Power Quality Enhancement in Solar/Wind/Battery Integrated Renewable Energy Systems Using UPQC with a Modified Robust PID Controller

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Abstract — The increasing integration of renewable energy sources into modern electrical networks has created significant challenges related to power quality, voltage regulation, harmonic distortion, reactive-power management, and dynamic stability. Solar photovoltaic (PV) and wind energy systems are inherently intermittent because their power generation depends on environmental conditions, while nonlinear loads and power electronic converters can further deteriorate voltage and current quality. This study proposes a Solar/Wind/Battery integrated renewable-energy system incorporating a Unified Power Quality Conditioner (UPQC) controlled by a Modified Robust Proportional–Integral–Derivative (MRPID) controller. The UPQC employs coordinated series and shunt voltage-source converters to compensate voltage- and current-related disturbances, while battery energy storage provides an energy-buffering mechanism between renewable generation and load demand. The proposed MRPID controller is developed to improve disturbance rejection, transient response, steady-state accuracy, and robustness compared with conventional PI and PID controllers. The complete system is modeled and simulated in MATLAB/Simulink under normal and disturbed operating conditions, including voltage sag, voltage swell, harmonic distortion, nonlinear loading, sudden load variations, and renewable-generation variations. Performance is evaluated using current total harmonic distortion (THD), RMS voltage, RMS current, active power, reactive power, power factor, and DC-link voltage. The simulation results demonstrate that the MRPID-controlled UPQC achieves a current THD of 2.50%, compared with 6.42% for PI and 3.87% for PID, corresponding to an 80.54% THD improvement. The proposed configuration also achieves 230 V RMS voltage, 104.80 A RMS current, 80 kW active power, 6 kVAR reactive power, 0.998 power factor, and 800 V DC-link voltage. The results demonstrate the potential of the proposed approach for improving power quality and dynamic performance in renewable-energy-based distribution systems and microgrids.

Keywords: Unified Power Quality Conditioner (UPQC); Solar Photovoltaic; Wind Energy; Battery Energy Storage; Modified Robust PID; Power Quality; Harmonic Distortion; Total Harmonic Distortion; Reactive Power Compensation; Renewable Energy; MATLAB/Simulink

I. Introduction

The transition from conventional fossil-fuel-based electricity generation toward renewable-energy-based power systems has accelerated because of increasing energy demand, environmental concerns, and the need for sustainable electricity generation. Solar photovoltaic (PV) and wind energy conversion systems have emerged as important renewable technologies because they can provide clean electricity while reducing dependence on conventional energy resources.

However, unlike conventional generation, renewable-energy sources exhibit significant variability because solar power depends on irradiation and temperature, whereas wind generation depends strongly on wind speed. Consequently, their integration into electrical networks introduces additional challenges associated with power fluctuations, voltage regulation, system stability, and power quality.

The increasing penetration of renewable-energy sources is also accompanied by extensive use of power electronic converters and nonlinear loads. These devices can introduce harmonic currents and voltage distortions into electrical networks. In addition, variations in renewable generation and load demand can produce voltage sag, voltage swell, voltage imbalance, reactive-power variations, poor power factor, and other power-quality disturbances. Such disturbances can adversely affect the efficiency, reliability, and operational performance of electrical equipment. Therefore, effective power-quality management has become an important requirement for renewable-energy-integrated electrical systems.

Battery energy storage systems (BESSs) provide an effective mechanism for reducing the effects of renewable intermittency. Excess energy generated by solar and wind sources can be stored in the battery and subsequently supplied when renewable generation decreases or load demand increases. Thus, combining solar PV, wind energy, and battery storage provides greater flexibility than relying on a single renewable source. However, energy storage primarily addresses energy balancing and cannot independently compensate all voltage- and current-related power-quality disturbances.

The Unified Power Quality Conditioner (UPQC) is an important power-conditioning device capable of simultaneously addressing voltage and current disturbances. A conventional UPQC consists of a series voltage-source converter and a shunt voltage-source converter connected through a common DC-link. The series converter compensates voltage-related disturbances, including voltage sag, voltage swell, voltage imbalance, and voltage harmonics. The shunt converter compensates current harmonics, reactive power, load imbalance, and power-factor deterioration. The broad applicability of UPQC for power-quality improvement and renewable-energy integration has been established in previous research and review studies (Gade et al., 2021).

Research on renewable-energy-integrated UPQC systems has progressively evolved from conventional compensation techniques toward intelligent, optimization-based, adaptive, and nonlinear control strategies. Mansor et al. (2020), for example, investigated a three-phase solar PV and battery energy storage system integrated with UPQC, demonstrating the potential of combining renewable generation, energy storage, and power-quality compensation. Similarly, research on photovoltaic-fed UPQC systems has investigated optimization-based control approaches for improving compensation performance, while harmonic-detection techniques have also been developed specifically for photovoltaic microgrids (Ni et al., 2020).

The integration of wind generation and battery storage has further increased the complexity of UPQC operation because both renewable generation and load conditions can vary dynamically. Studies have therefore investigated fuzzy, sliding-mode, artificial-intelligence, and optimization-based controllers to improve the dynamic performance of renewable-integrated UPQC systems. More recently, hybrid Solar/Wind/Battery configurations have been investigated with optimized PID, fractional-order PI, ANFIS, and other advanced control techniques (Srilakshmi et al., 2024; Yadav et al., 2024).

Although advanced intelligent and optimization-based techniques can improve UPQC performance, their implementation can involve increased computational requirements, parameter-tuning complexity, and controller-design effort. Conventional PI controllers are attractive because of their simple structure and ease of implementation, but their fixed parameters may provide limited performance under rapidly changing operating conditions. PID controllers introduce derivative action and can provide improved transient characteristics; however, their performance remains strongly dependent on appropriate gain selection.

Recent literature consequently indicates a need for robust control strategies that can provide improved dynamic performance without introducing the full complexity of highly intelligent or optimization-based controllers. The present research addresses this requirement by proposing a Modified Robust Proportional–Integral–Derivative (MRPID) controller for a Solar/Wind/Battery integrated UPQC system. The proposed approach maintains the fundamental PID control structure while introducing modifications intended to improve disturbance rejection, transient response, steady-state accuracy, and robustness.

The proposed system is modeled in MATLAB/Simulink and evaluated under different operating conditions, including voltage sag, voltage swell, harmonic disturbances, nonlinear loading, sudden load variations, and changes in renewable generation. The performance of the proposed MRPID controller is compared with conventional PI and PID controllers using current THD, RMS voltage, RMS current, active power, reactive power, power factor, and DC-link voltage. The research objectives are therefore to develop an integrated renewable-energy and UPQC configuration, implement the proposed robust controller, and establish its performance relative to conventional control strategies.

The reported simulation results indicate that the proposed MRPID-controlled UPQC provides substantial improvements. Current THD decreases from 12.85% without UPQC to 2.50% with MRPID, representing an 80.54% improvement. The system also achieves a power factor of 0.998 and reduces reactive power to 6 kVAR. These results support the effectiveness of the proposed approach for improving power quality in integrated renewable-energy systems.

II. Literature Survey

A. *UPQC for Power-Quality Improvement*

The Unified Power Quality Conditioner has become an important custom-power device for mitigating multiple power-quality disturbances in electrical distribution systems. Its combination of series and shunt converters enables simultaneous voltage and current compensation. Gade et al. (2021) reviewed the development of UPQC technology and discussed different converter topologies, compensation techniques, and control strategies. Their review demonstrates the evolution of UPQC from a conventional power-quality compensator toward a multifunctional device applicable to renewable-energy-based distribution systems.

Leon et al. investigated nonlinear optimal control of UPQC using feedback linearisation. Their work demonstrated that the nonlinear characteristics of UPQC systems could be addressed using advanced control rather than relying exclusively on conventional linear controllers. This study established an important foundation for subsequent research into nonlinear and robust UPQC control strategies.

Gade and Agrawal further investigated optimal utilization of UPQC using the JAYA optimization algorithm. Their work illustrates the movement from fixed-parameter controller design toward optimization-based approaches for improving UPQC performance. Such approaches can provide improved parameter selection, although optimization introduces additional computational and design requirements.

B. *Solar PV Integrated UPQC*

Solar PV generation has been increasingly combined with UPQC because the renewable source can contribute energy while the UPQC simultaneously improves power quality. However, variations in solar irradiation and temperature cause continuous changes in PV output, making controller performance an important consideration.

Mansor et al. (2020) investigated the construction and performance of a three-phase solar PV and battery energy storage system integrated with UPQC. Their work demonstrated the feasibility of combining renewable generation, battery storage, and UPQC within an integrated power system. This study is particularly relevant to the present research because it establishes the importance of battery-supported UPQC for renewable-energy applications.

Ni et al. (2020) investigated harmonic detection for UPQC applications in photovoltaic microgrids. Their work highlights that effective harmonic detection is an important component of UPQC control because inaccurate or slow disturbance identification can negatively affect converter compensation.

Dash et al. investigated PV-fed UPQC using optimization-based control. Their work demonstrates the increasing application of optimization techniques to improve UPQC performance under renewable-energy operating conditions.

C. Battery Energy Storage Integrated UPQC

Battery energy storage is increasingly important in renewable-energy systems because it can reduce the mismatch between renewable generation and load demand. The battery can store excess renewable energy and discharge when renewable generation is insufficient.

Mansor et al. (2020) demonstrated the integration of solar PV, BESS, and UPQC in a three-phase system. The study provides an important basis for combining energy management and power-quality compensation within the same system.

Srilakshmi et al. investigated PV, battery-storage, and UPQC configurations using advanced hybrid control. Their approach employed intelligent control techniques to improve DC-link regulation, current distortion, power factor, and voltage compensation. Although such techniques demonstrate strong compensation capability, their implementation can be more complex than conventional PID-based structures.

D. Wind Energy and Battery Integrated UPQC

Wind-energy-based UPQC systems must respond to continuous variations in wind speed in addition to changes in load demand. Chaudhary et al. (2020) investigated fault mitigation using a multi-converter UPQC with hysteresis control in a grid-connected wind system. Their research demonstrates the importance of fast converter control for disturbance mitigation in wind-integrated systems.

Other studies have investigated fuzzy-PI and hybrid control approaches for wind, battery, and UPQC systems. These studies demonstrate that combining renewable sources with energy storage and advanced UPQC control can improve harmonic compensation, voltage regulation, and power-factor performance.

E. Solar/Wind/Battery Integrated UPQC

Recent research has increasingly moved toward hybrid configurations combining solar PV, wind energy, and battery storage. Such configurations are more representative of future microgrids because they exploit multiple renewable resources while using storage to compensate for their intermittent nature.

Srilakshmi et al. (2024) proposed an integrated solar/wind/battery and electric-vehicle-fed UPQC using an enhanced Most Valuable Player Algorithm for parameter optimization and ANFIS-based power-flow management. The study addressed both power-quality improvement and power-flow management and reported THD values of approximately 4.5%, 2.26%, 4.09%, and 3.98% for different operating cases.

Yadav et al. (2024) investigated a three-phase solar PV, BESS, and wind-integrated UPQC. Their study considered voltage sag and swell together with changes in solar irradiation and temperature. An optimized fractional-order PI controller was employed. The results demonstrated the effectiveness of optimized control for improving THD and transient characteristics. However, the use of fractional-order control and metaheuristic optimization increases controller-design complexity.

These studies establish the feasibility of hybrid renewable-energy-integrated UPQC but also reveal a research opportunity for developing robust PID-based control with lower structural complexity.

F. Advanced Control Strategies for UPQC

The limitations of fixed-parameter PI and conventional PID controllers have encouraged the investigation of fuzzy logic, artificial neural networks, ANFIS, sliding-mode control, fractional-order control, adaptive control, and metaheuristic optimization.

Intelligent control methods can improve adaptability under nonlinear and dynamic conditions. However, they commonly require additional membership functions, training procedures, optimization parameters, or computational resources. Consequently, controller complexity becomes an important consideration when developing practical renewable-energy systems.

Recent research has also investigated AI-controlled UPQC systems and fuzzy-sliding-mode controllers. These developments demonstrate the current shift toward adaptive and nonlinear control for renewable-integrated UPQC systems. Nevertheless, the need remains for robust approaches that retain a relatively interpretable controller structure.

G. PI and PID Controllers

PI control remains one of the most widely used strategies for converter and DC-link regulation because of its simple structure. The PI controller consists of proportional and integral actions. The proportional term provides an immediate response to control error, whereas the integral term accumulates the error and reduces steady-state error.

The PID controller extends PI control by introducing derivative action. The derivative component responds to the rate of change of error and can improve transient response and damping. However, inappropriate controller gains can cause overshoot, oscillations, or slow settling.

The thesis literature identifies recent comparative work on PI and PID controllers for hybrid renewable-energy UPQC systems, where PID demonstrated better transient performance than PI. This establishes PID as an appropriate benchmark for evaluating the proposed MRPID controller.

H. Research Gap

The literature indicates four major gaps.

1) Limited focus on integrated configurations: Many earlier studies focused on individual renewable sources, whereas simultaneous solar, wind, and battery integration introduces more complex dynamic conditions.
2) High complexity of advanced controllers: Fuzzy, ANN, ANFIS, sliding-mode, fractional-order, and optimization-based controllers can improve performance but may increase computational and parameter-tuning complexity.
3) Limitations of conventional PI/PID: PI controllers provide simplicity but may have limited robustness, while conventional PID performance depends strongly on gain selection.
4) Limited investigation of MRPID for Solar/Wind/Battery-UPQC: Relatively fewer studies specifically investigate a Modified Robust PID controller

in a Solar/Wind/Battery-integrated UPQC while directly benchmarking it against both PI and PID controllers.

Therefore, this research proposes an MRPID-controlled UPQC and performs a systematic comparison with PI and PID controllers using multiple power-quality and dynamic-performance indicators.

III. Proposed Methodology

A. Overall Methodology

The proposed methodology consists of five major subsystems:

1) Solar photovoltaic generation system
2) Wind energy conversion system
3) Battery energy storage system
4) Unified Power Quality Conditioner
5) PI, PID, and proposed MRPID control system

The complete architecture is implemented in MATLAB/Simulink. The renewable sources provide electrical power, the battery manages energy fluctuations, and the UPQC compensates voltage- and current-related disturbances. The controllers generate the required converter control signals, which are converted into PWM switching pulses.

B. Solar PV Model

The PV subsystem converts solar irradiation into electrical energy. Its output depends mainly on solar irradiation, cell temperature, and the electrical operating point.

The output power is expressed as

$$P_{PV} = V_{PV} I_{PV} \quad (1)$$

where P_{PV} is the generated PV power, V_{PV} is the PV voltage, and I_{PV} is the PV current.

The PV system operates near its maximum power point to maximize renewable-energy extraction. Changes in irradiation and temperature alter the PV operating characteristics, making appropriate control necessary.

C. Wind Energy Conversion System

The wind-energy subsystem converts the kinetic energy of moving air into mechanical and subsequently electrical energy. The power available from the wind is

$$P_w = \frac{1}{2} pAv^3 \quad (2)$$

where ρ represents air density, A is the swept area of the turbine, and v is wind velocity.

The mechanical power extracted by the turbine is

$$P_m = \frac{1}{2} pAv^3 C_p\,(\gamma\beta) \quad (3)$$

where C_p represents the turbine power coefficient, λ is the tip-speed ratio, and β is the blade pitch angle.

Because wind velocity varies continuously, the generated power also varies. The battery and UPQC therefore provide important support for maintaining stable system operation.

D. Battery Energy Storage System

The BESS provides an energy-buffering function between renewable generation and load demand. When renewable generation exceeds demand, surplus energy is stored. When generation decreases or load demand increases, the battery supplies additional power.

The shunt converter is connected in parallel with the load and compensates current-related disturbances.

The source current can be expressed as

$$I_s = I_L - I_{comp} \quad (4)$$

where I_s is source current, I_L is load current, and I_{comp} is the compensating current generated by the shunt converter.

The shunt converter therefore reduces harmonic current, reactive-current components, and power-factor deterioration. The reported simulation results show that reactive power decreases to 6 kVAR and power factor increases to 0.998 under MRPID control.

E. DC-Link Capacitor

The series and shunt converters share a common DC-link. The DC-link capacitor provides energy exchange between the converters and maintains the required DC voltage.

The energy stored in the capacitor is

$$E_{dc} = \frac{1}{2} C_{dc} V_{dc}^2 \quad (5)$$

where C_{dc} is the DC-link capacitance and V_{dc} is the DC-link voltage.

Maintaining a stable DC-link voltage is essential for reliable converter operation. The proposed system reaches a reported DC-link voltage of 800 V under MRPID control.

F. PI Controller

The PI controller is used as the first benchmark controller:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau \quad (6)$$

where $e(t)$ is the control error, K_p is the proportional gain, and K_i is the integral gain.

The proportional component provides an immediate response, while the integral component reduces steady-state error.

G. PID Controller

The PID controller introduces derivative action:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (7)$$

where K_d represents the derivative gain.

The derivative component improves response to rapidly changing errors and can improve transient damping. However, excessive derivative action can increase sensitivity to measurement noise.

H. Proposed MRPID Controller

The proposed Modified Robust PID controller is developed to overcome the limitations associated with conventional PI and PID control under dynamic renewable-energy conditions. The controller follows the general PID structure but incorporates a robustness-oriented modification to improve controller behavior under disturbances. A generalized representation is

$$u_{MRPID}(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} + u_r(t) \quad (8)$$

Where $u_r(t)$ represents the robustness/modification component introduced by the proposed controller.

The MRPID controller is designed with the following objectives:

– faster transient response;
– improved disturbance rejection;
– reduced steady-state error;

- reduced overshoot;
- improved robustness;
- improved dynamic performance; and
- improved operation under renewable-generation variations.

The controller generates the reference control signals for the series and shunt converters, which are subsequently converted into PWM switching signals.

I. PWM Switching Strategy

PWM is employed to generate switching pulses for the series and shunt converters. The controller output is compared with a carrier signal to determine the switching states.

The duty ratio can be represented by

$$D = \frac{T_{on}}{T_s} \quad (12)$$

where $Ton$is the switching-on duration and $Ts$is the switching period.

Variation of the switching duty ratio enables the converter to generate the required compensating voltage or current.

J. Proposed Control Algorithm

The complete control process is implemented through the following sequence:

- Step 1: Solar PV and wind systems generate renewable power.
- Step 2: The BESS stores surplus energy and supplies energy during renewable-generation deficits.
- Step 3: Supply voltage, load voltage, source current, load current, and DC-link voltage are measured.
- Step 4: Measured variables are compared with their respective reference values.
- Step 5: Control errors are calculated.
- Step 6: The selected PI, PID, or MRPID controller processes the error.
- Step 7: Reference signals for the series and shunt converters are generated.
- Step 8: PWM generates converter switching pulses.
- Step 9: The series converter compensates voltage disturbances.
- Step 10: The shunt converter compensates current harmonics and reactive current.
- Step 11: The DC-link voltage is regulated.
- Step 12: System performance is evaluated using THD, RMS voltage, RMS current, active power, reactive power, power factor, DC-link voltage, rise time, settling time, overshoot, and transient response.

IV. RESULTS

The proposed Solar/Wind/Battery integrated system is implemented in MATLAB/Simulink. The system consists of renewable-energy generation sources, battery energy storage, power electronic converters, UPQC, controllers, measurement units, and the connected load.

The solar PV and wind energy conversion systems provide renewable electrical power, while the battery energy storage system supports the system during variations in renewable generation. The UPQC is connected to compensate for voltage- and current-related disturbances.

The UPQC consists of a series converter and a shunt converter. The series converter is responsible for maintaining the desired voltage at the load side, while the shunt converter compensates current-related disturbances such as harmonic currents and reactive-power requirements.

The controller receives the measured system variables and compares them with their corresponding reference values. The resulting error is processed through the selected controller, and the generated control signal is used to produce PWM switching pulses for the converters. The coupling transformer provides the required electrical interface between the UPQC converter and the electrical network. It plays an important role in transferring the compensating voltage generated by the series converter to the system.

The output waveform of the coupling transformer is used to observe the voltage behavior after the compensation mechanism. A properly controlled UPQC should provide an improved and regulated voltage waveform despite disturbances in the supply.

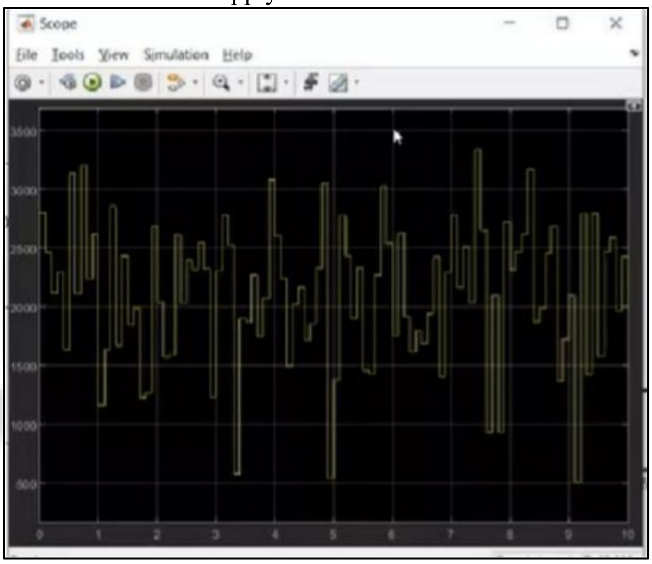

Fig. 2: Coupling transformer output

The coupling-transformer output should be analyzed in terms of waveform quality, magnitude, and stability. The waveform obtained from the simulation provides an indication of the effectiveness of the series compensation mechanism. Any improvement in the voltage waveform demonstrates the ability of the UPQC to compensate voltage-related disturbances.

Total Harmonic Distortion (THD) is one of the most important parameters used to evaluate power quality. It indicates the amount of harmonic distortion present in the electrical waveform. A lower THD value indicates that the waveform is closer to the desired sinusoidal waveform.

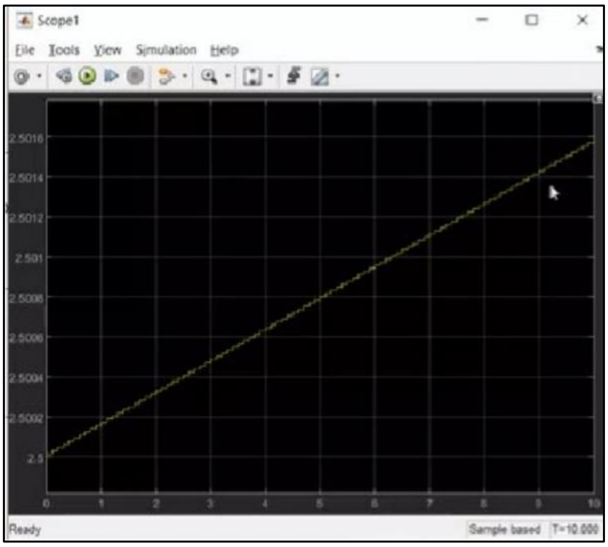

Fig. 3: THD output of proposed work

The reported current THD values for the four configurations are presented in Table 2.

Controller Configuration	Current THD (%)
Without UPQC	12.85
UPQC + PI	6.42
UPQC + PID	3.87
UPQC + MRPID	2.50

Table 2: Comparative Current THD Performance

Source: Simulation results from the proposed work.

The results show a considerable reduction in current THD after the implementation of UPQC. Without UPQC, the current THD is 12.85%. With the PI controller, THD decreases to 6.42%, representing a substantial improvement. The PID controller further reduces THD to 3.87%.

The best performance is obtained with the proposed MRPID controller, where current THD decreases to only 2.50%. Therefore, the MRPID controller provides the lowest harmonic distortion among the compared configurations.

The THD improvement values further demonstrate this result.

Controller	Current THD (%)	THD Improvement (%)
Without UPQC	12.85	—
PI	6.42	50.04
PID	3.87	69.88
MRPID	2.50	80.54

Table 3: THD Improvement for Different Controllers

The MRPID controller provides a reported 80.54% THD improvement, compared with 50.04% for PI and 69.88% for PID.

This result indicates that the proposed MRPID control strategy provides improved harmonic compensation compared with both conventional PI and PID controllers.

RMS voltage is an important parameter for evaluating voltage regulation and the effectiveness of voltage compensation.

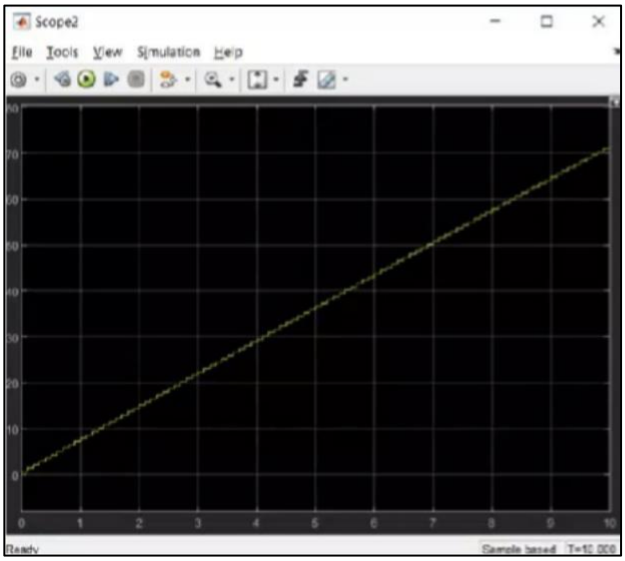

Fig. 4: RMS voltage (Vms) output of proposed work

Configuration	RMS Voltage (V)
Without UPQC	184.00
UPQC + PI	218.50
UPQC + PID	225.80
UPQC + MRPID	230.00

Table 4: Comparative RMS Voltage

The RMS voltage increases from 184.00 V without UPQC to 218.50 V with PI. The PID controller further improves the RMS voltage to 225.80 V, while the MRPID controller provides the highest reported value of 230.00 V.

The result indicates that the proposed MRPID-controlled UPQC provides improved voltage regulation compared with the other configurations considered in the study.

RMS current provides information regarding the current drawn by the system and the effect of compensation on current requirements.

Configuration	RMS Current (A)
Without UPQC	108.60
UPQC + PI	106.20
UPQC + PID	105.40
UPQC + MRPID	104.80

Table 5: Comparative RMS Current

The RMS current decreases progressively from 108.60 A without UPQC to 106.20 A with PI, 105.40 A with PID, and 104.80 A with MRPID.

The reduction in RMS current indicates improved current compensation and reduced unwanted current components. The MRPID controller provides the lowest RMS current among the compared configurations.

Active power represents the useful electrical power delivered to the load or utilized by the system.

Configuration	Active Power (kW)
Without UPQC	76.20
UPQC + PI	78.10
UPQC + PID	79.20
UPQC + MRPID	80.00

Table 6: Comparative Active Power

The active power increases from 76.20 kW without UPQC to 78.10 kW with PI and 79.20 kW with PID. The

MRPID controller provides the highest reported active power of 80.00 kW.

This improvement indicates better utilization of the available electrical power under the proposed compensated configuration.

Reactive power is an important parameter for assessing the effectiveness of power-factor correction and reactive-current compensation.

Configuration	Reactive Power (kVAR)
Without UPQC	30.00
UPQC + PI	18.00
UPQC + PID	12.00
UPQC + MRPID	6.00

Table 7: Comparative Reactive Power

A substantial reduction in reactive power is observed after applying the UPQC. Reactive power decreases from 30 kVAR without UPQC to 18 kVAR with PI and 12 kVAR with PID.

The proposed MRPID controller achieves the lowest reactive power of 6 kVAR. This represents a significant reduction compared with the uncompensated system.

The result indicates that the MRPID-controlled UPQC provides improved reactive-power compensation and consequently contributes to better utilization of the electrical system.

Power factor is an important indicator of the effectiveness of power utilization. A power factor close to unity indicates improved utilization of electrical power and reduced reactive-power requirements.

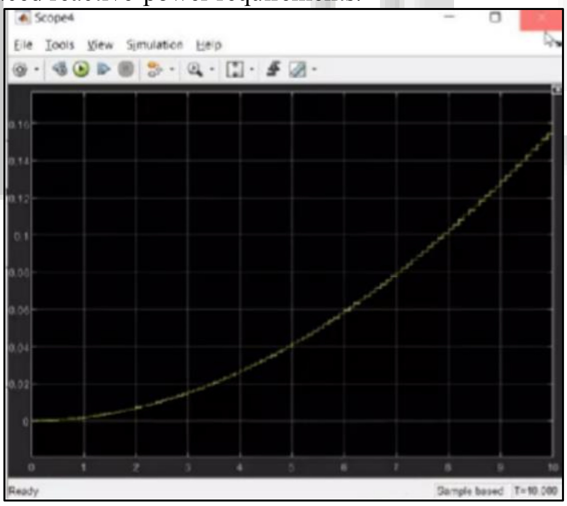

Fig. 5: Power factor output of proposed work

Configuration	Power Factor
Without UPQC	0.930
UPQC + PI	0.970
UPQC + PID	0.990
UPQC + MRPID	0.998

Table 8: Comparative Power Factor

The power factor improves from 0.93 without UPQC to 0.97 with PI and 0.99 with PID. The proposed MRPID controller achieves a power factor of 0.998, which is closest to unity among the compared configurations.

This improvement is consistent with the reduction in reactive power observed in the previous section. Therefore, the MRPID-controlled UPQC provides better reactive-power compensation and improved power-factor performance.

The DC-link voltage is a critical parameter in UPQC operation because the series and shunt converters are connected through the common DC link. Maintaining a stable DC-link voltage is necessary for effective converter operation.

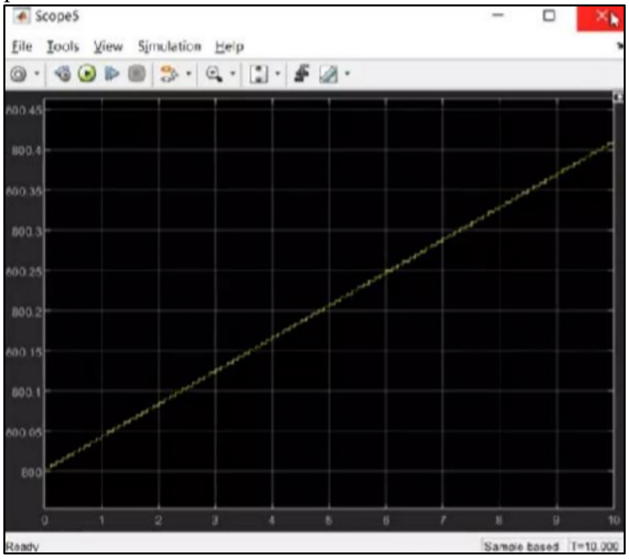

Fig. 6: DC-link voltage (VDC) output of proposed work

Configuration	DC-Link Voltage (V)
Without UPQC	768
UPQC + PI	790
UPQC + PID	797
UPQC + MRPID	800

Table 9: Comparative DC-Link Voltage

The reported DC-link voltage increases from 768 V without UPQC to 790 V with PI and 797 V with PID. The MRPID-controlled system achieves 800 V

V. Conclusion

This study presented a Solar–Wind–Battery integrated power quality enhancement system based on a Unified Power Quality Conditioner (UPQC) with a Modified Robust PID (MRPID) controller. The proposed configuration was developed to address major power quality problems associated with renewable-energy-integrated grids, including harmonic distortion, voltage disturbances, reactive power demand, and variations caused by nonlinear and changing loads. The performance of the proposed controller was evaluated in MATLAB/Simulink under different operating conditions and compared with conventional PI- and PID-based UPQC controllers. The simulation results demonstrate the effectiveness of UPQC in improving the quality of grid power, while the proposed MRPID controller provides superior performance compared with the conventional controllers. The source-current THD was reduced from 12.85% without UPQC to 6.42% with PI, 3.87% with PID, and 2.50% with the proposed MRPID controller. This corresponds to an overall THD improvement of approximately 80.54% compared with the uncompensated condition. The proposed system also achieved a nearly unity power factor of 0.998, maintained an RMS voltage of 230 V, and regulated the DC-link voltage around 800 V. These results indicate that the MRPID-controlled UPQC can effectively compensate current harmonics and voltage-related disturbances while maintaining stable operation of the integrated renewable-energy system. Overall, the results confirm that combining renewable energy sources, battery energy storage, UPQC, and robust control provides an effective approach for improving power quality in modern grid-connected systems. The proposed MRPID strategy offers improved disturbance rejection and dynamic regulation compared with PI and PID control. Future work can focus on real-time hardware implementation, experimental validation, adaptive controller tuning, and testing under highly variable renewable-generation and grid conditions to further establish the practical applicability of the proposed approach.

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