vs. 0.95), and improved voltage regulation (1.7% vs. 4.2%).

Keywords: *pi controller; pid controller; power quality; renewable energy; unified power quality conditioner.*

Introduction

The efficiency and dependability of power systems are severely weakened by power quality issues such as voltage sags, swells, harmonics and unbalanced circumstances (Choudhury & Sahoo, 2024). Numerous specialized power devices have been suggested to lessen these disruptions; nevertheless, the unified power quality conditioner (UPQC) has drawn a lot of interest because of its capacity to manage both voltage and current related problems at the same time (Elkasem et al., 2024). Recent research has demonstrated how well UPQC works to compensate for harmonics, maintain steady voltage profiles and enhance system performance under dynamic load scenarios (Ranjan & Choudhary, 2024). The performance of UPQC is largely determined by its control method (Jeevanantham & Srinath, 2022). Due to their dependability and simplicity of use, traditional controllers like proportional-integral (PI) and proportional-integral-derivative (PID) are frequently chosen (Trivedi et al., 2024). PI controllers are widely used in shunt active filters for harmonic reduction and DC-link voltage regulation (Saggu et al., 2018). PID controllers extend the capabilities of PI by incorporating a derivative component, which enhances the transient response and stability of the system (Srilakshmi et al., 2025).

Several studies have demonstrated that PID-based control can achieve faster settling time, reduced overshoot, and better disturbance rejection in active power filter and UPQC applications (Srilakshmi et al., 2025). (Alqahtani et al., 2020) examined PI and PID controllers for engine speed control, concluding that PID outperformed PI in transient response and overshoot reduction; however, their work did not address power quality (PQ) applications. (Borase et al., 2021) provided a comprehensive review of PID tuning methods, highlighting advantages and limitations across various control systems, though the study remained mostly theoretical without real-time PQ validation. (Izci et al., 2022) integrated PID with artificial ecosystem optimization in a buck converter, achieving faster settling time and reduced overshoot, yet the focus was restricted to converters without UPQC applications. (Nikkhah Kashani, 2022) proposed a cascade non-integer

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controller within a UPQC framework and demonstrated superior harmonic suppression compared to conventional PI, though only the shunt part was analyzed without a complete UPQC study.

Similarly, (Soomro et al., 2022) compared PID and sliding mode controllers (SMC) for a matrix-converter-based dynamic voltage restorer (DVR), finding that SMC enhanced robustness under parameter variations; however, their analysis was limited to simulations without hardware implementation. Ucchas et al., (2022) investigated PI and PID controllers for a single-phase pulse width modulated (PWM) inverter in MATLAB/Simulink, reporting that PID achieved faster transient response and lower steady-state error, though the scope was confined to inverter-level studies. Nicola et al., (2023) compared proportional integral-grey wolf optimization (PI-GWO), fractional order proportional integral derivative (FOPID) and reinforcement learning-based controllers for UPQC under nonlinear loads, showing that FOPID yielded better THD reduction and faster dynamics than PI-GWO, but only in simulation with limited disturbance types.

Table 1 Summary of related works on UPQC control

Authors / Year	Controller(s) Used	Application / Test Case	Main Findings	Limitations / Gaps
Alqahtani et al., 2020	PI, PID	Engine speed control	PID superior in transient and overshoot reduction	Not in power electronics; lacks application to power quality devices
Borase et al., 2021	Review of PID tuning methods	Various control systems	Comprehensive PID tuning analysis; highlighted strengths and limitations	Mostly theoretical; few comparative studies on real-time PQ applications
Izci et al., 2022	PID with artificial ecosystem optimization	Buck converter	Optimization improved PID performance, faster settling, reduced overshoot	Focused on converter only; no UPQC context
Nikkhah Kashani, 2022	Cascade non-integer controller	Shunt Active Filter in UPQC framework	Achieved superior harmonic suppression versus conventional PI	Focused only on shunt part; no complete UPQC comparative study
Soomro et al., 2022	PID and SMC	Matrix-converter-based DVR	SMC improved robustness vs PID under parameter variations	Simulation only; hardware study missing
Ucchas et al, 2022	PI and PID	Single-phase PWM inverter	PID controller provided faster transient response and lower steady-state error than PI	Limited to inverter-level study; not extended to full UPQC; no hardware implementation
Nicola et al., 2023	PI–GWO, FOPID	UPQC with nonlinear loads	FOPID controllers achieved lower THD and faster dynamic response than PI-GWO	Simulation only; no hardware validation; limited disturbance types
Aldosary, 2024	FOPID	PQ compensation in distribution networks	FOPID improved transient and steady-state performance over PID	Tuning complexity; practical implementation unaddressed
Joshi et al., 2024	PI, ANN	DVR under nonlinear loads	ANN showed better voltage quality improvement than PI	Comparative study limited to DVR; no PID benchmark
Kakani et al., 2024	PI, PID	Coupled tank systems	PID better for level and flow control; faster dynamic response	Industrial process control; not power electronics; no UPQC relevance
Singh et al., 2024	ANN	Dual-phase UPQC, adaptive neural network tuning	Improved adaptivity to load variations; reduced THD and faster response	AI methods increase complexity; no PI versus PID baseline comparison
Yu et al., 2024	PI with different PLL schemes	UPQC under phase-locking variations	Advanced PLL and PI enhanced stability and sag/swell compensation	Focus only on PLL impact; PI tuning unchanged; no comparative benchmarking
Warrier et al., 2024	Complex-order PI	DC-DC converters	Improved control performance versus standard PI; better robustness to load variations	Focused only on converters; PI versus PID comparison limited

Aldosary, (2024) employed FOPID for PQ compensation in distribution networks, improving both transient and steady-state performance over PID, yet tuning complexity and practical implementation were unaddressed. Joshi et al., (2024) analyzed PI and artificial neural network (ANN) controllers for DVR applications, where ANN provided superior voltage quality improvement, but lacked a PID benchmark comparison. (Kakani et al., 2024) tested PI and PID in coupled tank

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systems, demonstrating PID's superiority in dynamic response, although the work was unrelated to PQ or UPQC. Recent literature explores non-linear and AI-assisted controllers (Singh et al., 2024; Yu et al., 2024; Warrier et al., 2024), reporting improved transient performance and THD reduction in simulation; however, these studies are often simulation-centric and lack standardized benchmarking and experimental validation. Table 1 shows the summary of literature review on UPQC control.

Research Gaps and Motivation

Recent literature explores non-linear and AI-assisted controllers, reporting improved transient performance and THD reduction in simulation; however, these studies are often simulation-centric and lack standardized benchmarking and experimental validation. From the reviewed literature, several gaps are identified:

1. Lack of a comprehensive comparative analysis of PI and PID controllers applied to UPQC under identical conditions.
2. Limited focus on evaluating both steady-state and dynamic responses of controllers in power quality enhancement.
3. Insufficient exploration of the practical implications of controller selection for real-world power systems.

These gaps motivate a systematic comparative assessment of PI and PID controllers under a unified benchmark including both steady-state and dynamic metrics, which is the focus of the paper. This paper provides a systematic comparative assessment of PI and PID controllers in UPQC integrated hybrid renewable energy system. A photovoltaic system, wind turbine and battery energy storage system are all integrated with UPQC in the suggested system.

Control Structure of UPQC

The control structure of UPQC for analysis of voltage and current disturbances in PQ issues is shown in Figure 1. On the utility side of a dynamic smart grid, this study's research technique replicates PQ problems (Yadav & Yadav, 2023; Saggu et al., 2017). The focus is on using UPQC to operate in an effective manner to manage PQ concerns such as voltage sag, swell, disturbances and total harmonic distortion. As seen in Figure 1, two filters are used to control voltage and current fluctuations make up the UPQC. Series active power filter (APF) handles voltage PQ problems, whereas shunt APF manages current disturbances in the smart grid (SG) structure. $V^{abc}\ and\ I^{abc}$represent the three phase voltages and current. The series compensation voltage V_{se}^{abc} and shunt compensation current I_{sh}^{abc} are estimated by comparing the supply voltages and currents with reference voltages and currents. The dc-link voltage V^{dc} is maintained with a suitable control algorithm (Rekioua et al., 2023). The control architectures for series control, shunt control and dc-link voltage control are described below.

Control Strategy for Shunt Active Power Filter

The shunt active power filter functions as a controlled current generator, providing reactive power and current correction. Its role is to compensate for the load current, ensuring that the source currents drawn from the network become sinusoidal, balanced and synchronized with the positive-sequence system voltages, thereby compensating for current disturbances like sag, swell and harmonics.

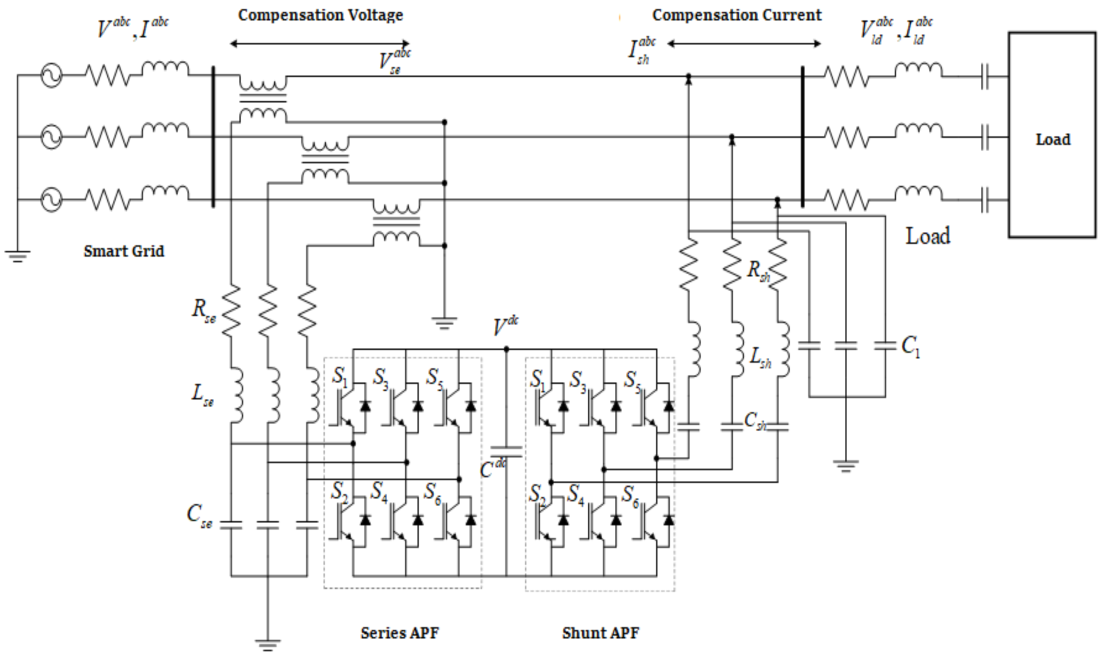

Figure 1 Control structure of UPQC

Clark's Transformation (Prasad et al., 2022) is used to convert the three-phase voltages and currents into λ and μ components as represented by Eq. (1) and Eq. (2).

$$\begin{bmatrix} V_{sup}^{0} \\ V_{sup}^{\lambda} \\ V_{sup}^{\mu} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sup}^{a} \\ V_{sup}^{b} \\ V_{sup}^{c} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_{sup}^{0} \\ V_{sup}^{\lambda} \\ V_{sup}^{\mu} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sup}^{a} \\ V_{sup}^{b} \\ V_{sup}^{c} \end{bmatrix} \tag{2}$$

V_{sup}^{λ}, V_{sup}^{μ} are the phase neutral supply voltages and I_{ld}^{λ}, I_{ld}^{μ} are the phase neutral load currents. V_{sup}^{a}, V_{sup}^{b}, V_{sup}^{c} are the three phase supply voltages and I_{ld}^{a}, I_{ld}^{b}, I_{ld}^{c} are the three phase load currents. The instantaneous values of power are computed using phase neutral supply voltages and load currents. Eq. (3) and Eq. (4) are used to compute the real and reactive powers and the expression for the reference currents respectively (Gulzar et al., 2023).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_{sup}^{\lambda} & V_{sup}^{\mu} \\ -V_{sup}^{\mu} & V_{sup}^{\lambda} \end{bmatrix} \begin{bmatrix} I_{ld}^{\lambda} \\ I_{ld}^{\mu} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{ld}^{\lambda} \\ I_{ld}^{\mu} \end{bmatrix} \tag{4}$$

I_a^*, I_b^*, I_c^* are the reference currents for shunt active power filter. The erroneous current, which must be corrected with the aid of PI or PID controller and control algorithm that produces the pulses needed by the shunt active power filter, is calculated by comparing the reference current.

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Control Strategy for Series Active Power Filter

The series active power filter offers voltage compensation by producing a compensation voltage using the pulse width modulated converter. This voltage is introduced in series with the supply voltage to ensure sinusoidal and balanced voltage at the point of common coupling (PCC). The compensatory capabilities of the UPQC device rely on the optimal regulation of the dc connection voltage. The direct-quadrature (d-q) axis are created using the Clark's transformation (Lei et al., 2022) as shown by Eq. (5).

$$\begin{bmatrix} V^0 \\ V^d \\ V^q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sin(\lambda t) & \sin(\lambda t - \frac{2\pi}{3}) & \sin(\lambda t + \frac{2\pi}{3}) \\ \cos(\lambda t) & \cos(\lambda t - \frac{2\pi}{3}) & \cos(\lambda t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V^a \\ V^b \\ V^c \end{bmatrix} \tag{5}$$

V^a, V^b, V^c represent the three phase voltages and V^d, V^q are the direct axis and quadrature axis voltages. Eq. (6) expresses the smoothed direct axis voltage which is obtained with the use of a low pass filter.

$$V_{dc}^d = V^d - V_{ac}^d \tag{6}$$

V_{ac}^d, V_{dc}^d are the voltages of the ac component and dc component, respectively. After that, three phase reference voltages are generated using Eq. (7).

$$\begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\lambda t) & \frac{1}{2} & \frac{1}{2} \\ \sin(\lambda t) & \sin(\lambda t - \frac{2\pi}{3}) & 1 \\ \cos(\lambda t) & \cos(\lambda t - \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_{dc}^d \\ V^q \\ V^0 \end{bmatrix} \tag{7}$$

V_a^*, V_b^*, V_c^* are the reference voltages for series active power filter. The necessary control pulses are then generated utilizing the PI or PID controller.

DC-Link Voltage Control

The DC-link voltage is crucial as its variations during transients (like sag or swell) impact the series injected voltage and consequently, the load voltage magnitude. An enhanced sinusoidal pulse width modulated voltage controller is recommended for the series compensator, which continually adjusts the amplitude modulation ratio in response to changes in the DC-link voltage. Furthermore, an adaptive DC-link voltage controller is proposed to limit the deviation during transient events and maintain a small steady-state error (Alajrash et al., 2024).

Basics of PI and PID Controllers

The UPQC is a radical power electronic device designed to mend power quality by concurrently compensating voltage and current turbulences. It incorporates a series APF and a shunt APF to accomplish voltage-related problems and load current alterations, respectively. This dual compensation mechanism makes the UPQC an effective solution for safeguarding stable and high-quality power transfer. The efficiency of UPQC operation is basically governed by its control strategy, which defines its capability to react to power quality turbulences efficiently (Yadav et al., 2020). The two most commonly used control strategies for UPQC are PI and PID controllers. The PI controller comprises of a proportional component, which make sure abrupt response to errors and an integral component, which reduces steady-state errors over time. The output of a PI controller is the sum of two gain parameters (K_P and K_I) , is expressed by Eq. (8) (Venkatesan et al., 2024).

$$U_{PI} = K_P E + K_I \int E dt \tag{8}$$

Here, U_{PI} is the PI controller output.

On the other hand, the PID controller outspreads the PI control mechanism by adding a derivative component, which heightens system sensitivity to dynamic turbulences. The derivative component foretells error deviations, allowing faster rectifications and refining transient stability. The result of a PID controller is the sum of three gain parameters (K_P, K_I and K_D), is expressed by Eq. (9) (Yadav et al., 2020).

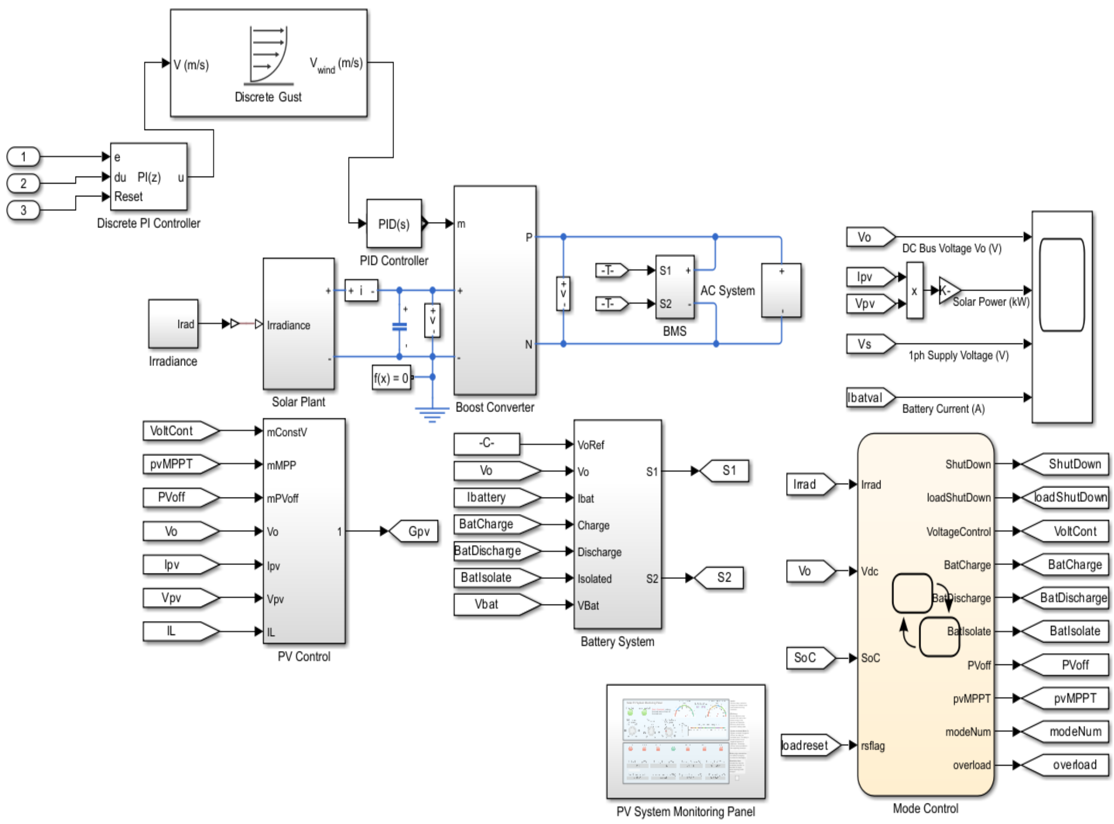
$$U_{PID} = K_P E + K_I \int E dt + K_D \frac{dE}{dt} \tag{9}$$

Here, U_{PID} is the PID controller output. Where K_P, K_I and K_D are proportional, integral and derivative gain parameters, respectively. E is an error signal (Hazarathaiah et al., 2023).

Results

This section presents the results obtained from the simulations performed in MATLAB/Simulink using the proposed system. Figure 2 illustrates the proposed system which is an integration of UPQC with a renewable energy system, incorporating PI and PID control mechanisms to regulate power quality parameters effectively. The proposed system consists of a PV module, wind system and battery management system (BMS), boost converter, mode control and AC system, all working together to ensure stable power delivery. The discrete PI controller is used to regulate wind speed variations, ensuring that wind energy inputs remain stable. It takes error signals and processes them through a PI control loop, adjusting system parameters accordingly.

The PID controller further refines the control by incorporating a derivative term, which helps in reducing overshoot and improving response time. This controller manages the boost converter, which regulates the DC voltage output from the solar plant and battery system, ensuring a consistent power supply. The solar plant module generates power based on irradiance levels, which are monitored and controlled through PV control logic. The generated power is given to the boost converter to step up the voltage to the essential level. The battery system, connected through the BMS, manages charging, discharging and isolation of the energy storage to ensure efficient energy utilization. The mode control unit is responsible for managing system operations, including shutdown, load balancing and voltage control. It ensures smooth integration between solar power, battery storage, and AC system loads, stabilizing the DC bus voltage and mitigating fluctuations. The PV system monitoring panel provides real-time data visualization, allowing users to track system performance.



UPQC WITH PI and PID

Figure 2 UPQC with PI and PID Controllers

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Table 2 presents the MATLAB/Simulink parameters used for the proposed system.

Table 2 MATLAB/Simulink parameters

Block/Component	Parameter	Rating
	Supply Voltage (Line-to-Line, RMS)	415 V
	Grid Frequency	50 Hz
System	Source Impedance	R = 0.01 Ω, L = 2 mH
	Load Type	Nonlinear (5 kVA)
	Load Resistance	20 Ω
	Load Inductance	50 mH
DC-Link Capacitor	Capacitance	2200 µF
	Reference DC-Link Voltage	700 V
PV Module	Rated Power	5 kW
	Irradiance	1000 W/m² (variable)
	Temperature	25 °C
	Rated Power	5 kW
Wind Turbine	Rated Wind Speed	12 m/s
	Cut-in Wind Speed	3 m/s
	Cut-out Wind Speed	25 m/s
Battery	Rated Voltage	400 V
	Capacity	50 Ah
	State of Charge Limits	20–80%
	Switching Frequency	10 kHz
Converters and Controllers	Series APF Filter Inductance	2.5 mH
	Shunt APF Filter Inductance	2 mH
Controller Parameters	PI Controller	Kp = 0.5, Ki = 30
	PID Controller	Kp = 0.8, Ki = 40, Kd = 0.01

The flow chart of the implementation of the proposed technique is represented by Figure 3.

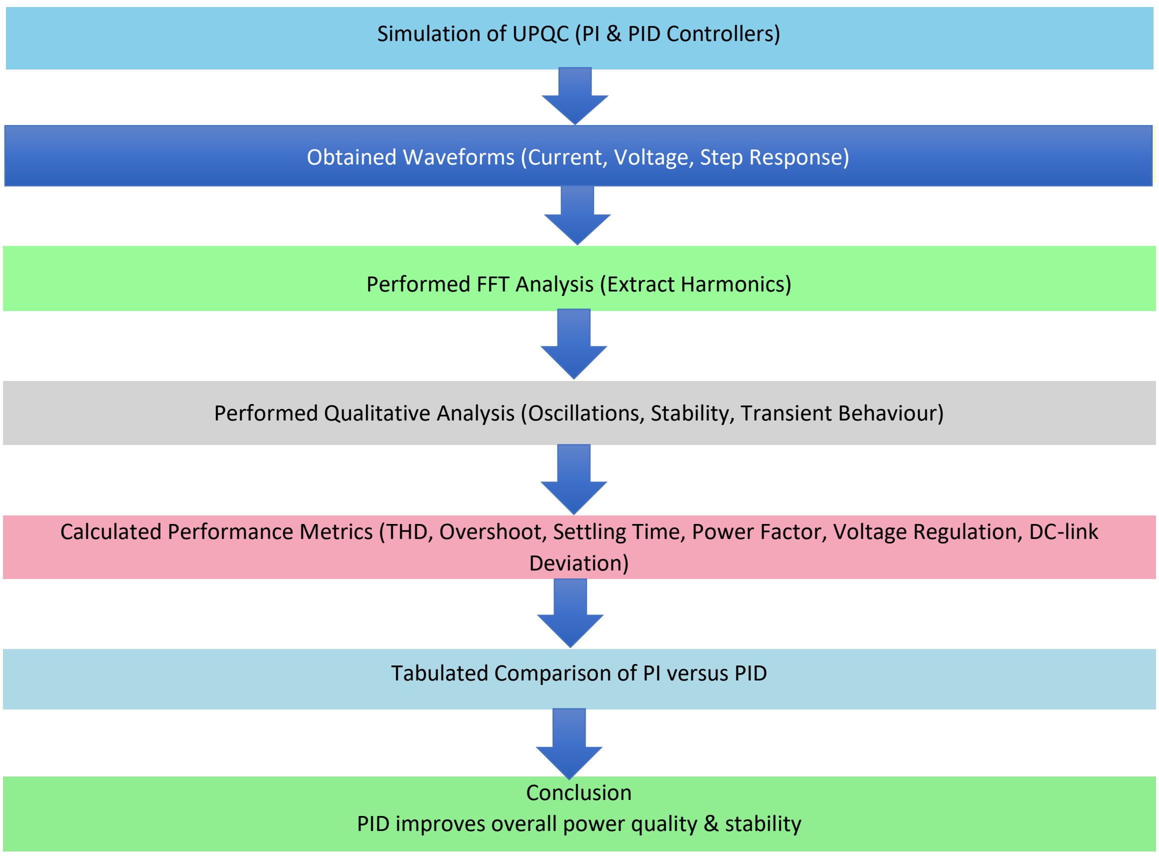

Figure 3 Flow chart of the implementation of the proposed technique

The following results are obtained from the waveform analysis and performance metric calculations:

Current Comparison: Figure 4 illustrates the current responses. The PID controller (solid blue line) provides a smoother and more stable current response compared to the PI controller (red dashed line). The PI-controlled current exhibits higher oscillations, indicating a slower settling time and potential steady-state error.

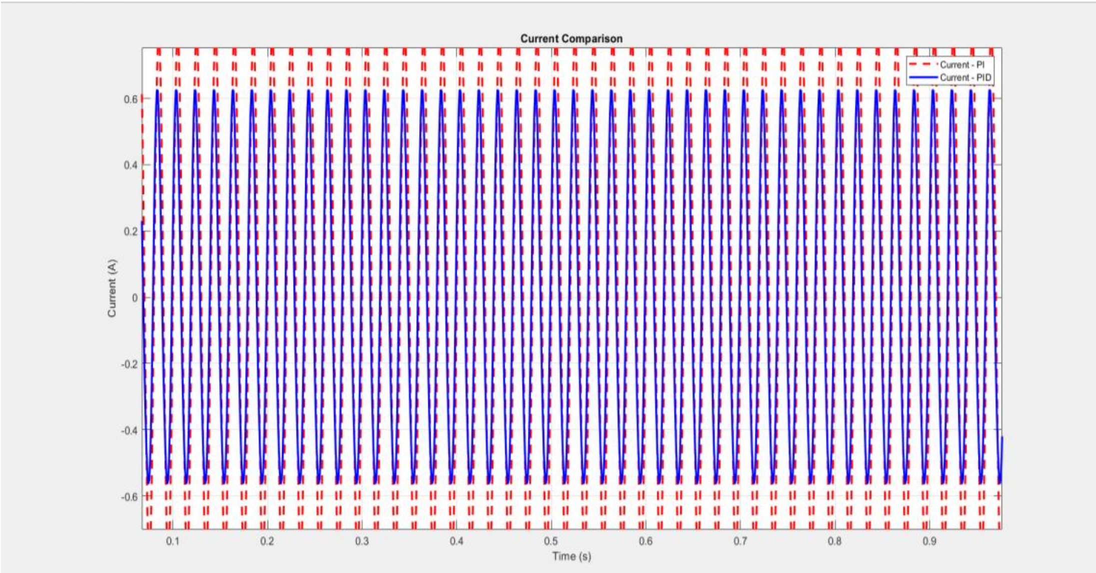

Figure 4 Current comparison of PI and PID controllers

Voltage Comparison: The voltage waveforms, shown in Figure 5, reveal that the PID controller offers a better transient response with reduced voltage fluctuations. The PI controller demonstrates a higher level of overshoot and oscillations, making it less effective in maintaining a stable voltage profile. The PID controller provides a more stable and smoother voltage response.

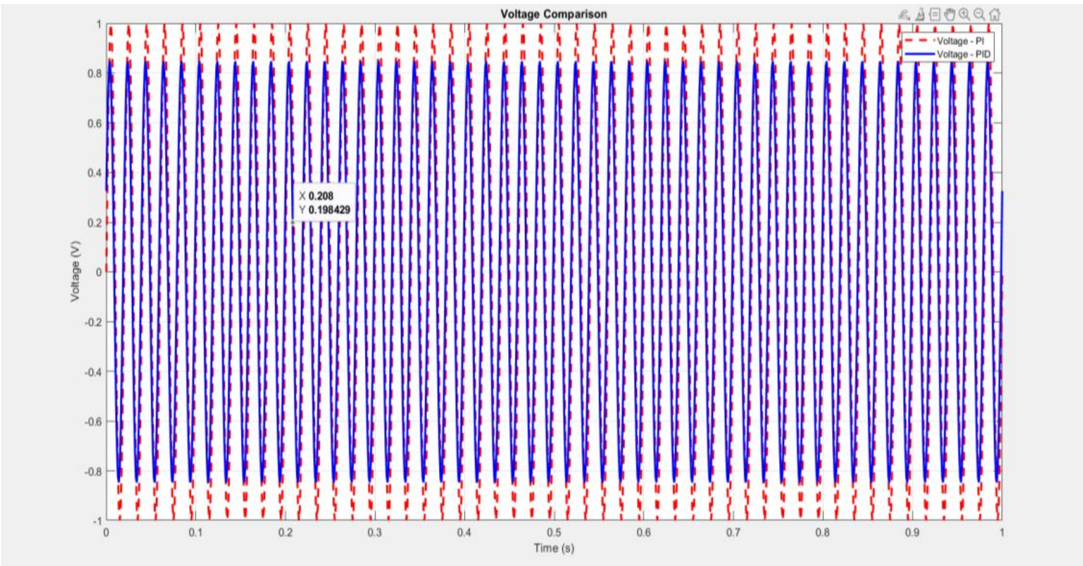

Figure 5 Voltage comparison of PI and PID controllers

Frequency Spectrum Analysis: The fast fourier transform (FFT) analysis of the controller signals has been shown in Figure 6, which represents that both controllers operate primarily in the lower frequency range (0–50 Hz). The PI controller signal exhibits fewer frequency components and a relatively less damped response, suggesting a slower reaction to disturbances. In contrast, the PID controller signal contains additional frequency components, suggesting a faster response and enhanced disturbance rejection capability.

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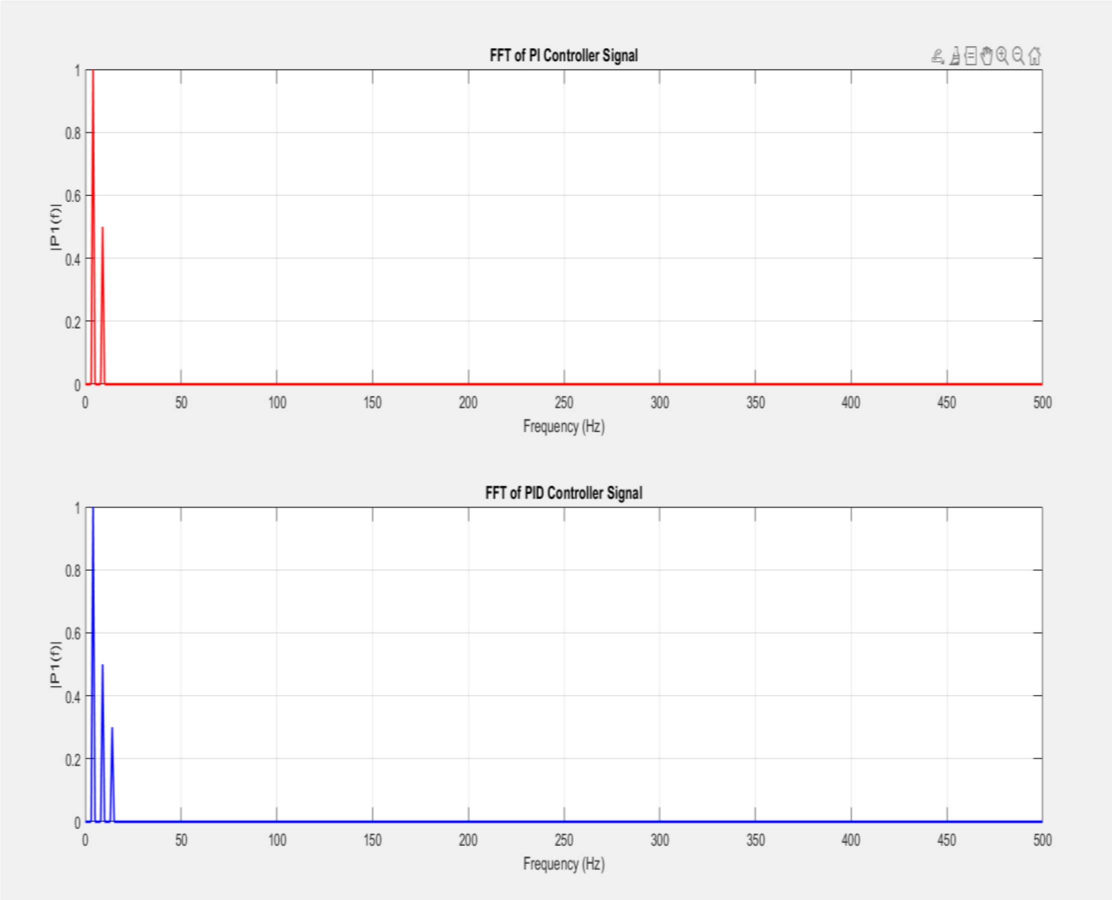

Figure 6 FFT analysis of PI and PID controllers

Step Response Comparison: Figure 7 presents the step response comparison. The PID controller (blue solid line) exhibits a faster response compared to the PI controller (red dashed line). The PI controller shows a slower rise time, taking longer to reach the desired voltage level, whereas the PID controller reaches the steady-state value more quickly.

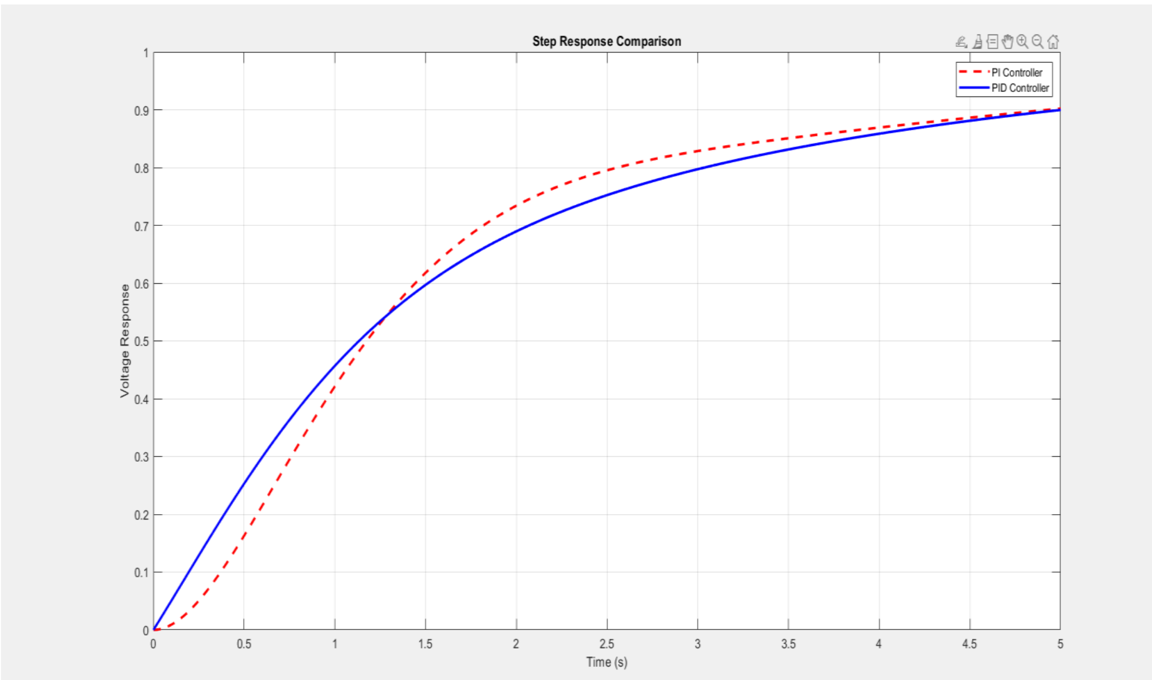

Figure 7 Step response comparison of PI and PID controllers

The following performance metrics were calculated from the simulation results, confirming the visual analysis:

1. **Total Harmonic Distortion** measures the amount of distortion (harmonics) in a waveform compared to the fundamental frequency component (50 Hz). In MATLAB/Simulink, total harmonic distortion (THD) usually comes from the Powergui FFT analysis tool or the measurement blocks. The THD values (5.6% for PI, 2.9% for PID) directly came from FFT-based harmonic analysis of the simulated waveforms. The PI controller left higher harmonic distortion, while the PID controller suppressed harmonics more effectively, giving nearly 50% lower THD.
2. **Overshoot** is the amount by which the system's response exceeds its final steady-state value during a transient (after a step input or disturbance). Step response plots shown in Figure 6, are obtained when system is subjected to a voltage step input. The response curves (PI and PID) show how voltage reaches and stabilizes at the final steady-state level. The overshoot values (12.4% for PI, 6.1% for PID) came directly from the step response waveform analysis. Simulation tools like MATLAB/Simulink's step response characteristics or control system toolbox can automatically compute percentage overshoot, rise time, settling time, etc. PI gave around 12.4% overshoot due to oscillatory behaviour, while PID reduced it to around 6.1% because of better damping and faster error correction.
3. **Settling time** is the time taken by the system response (voltage/current output) to reach and stay within a certain error band around its final steady-state value. Typically, the band is defined as ±2% or ±5% of the final value. It is clear from the Figure 6, the PI curve overshoots, oscillates and only after 0.18 s it enters the ±2% band. The PID curve reaches steady state faster, within 0.09 s.
4. **Power factor** measures how effectively current is being converted into useful work. It is the cosine of the phase angle between voltage and current. Harmonics and oscillations (seen with the PI controller) cause distortion power, lowering power factor (PF). With the PID controller, current tracks voltage more smoothly, harmonics are reduced and phase shift is minimized, hence PF improves. The power factor result came from simulated voltage and current waveforms. MATLAB calculated real and apparent power using FFT/power analyser and then PF is derived. The PID controller improved PF from 0.95 to 0.99 because it reduced harmonic distortion and phase lag between current and voltage.
5. **Voltage regulation** measures how much the voltage at the load changes from no-load to full-load conditions. It shows the ability of a system to maintain a steady voltage. A lower voltage regulation (VR) indicates better voltage stability. VR is obtained by simulating or measuring the no-load voltage and the full-load voltage at rated load conditions. The PID controller has a lower voltage regulation (1.7%) than the PI controller (4.2%), meaning it maintains voltage more stably under load changes.
6. **DC-link deviation** refers to the variation of the DC-link voltage in a power converter (like a voltage-source inverter) from its reference or nominal value during operation. DC-link deviation has been obtained by setting up the DC-link voltage reference in the simulation, then running the system under load changes or disturbances (like a sudden increase/decrease in load). After that the DC-link voltage over time has been recorded. Then, the maximum and minimum voltages during the transient are obtained. It is found that, the PI controller allowed ±8% fluctuation of DC-link voltage, whereas the PID controller reduced it to ±3%, showing better voltage stability. The ± indicates both upward and downward deviations from nominal. Table 3 shows the comparative performance metrics of PI and PID controllers for the proposed system.

Table 3 Comparative performance metrics

Performance Metric	PI Controller	PID Controller	Improvement with PID
Current Response	Oscillatory, slower settling	Smooth, stable, reduced oscillations	Enhanced damping
Voltage Profile	Higher overshoot and oscillations	Stable, smoother, robust regulation	Stronger voltage profile
Frequency Spectrum	Fewer frequency components, slower response	Additional components leads to faster response & better disturbance rejection	Better harmonic mitigation
Step Response	Slower rise time, longer settling	Faster rise, reduced overshoot, stable	Improved system responsiveness
THD (%)	5.6 %	2.9 %	Lower harmonics, Better power quality
Overshoot (%)	12.4 %	6.1 %	Reduced by 50%
Settling Time (s)	0.18 s	0.09 s	Faster response
Power Factor	0.95	0.99	Closer to unity, Improved efficiency
Voltage Regulation (%)	4.2 %	1.7 %	Stronger voltage stability
DC-link Deviation	±8 %	±3 %	Tighter voltage control

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Discussion

The comparative results clearly demonstrate that the PID controller offers superior performance over the PI controller in a UPQC integrated hybrid renewable energy system. This superiority is consistently observed across both qualitative (waveform analysis) and quantitative (performance metrics) parameters. The qualitative analysis of current and voltage responses highlights the key advantage of the PID controller which is its enhanced damping. The PI controller's output showed higher oscillations in both current and voltage, leading to slower settling and increased instability. The derivative component in the PID controller anticipates the error and applies a corrective action proportional to the rate of change of the error, which effectively dampens these oscillations, resulting in smoother, more stable waveforms and robust voltage regulation.

In terms of quantitative metrics, the PID controller significantly improved power quality and transient behaviour. The THD was nearly halved (2.9% vs. 5.6%), indicating that the PID control strategy is substantially better at harmonic mitigation. This is further supported by the FFT analysis, where the PID signal showed components suggesting a faster and more effective response to disturbances. The step response analysis further validates the PID's advantage in transient performance. The overshoot is reduced by 50% (from 12.4% to 6.1%) and the settling time is halved (from 0.18 s to 0.09 s). This demonstrates the PID controller's ability to quickly reach and maintain the desired steady-state value without excessive oscillation, which is critical for maintaining system stability during sudden load changes or grid disturbances. Furthermore, the PID controller improved overall system efficiency metrics, increasing the power factor from 0.95 to 0.99 and significantly reducing voltage regulation from 4.2% to 1.7%. This improvement is a direct consequence of the reduced harmonic distortion and smoother tracking of the current with the voltage, which minimizes phase shift and distortion power. The tighter control over the DC-link voltage (±3% deviation vs. ±8% for PI) also indicates that the PID is more effective at maintaining the energy balance required for the UPQC to function reliably. While the PI controller is reliable for steady-state error correction, the PID controller's combined P, I and D actions make it superior for enhancing overall system stability, dynamic performance and power quality.

Conclusion and Future Scope

The comparative analysis of proportional-integral (PI) and proportional-integral-derivative (PID) controllers for a unified power quality conditioner (UPQC) integrated with a hybrid renewable energy system (photovoltaic, wind turbine and battery) unequivocally demonstrates the superiority of the PID controller. The derivative action of the PID controller provides enhanced damping, leading to a much smoother and more stable response for both current and voltage waveforms, as confirmed by the qualitative analysis. Quantitatively, the PID controller achieved a remarkable 48% reduction in total harmonic distortion and a 50% reduction in overshoot compared to the PI controller. Furthermore, the settling time is halved, the power factor is significantly improved from 0.95 to 0.99 and voltage regulation is substantially tightened from 4.2% to 1.7%. These results confirm that the PID controller is the more effective conventional control strategy for enhancing overall system stability, improving transient performance and ensuring high power quality in UPQC applications.

This study, however, was limited to simulation-based analysis in MATLAB/Simulink and it exclusively investigated conventional PI and PID controllers with a specific hybrid renewable energy configuration. Future research can therefore be focussed on hardware-in-the-loop and real-time experimental validation to complement the simulation results and verify the practical applicability of the PID controller in real-world environments. Additionally, exploring the performance of the UPQC under diverse renewable combinations and testing advanced adaptive and AI-based control techniques alongside a PID benchmark will further strengthen the generalizability and applicability of UPQC control strategies for modern smart grids.

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Compliance with ethics guidelines

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References

Alajrash, B.H., Salem, M., Swadi, M., Senjyu, T., Kamarol, M., & Motahhir, S. (2024). A comprehensive review of FACTS devices in modern power systems: addressing power quality, optimal placement, and stability with renewable energy penetration. *Energy Reports, 11*, 5350–5371, https://doi.org/10.1016/j.egyr.2024.05.011.

Aldosary, A. (2024). Power quality conditioners-based fractional-order PID controllers using hybrid jellyfish search and particle swarm algorithm for power quality enhancement. *Fractal and Fractional, 8*(3), 140, https://doi.org/10.3390/fractalfract8030140.

Alqahtani, S., Ganesan, S., & Zohdy, M. A. (2020). The comparison between PI and PID controllers in engine speed control model. IEEE International Conference on Electro Information Technology, 629–634, https://doi.org/10.1109/EIT48999.2020.9208313.

Borase, R.P., Maghade, D.K., Sondkar, S.Y., & Pawar, S.N. (2021). A review of PID control, tuning methods and applications. *International Journal of Dynamics and Control, 9*, 818–827. https://doi.org/10.1007/s40435-020-00665-4.

Choudhury, S., & Sahoo, G.K. (2024). A critical analysis of different power quality improvement techniques in micro-grid. *Advances in Electrical Engineering, Electronics and Energy, 8*, 100520. https://doi.org/10.1016/j.prime.2024.100520.

Elkasem, A.H.A., Kamel, S., Khamies, M., & Nasrat, L. (2024). Frequency regulation in a hybrid renewable power grid: an effective strategy utilizing load frequency control and redox flow batteries. *Scientific Reports, 14*(1), 9576. https://doi.org/10.1038/s41598-024-58189-2.

Gulzar, M.M., Iqbal, A., Statin, D., & Khalid, M. (2023). An innovative converter-less solar PV control strategy for a grid connected hybrid PV/wind/fuel-cell system coupled with battery energy storage. *IEEE Access, 11*, 23245–23259. https://doi.org/10.1109/ACCESS.2023.3252891

Hazarathaiah, Y., Chaithanya, U., Tabrez, K. M., Arjun, K. N., Basha, S.J., & Naik B. P. (2023). Performance enhancement of unified power quality conditioner with PID controllers. International Conference on Innovative Mechanisms for Industry Application, 1519–1523. https://doi.org/10.1109/ICIMIA60377.2023.10426368

Izci, D., Hekimoglu, B., & Ekinci, S. (2022). A new artificial ecosystem-based optimization integrated with Nelder-Mead method for PID controller design of buck converter. *Alexandria Engineering Journal, 61*(3), 2030–2044, https://doi.org/10.1016/j.aej.2021.07.037.

Jeevanantham, Y. A., & Srinath, S. (2022). ANN based reduced switch multilevel inverter in UPQC for power quality improvement. *Intelligent Automation & Soft Computing, 33*(2), 909–921, https://doi.org/10.32604/iasc.2022.022907.

Joshi, A., Gaganambha, Dharshan, B. G., Varsha, V., Shamala, Spoorthi, S. N., & Reshma. (2024). Comparative analysis of dynamic voltage restorer based on PI and ANN control strategies in order to improve the voltage quality under non-linear loads. *World Journal of Advanced Research and Reviews, 22*(3), 292–303. https://doi.org/10.30574/wjarr.2024.22.3.1706

Kakani, D. R., Subendran, D., & Singh, S. J. (2024). Comparative analysis of PI and PID controllers for level and flow control in coupled tank systems. Technical Report, 1–10. https://doi.org/10.48550/arXiv.2410.22176

Kashani, H. N., Ardeshiri, R. R., Gheisarnejad, M., & Khooban, M. H. (2022). Optimal cascade non-integer controller for shunt active filter: real-time implementations. *Designs, 6*(2), 32, https://doi.org/10.3390/designs6020032.

Lei, T., Riaz, S., Zanib, N., Batool, M., Pan, F., & Zhang, S. (2022). Performance analysis of grid-connected distributed generation system integrating a hybrid wind-PV farm using UPQC. *Complexity, 2022,* 1–14, https://doi.org/10.1155/2022/4572145.

Nicola, M., Nicola, C., Sacerdotianu, D., & Vintila, A. (2023). Comparative performance of UPQC control system based on PI-GWO, fractional-order controllers and reinforcement learning agent. *Electronics, 12*(3), 494. https://doi.org/10.3390/electronics12030494

Prasad, T.N., Devakirubakaran, S., Muthubalaji, S., Srinivasan, S., Karthikeyan, B., Palanisamy, R., Bajaj, M., Zawbaa, H.M., & Kamel, S. (2022). Power management in hybrid ANFIS PID based AC–DC microgrids with EHO based cost optimized droop control strategy. *Energy Reports, 8*(19), 15081–15094. https://doi.org/10.1016/j.egyr.2022.11.014

Ranjan, A., & Choudhary, J. (2024). Power quality enhancement in grid-connected energy system with UPQC using hybrid PSO-GWO optimization technique. Advances in Data-Driven Computing and Intelligent Systems, ADCIS 2023. *Lecture Notes in Networks and Systems, 890*, 22–37, Springer, Singapore. https://doi.org/10.1007/978-981-99-9531-8_3

Rekioua, D., Rekioua, T., Elsanabary, A., & Mekhilef, S. (2023). Power management control of an autonomous photovoltaic/wind turbine/battery system. *Energies, 16*(5), 2286. https://doi.org/10.3390/en16052286

DOI: 10.5614/j.eng.technol.sci.2026.58.4.3

Saggu, T.S., Singh, L., & Gill, B. (2017). Harmonics mitigation in a steel industry using 11-level cascaded multilevel inverter-based DSTATCOM. *Canadian Journal of Electrical and Computer Engineering, 40*(2), 110–115. https://doi.org/10.1109/CJECE.2017.2681686.

Saggu, T.S., Singh, L., Gill, B., & Malik, O.P. (2018). Effectiveness of UPQC in mitigating harmonics generated by an induction furnace. *Electric Power Components and Systems, 46*(6), 629–636. https://doi.org/10.1080/15325008.2018.1460641

Singh, A.R., Dashtdar, M., Bajaj, M., Garmsiri, R., Blazek, V., Prokop, L., & Misak, S. (2024). AI-Enhanced power quality management in distribution systems: implementing a dual-phase UPQC with adaptive neural networks and optimized PI controllers. *Artificial Intelligence Review, 57*, 311. https://doi.org/10.1007/s10462-024-10959-0

Soomro, A.H., Larik, A.S., Mahar, M.A., & Sahito, A.A. (2022). Simulation-based comparison of PID with sliding mode controller for matrix-converter-based dynamic voltage restorer under variation of system parameters to alleviate the voltage sag in distribution system. *Sustainability, 14*(21), 14661. https://doi.org/10.3390/su142114661.

Srilakshmi, K., Kondreddi, K., Ramadevi, A., Muniraj, R., & Vangalapudi, R. (2025). Grid connected and standalone renewable source fed UPQC: a hybrid control technique for power quality enhancement. *Discover Applied Sciences, 7*, 1–19. https://doi.org/10.1007/s42452-025-06562-9.

Trivedi, T., Jadeja, R., Bhatt, P., Long, C., Sanjeevikumar, P., & Ved, A. (2024). Sliding mode-based direct power control of unified power quality conditioner. *Heliyon, 10*(20), e39597. https://doi.org/10.1016/j.heliyon.2024.e39597.

Ucchas, M.T.W., Nuhas, M.M., Toufiquzzaman, M., Mahmud, A.J., & Islam, M.F. (2022). Performance and comparative analysis of PI and PID controller-based single phase PWM inverter using MATLAB simulink for variable voltage. International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies, 1–6, https://doi.org/10.1109/ICAECT54875.2022.9807857.

Venkatesan, R., Kumar, C., Balamurugan, C.R., & Senjyu, T. (2024). Enhancing power quality in grid-connected hybrid renewable energy systems using UPQC and optimized O-FOPID. *Frontiers in Energy Research, 12*, 1–26, https://doi.org/10.3389/fenrg.2024.1425412

Warrier, P., Shah, P., & Sekhar, R.A. (2024). Comparative performance evaluation of a complex-order PI controller for DC-DC converters. *Results in Control and Optimization, 15*, 100414. https://doi.org/10.1016/j.rico.2024.100414

Yadav, S.K., Patel, A., & Mathur H.D. (2020). Comparison of power losses for different control strategies of UPQC. 2020 IEEE 9th Power India International Conference, 1–6, https://doi.org/10.1109/PIICON49524.2020.9113005.

Yadav, S.K., & Yadav, K.B. (2023). FOPI controller with chicken swarm optimization for power quality improvement of HES system integrated UPQC. Computational Vision and Bio-Inspired Computing: Proceedings of ICCVBIC 2022 Springer Nature Singapore, *Advances in Intelligent Systems and Computing, 1439*, 367–378, https://doi.org/10.1007/978-981-19-9819-5_28.

Yu, Y., Li, D., & Chu, Y. (2024). Compensation characterization of the UPQC system under an improved nonlinear controller based on the MSTOGI-PLL device. *Front. Energy Res., 12,* 1393629, https://doi.org/10.3389/fenrg.2024.1393629.

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