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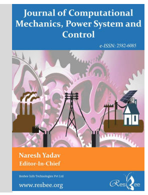

Power Quality Enhancement in Hybrid Renewable Energy Source-Based Distribution System: Upqc with Coati-Zebra-Based Pid Controller

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Abstract: A power distribution system that combines two or more sources of renewable energy, such as biomass, solar, hydro, or wind, to generate and provide electricity to customers is known as a Hybrid Renewable Energy Source-Based Distribution Source (HRES). In a distribution system based on HRES, Power Quality (PQ) enhancement is crucial to ensure the electricity offered by steady, dependable, and appropriate for both industrial and consumer loads. The PQ issues caused by the distribution system also include harmonics, voltage sags, and swells. Thus, the paper proposed a novel Unified Power Quality Conditioner (UPQC) with COATI-ZEBRA (COAZ)-based PID controller for improving PQ in HRES. The COAZ method improves the PID controller parameters for enhancing PQ performance, and the suggested controller alleviates these problems by adjusting the harmonics and voltage disturbances. The proposed COAZ algorithm is created based on the integrated characteristics and features of the Zebra Optimization Algorithm (ZOA) and Coati Optimization Algorithm (COA). To further strengthen system resilience and robustness, the COAZ-based PID controller is tested under varying load conditions and renewable energy input fluctuations, ensuring real-time adaptability. The framework is proven in MATLAB 2021b, and the recommended method's performance is assessed by risetime, settlingtime, settlingmin, settlingmax, peak, and peaktime, respectively. The suggested PID-based COAZ strategy obtained a minimal ratio of 0.3634 for RiseTime, which is less than that of other methods already in use, including COA of 0.36398, ZOA of 0.3637, and ZOA of 0.364, respectively. The proposed method for effective PQ enhancement is validated by comparing its performance to existing methods.

Keywords: Power Quality; Power Distribution System; Proportional-Integral-Derivative controller; Hybrid Renewable Energy Source; Unified Power Quality Conditioner

Nomenclature

Abbreviation	Description
HRES	Hybrid Renewable Energy Source-Based Distribution Source
PQ	Power Quality
COAZ	COATI-ZEBRA-based Optimization Algorithm
BESS	Battery Energy Storage System
PID	Proportional-Integral-Derivative
DG	Distribution Generation
FACT	Flexible AC Transmission
PV	Photovoltaic
WT	Wind Turbine
OPQE	Optimum Power Quality Enhancement
COA	Coati Optimization Algorithm
ASO	Atom Search Optimization
PI	Proportional-Integral
VSCs	Voltage Source Converters
ZOA	Zebra Optimization Algorithm
THD	Total Harmonic Distortion
PRES	Power Reinforcement and Enhancement Strategies
RES	Renewable Energy Sources
QZSI	Quasi-Z-Source Inverter
AC	Alternating Current
UPQC	Unified Power Quality Conditioner
BWO	Black Widow Optimization
DC	Direct Current
DPFC	Distributed Power Flow Controller

SPV	Solar PV
QZSI-UPQC	Quasi-Z-Source Inverter Unified Power Quality Conditioner
HPS	hybrid power system
FOPID	fractional-order PID
DPFC -BWO	Distributed Power Flow Controller Black Widow Optimization
STATCOM	Static Compensator
qZSI	Quasi-Z-Source Inverter
AFF	Adaptive Frequency Fixed
SOGI	Second Order Generalized Integrator
AFF- SOGI	Adaptive Frequency Fixed Second Order Generalized Integrator
SPVA	Solar Photovoltaic Array
UPQC-SPVA	Unified Power Quality Conditioner Solar Photovoltaic Array

1. Introduction

In the current era, the DG industries are expanding quickly globally. However, DGs are difficult to install and resize. Along with the fact that the cost of producing electricity is rising daily, it is also crucial to minimize distribution system losses and difficult to improve efficiency and quality [6]. Generally, PQ is a technique for grounding and energizing electrical devices that ensures proper operation. Because of the distortion, harmonic disruptions, and voltage fluctuations created, adjustable speed drives, microprocessor-based equipment, etc., improving PQ is essential [7]. The most common PQ issue is voltage sag, which results in power loss and damages the device. These voltage drops have the potential to cause physical damage to delicate electronics like computers and industrial machinery, as well as equipment faults and process disruptions [8]. In particular, distributed generations (DG) units connected to weak grids are more prone to PQ disturbances, amplifying the need for effective compensation mechanisms. Therefore, ensuring high-quality power delivery in DG-integrated systems requires advanced mitigation techniques, such as custom-designed UPQC systems and intelligent control algorithms. These approaches not only protect sensitive loads but also help meet grid code compliance for renewable-based systems.

When a tension or disturbance arises, energy storage devices like batteries and condensers are employed to control the load [9]. Due to the restricted energy storage ability, the UPQC's compensation process becomes limited when these energy storage units are used. However, integrating HRES systems with grid-connected load systems faces several difficulties because the non-linear and unbalanced loads in the system are susceptible to PQ problems, which are one of the main obstacles [10]. To achieve UPQC, two VSCs are combined, one has a series connection to the load, whereas the other has a parallel connection [11]. These configurations allow the UPQC to compensate both for voltage disturbances and current-related PQ issues simultaneously, enhancing system reliability under dynamic load and source variations.

This research examines a hybrid system that combines a distribution system, PV, wind, and BESS to provide the necessary load demand [12]. One of the issues with hybrid distribution systems is instability. The system mostly creates PQ issues, including sag, swell, harmonics, and others. These PQ problems primarily arise in HRES systems because wind and solar energy sources are unpredictable due to environmental variables. Similarly, the filter circuits and FACT devices in the system can help to reduce these PQ problems [13]. Nevertheless, there are many devices available that are categorized according to series and shunt devices because of the development of power electronics devices and control techniques [14]. However, conventional methods often lack the intelligence and adaptability required to efficiently handle complex non-linear interactions in modern HRES environments. An appropriate controlling strategy is necessary in HRES-based distribution systems to preserve stability and reduce PQ issues [15]. In this context, optimization-based control strategies are gaining momentum as they provide enhanced tuning capabilities for dynamic and uncertain system conditions. This study's primary objective is to improve the PQ in an HRES-based distribution system by compensating for the PQ problems. The primary contributions are as follows:

- To design UPQC for lowering PQ problems in HRES, such as sag, swell, harmonics, and so forth, which are primarily caused by non-linear load conditions.
- To introduce the COAZ Algorithm to maximize the controllers' performance. This optimization improves the accuracy and effectiveness of power generation and distribution, which increases the system's capacity to provide energy to a connected load.
- To develop a hybrid metaheuristic controller that integrated the strengths of the Coati Optimization Algorithm (COA) and the Zebra Optimization Algorithm (ZOA) to create a robust COAZ approach capable of real-time PQ management.

The organization of the work is given as follows: Section 2 explains the comprehensive literature survey of the PQ enhancement models in the HRES system. Section 3 illustrates the suggested approach of PQ enhancement in HRESs using a COAZ-enabled PID controller model. Section 4 represents the simulation results, including a performance comparison of the COAZ method with traditional techniques, and the calculation of different metrics used in the system. Finally, Section 6 concludes the paper.

2. Literature Survey

2.1 Related Works

In 2021, Rami et al. [1] suggested OPQE for grid-connected hybrid power systems that combine battery storage, wind turbines, and solar photovoltaics as part of a sophisticated control scheme. The main objective was to reduce power loss and THD while controlling voltage. The developed technique has been tested in several modes: PRES > 0, PRES = 0, and concurrently to enhance RES power injection and PQ reinforcement. The effectiveness of the proposed approach was then assessed by contrasting the outcomes with those attained using PI controllers from previous publications. However, the study did not address optimization of the controller parameters for adaptive performance under varying environmental conditions, which is critical in real-world HRES application.

In 2020, M. Vijayakumar et al. [2] proposed a UPQC powered by SPV and based on a QZSI to improve PQ. The primary purposes of QZSI were to decrease the required elements, eliminate harmonic content, and boost the flexible DC voltage to any range of desired AC output voltages. The SPV system, containing an energy storage unit, was used by the proposed UPQC to maintain the grid's active power requirements while establishing long-term current and voltage interruptions. The experimental results demonstrate that the suggested SPV-supported QZSI-UPQC increases the power performance of the linked SPV power distribution system by producing sinusoidal grid currents of about 1.2% of THD. Despite its improved harmonic performance, the system lacks a robust control optimization framework to dynamically tune performance under fluctuating loads.

In 2021, B. Srikanth et al. [3] offered a DPFC, a flexible device which used to handle a range of PQ issues, like voltage swell, sag, interruption, and harmonic abstraction in an HPS. Mitigating PQ issues and compensating for load demand in the HRES scheme were the primary goals of the endeavor. A FOPID controller that had been adjusted using the BWO approach powered the DPFC-PQ. The findings demonstrated that the PQ issues in grid-connected HRESs were reduced by the suggested BWO-FOPID controller for DFPC. The performance of the proposed system was evaluated once its design was implemented using the MATLAB/Simulink platform. However, the FOPID tuning using BWO may not provide the best convergence rate or solution diversity in highly dynamic renewable environments.

In 2023, M. Vijayakumar et al. [4] presented a new smart grid application to regulate the electricity facilities. A STATCOM device was used to eliminate unwanted harmonics, correct for reactive power in the power sources, and enhance power quality and flow in the distribution system. An AFF-SOGI had been used to regulate the suggested compensator. The system effectively decreased the source current's THD from 25.5% to 1.3%, according to the testing results. Moreover, the technique had demonstrated its ability to supply active power to the load. Nevertheless, the approach lacks scalability and may not effectively respond to dynamic grid disturbances without a metaheuristic-tuned control strategy.

In 2020, Sanjenbam et al. [5] proposed a modified generalized integrator that could eliminate DC offsets to operate a system that combined a UPQC and SPVA (UPQC-SPVA). By balancing grid currents, reducing grid voltage sag and swell, compensating reactive power, and reducing harmonics, this SPVA control algorithm enhances PQ. The UPQC-SPVA system was tested on a laboratory prototype, and the results demonstrated that it functions well under a range of disturbances, such as load unbalancing, harmonic correction, changes in solar irradiation, and sag/swell voltage. Still, the computational overhead of the offset-removal process could limit its application in real-time industrial systems.

2.2 Problem Statement

This section details the drawbacks associated with the existing methods of power quality enhancement strategies. The UPQC-PQ-ASO-based FOPID controller [1] uses an ASO-based FOPID controller to reduce THDs associated with voltage/current and to alleviate PQ issues. Moreover, they have the disadvantages of intricate control algorithms and possible instability in specific operating scenarios. Additionally, the lack of adaptive learning or hybrid optimization methods reduces its potential in complex nonlinear environments. The QZSI-UPQC was proposed in [2] to alleviate harmonic content, minimize the necessary elements, and boost the adjustable DC voltage to any desired AC output voltage. The model was challenging, primarily due to increased harmonic distortion. It also lacks fine-tuned control under multi-modal grid variations, which could affect voltage regulation consistency. BWO-DPFC-PQ was proposed in [3] to resolve PQ problems and modify the HRES strategy to prepare for load demand. However, it also had the drawback of that it may be not producing the best power by quickly shifting the air conditions.

This makes it less effective in systems that depend heavily on intermittent renewable energy resources like wind and solar. Furthermore, the STATCOM based on the qZSI in [4] exhibited increased choice in switching situations, decreased stress on switching devices, and a larger voltage gain. The possibility of system instability in grid-connected systems was a major disadvantage that may result in undesired oscillations. Moreover, the lack of integration with optimization algorithms limits its adaptability for real-time corrective actions. In [5], it was demonstrated that a generalized integrator modification with DC offset removal capabilities may be used to operate a UPQC with UPQC-SPVA system. In the presence of DC offsets, this method ensures stable PQ increase while reducing the requirement for intricate sensor systems. Also, it might be more complicated than simpler control systems, and the DC offset minimization feature could add computational overhead of its own. This motivates the development of hybrid, computationally efficient optimization strategies to strike a balance between complexity and performance.

3. Proposed Methodology

To produce electricity more efficiently and steadily than with a single source, HRES uses at least two renewable energy sources. The irregular and fluctuating characteristics of renewable energy sources, such as wind and solar, led to PQ issues for HRES, including voltage sags, swells, and harmonics. Thus, the PQ in HRES must be improved. This enhancement of PQ reduces the negative impacts associated with the loads. Similarly, FACTS devices, UPQC, and sophisticated control algorithms are some of the methods and procedures used to improve PQ in HRES. But also, the enhancement of PQ in HERS faced several challenges of load imbalances, harmonics, and voltage sags, respectively. To overcome these problems, the model proposed a novel COAZ optimized UPQC with a PID controller for the HRES-based distribution system. In the proposed model, the hybrid source, such as wind and solar, acts as the input source. The excess power produced by the PV and WT is expected to be stored in the battery. The UPQC controller receives the input power that has been collected from the PV and WT systems. Initially, the obtained PV power is fed into the PV-connected DC/DC converter. This converter can act as the intermediate layer for connecting the sources to the UPQC controller. Simultaneously, the obtained WT power is delivered into the WT-connected AC/DC converter to transform the turbine's AC power to DC power. Then, the output of the WT-connected AC/DC converter is sent into the DC/DC converter, which converts the fluctuating AC power into a constant DC voltage. Similarly, by adjusting load demand, the battery power is transmitted into the battery-connected DC/DC converter, which effectively converts the DC voltage from a battery into a different DC voltage. Thus, the output PV, WT, and battery power are combined and sent into the grid. However, the faulty circumstances and non-linear load cause PQ problems in the grid of the HRES. Thus, the UPQC controller is used on the grid side. The UPQC helps in compensating for PQ issues, non-linear, unbalanced loads, sag, and swell. The UPQC structure in this model includes both a shunt and series compensator, ensuring dual-action control over voltage and current distortions simultaneously. To enhance the parameter of the UPQC, the novel COAZ is employed, which is based on the combined features of COA and ZOA [3], to optimize the performance of the filters by injecting the appropriate power to compensate for the PQ issues through the PID controller. The COAZ algorithm intelligently adjusts the PID gains in real time based on a dynamic error fitness function, enabling faster response to system transients and minimizing steady-state error. This adaptive tuning mechanism improves the overall system reliability and ensures optimal performance even under paid fluctuations in renewable energy inputs. Fig. 1 displays the schematic representation of the proposed COAZ optimized UPQC with a PID controller for HRESs. Furthermore, the proposed framework has been validated under various load scenarios and fault conditions, demonstrating its robustness in maintaining PQ across diverse operational challenges.

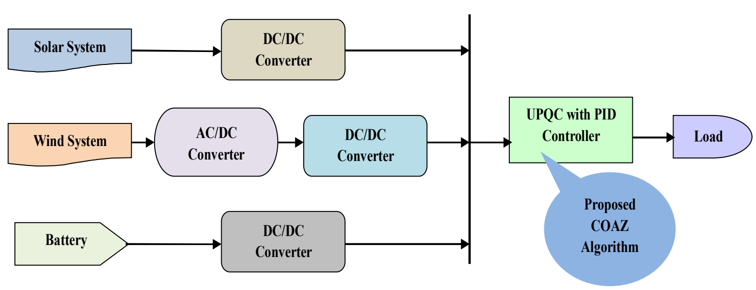

Fig. 1 *Configuration of power quality enhancement using COAZ optimized UPQC with PID controller*

3.1 PID-based UPQC

In this model, the UPQC is used as a control device to compensate for the voltage variation and imbalance, and it is used to fully adjust and synchronize the voltage on the load side. To improve PQ, a UPQC employs both series and shunt active filters to manage several problems, including voltage sags and swells, reactive power, as well as harmonics of current and voltage. In control systems, the PID controller serves as an instrument that is used to adjust process variables such as temperature, flow, pressure, and speed. In this model, the PID controller is used to improve the PQ by lowering harmonic distortion and improving voltage regulation in the model. Thus, to control and enhance PQ in a power distribution system, a UPQC system utilizes the capabilities of a PID controller. However, the UPQC's active filters inject or absorb reactive power and harmonic currents, which are accurately managed by the PID controller, to reduce PQ issues linked to voltage and current. This control scheme ensures minimal steady-state error and faster transient response, which is critical for real-time compensation in HRES applications.

In this proposed model, the UPQC injects the required power to compensate for PQ issues using a PID controller. However, it is often employed for control, assisting in precisely controlling the injected power, guaranteeing accurate compensation for reactive power, harmonics, and other PQ issues. It also addresses PQ issues about both current and voltage. The PID controller's tuning parameters are dynamically adjusted using the proposed COAZ algorithm, leading to improved control precision and enhanced robustness under load variation and fault conditions.

3.2 COAZ Optimization Algorithm

COAZ optimization algorithm is the combination of the COA and ZOA. The application of the COAZ algorithm covers PQ enhancement in HRES, where striking a balance between exploration and exploitation is essential. During the first phase of the ZOA, members received updates on two natural behaviours of zebras. The best member of the population in ZOA is the pioneer zebra, which guides other members of the population to where it is in the search space. Therefore, Eq. (1) and Eq. (2) can be utilized to demonstrate computationally how zebras adjust their position throughout the foraging stage. This simulates herd-based navigation toward optimal regions in multidimensional solution space.

$$y_{i,j}^{new.P1} = y_{i,j} + r.\left(PZ_j - I.y_{i,j}\right) \tag{1}$$

$$Y_i = \begin{cases} Y_i^{new,P1}, & G_i^{new,P1} < G_i, \\ Y_i & else, \end{cases} \tag{2}$$

where, PZ_j denoted its j^{th} dimension, $I = round(1 + rand)$, where $rand$ is a random number in the interval $[0, 1]$, $Y_i^{new,P1}$ is the new position of the i^{th} zebra constructed on the initial phase $y_{i,j}^{new.P1}$ is the j^{th} dimension value, $G_i^{new,P1}$ is the objective function value, where r is a random number in the interval $[0, 1]$, PZ representing that the pioneer zebra is the best member.

However, the position of the iguana is presumed to be that of the best member of the population in the COA design. It is also stated that half of the coast waits for the iguana to fall to the ground, while the other half climbs the tree. Thus, Eq. (3) is used to numerically recreate the position of the coati as it rises from the tree.

$$Y_i^{P1} : y_{i,j}^{P1} = y_{i,j} + r.(Iguana_j - I.y_{i,j}), for \quad i = 1,2,....,\left[\frac{N}{2}\right] and \quad j = 1,\ 2,........,\ m \tag{3}$$

If it increases the value of the objective function, the new location computed for each coati is acceptable for the update process; if not, the coati stays in its previous position. This update

$i = 1,2,......,N$ is the condition for the simulation using Eq. (4).

$$Y_i = \begin{cases} Y_i^{P1}, & G_i^{P1} < G_i \\ Y_i, & else. \end{cases} \tag{4}$$

Unlike ZOA alone, COA enhances exploration by introducing asymmetric climbing and descent behaviour, which helps in avoiding local optima. However, ZOA still faces a significant imbalance between exploration and exploitation. Thus, the model correlated COA with ZOA, which may be able to address the limitations in the ZOA, especially during its initial exploration phase 1.

The optimized COAZ updated the new position by linking the COA and ZOA in Eq. (1) and Eq. (3) to give Eq. (5),

$$Y_i^{P1} : y_{i,j}^{new,2P1} = y_{i,j} + r.(PZIguana_j - I.y_{i,j}), for \quad i = 1,2,....,\left[\frac{N}{2}\right] and \quad j = 1,\ 2,........,\ m \tag{5}$$

If the model increases the value of the objective function, the new location determined for each coati is acceptable for the update process; if not, the coati stays in its previous position. The ZOA and COA linked from Eq. (2) and Eq. (4) to produce a new optimized COAZ algorithm to improve the performance of the proposed model are given in Eq. (6),

$$Y_i = \begin{cases} Y_i^{new.2P1}, & G_i^{new,2P1} < G_i \\ Y_i, & else. \end{cases} \tag{6}$$

In COAZ, the iguana's location in the search space is represented as $PZIguana$ that determines the best member position, $y_{i,j}^{new,2P1}$ also includes the j^{th}dimension, $G_i^{new,2P1}$specifies the objective function value, Y_i^{P1} is represented by the new position computed for the i^{th} coati, and r is a random real integer in the interval [0,1]. The j^{th}dimension Iguana is $Iguana_j$ I denoted by an integer chosen at random from the collection $\{1 \quad 2\}$. These combined equations result in a hybrid optimization technique that dynamically balances convergence speed and solution diversity, particularly useful for real-time PID tuning.

Generally, the COAZ can optimize several factors, including power flow, energy management, and system model. In this suggested model, the COAZ is employed in the UPQC with a PID controller to optimize UPQC's performance, especially when dealing with PQ issues. By adaptively tuning PID parameters in response to real-time system feedback, COAZ significantly enhances the robustness of the UPQC system under varying grid and load conditions. By utilizing the advantages of both COAZ and PID control, the system intends to enhance PQ by removing harmonics and adjusting for variations in voltage and current.

4. Results and Discussions

Simulation studies on estimating the effectiveness of the COAZ optimized UPQC with a PID controller for the HRES model are shown in this section. MATLAB/Simulink 2021b was used to create a simulation framework that examined how well different strategies enhanced PQ from an HRES. The suggested method is contrasted with existing PID controller-based ASO, COA, ZOA, and GA methods. The performance of the ASO, COA, ZOA, GA, and PI controllers also has a strong connection to the results obtained to evaluate how well COAZ produces the best results. The suggested model will be compared with several current models under load conditions, including disturbance and non-disturbance. This comparative analysis helps validate the superiority of the COAZ approach in terms of dynamic response, harmonic mitigation, and voltage stability. All controllers were tested under identical HRES simulation conditions to ensure fairness in the performance comparison.

4.1. Analysis of proposed model under sag condition

In the context of HRES, sags can significantly disrupt the performance of sensitive loads. Fig. 2 represents the analysis of different metrics of the proposed COAZ optimized UPQC with a PID controller for HRES during a sag condition.

During sag condition, the voltage compensation Vcomp of the proposed COAZ model yields the following values at time t=0: $R = 3.0495483812611 \times 10^{-8}$, $Y = 1.21376316353381 \times 10^{-8}$,$B = -8.52734626330918 \times 10^{-9}$. Similarly, the load current of the proposed COAZ model at the same time yielded $R = -2.03496666116325 \times 10^{-6} B = 0.000539838114372635$, respectively. The simulation indicates a rapid response from the UPQC, with voltage sag corrected within few milliseconds and load current distortion effectively minimized. Compared to traditional controllers, the COAZ-PID system demonstrated faster recovery times and commercial loads are not adversely affected. This performance is critical for grid-connected HRES systems, where voltage instability due to renewable intermittency is a frequent challenge.

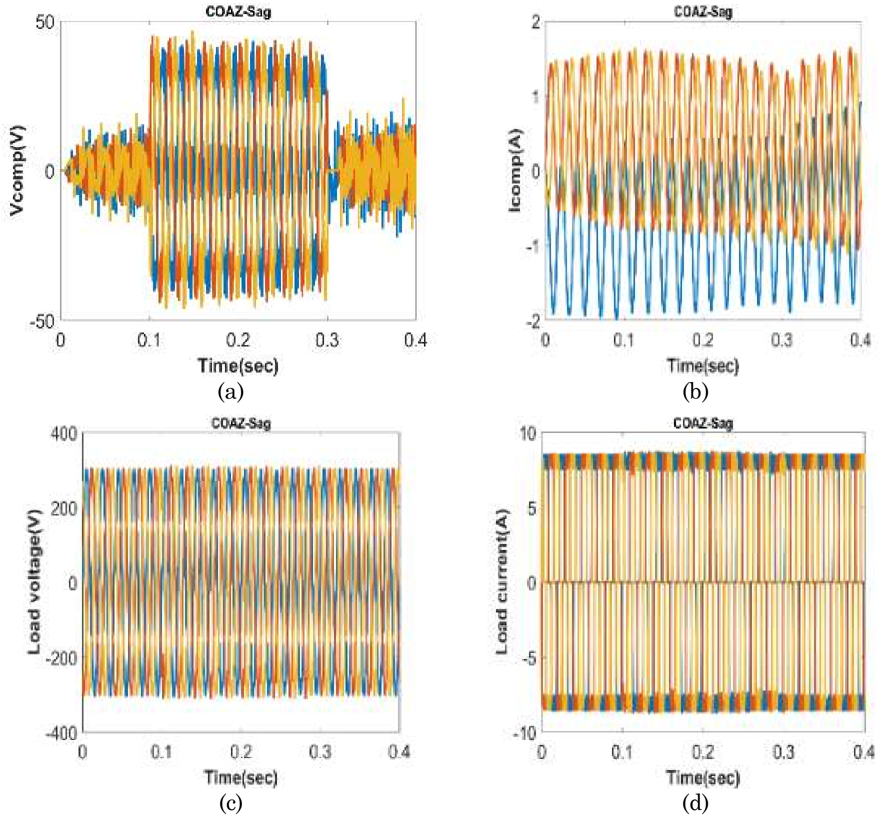

Fig. 2 *Analysis during sag condition (a) Voltage Compensation, (b) Current Compensation, (c) Load Voltage, (d) Load Current*

4.2 Analysis of the proposed model under swell conditions

Fig. 1 represents the analysis of different metrics of the proposed COAZ optimized UPQC with a PID controller for HRES during swell conditions. During swell condition, the voltage compensation Vcomp of the proposed COAZ model yields the following values at time t=0: $R = 1.81853762239788 \times 10^{-8}$, $Y = 1.03510048574495 \times 10^{-9}$,$B = -2.06414563141996 \times 10^{-8}$. Similarly, the load current of the proposed COAZ model at the same time yielded $R = -2.03496670386069 \times 10^{-6} B = 0.000539838118096358$, respectively. Voltage swell, like sag, can severely affect the stability and lifespan of electrical equipment by overstressing components. The proposed COAZ-PID model quickly detects the swell and injects counteractive power using its series filter to maintain voltage within permissible limits. As shown in the results, the model stabilizes the voltage profile within a very short settling time, demonstrating robust swell compensation. Furthermore, the load current remains sinusoidal and stable, confirming that both voltage and current quality are preserved. Compared to GA, COA, and ZOA, the COAZ model consistently achieved a lower peak overshoot and quicker voltage settling, as validated through simulation metrics.

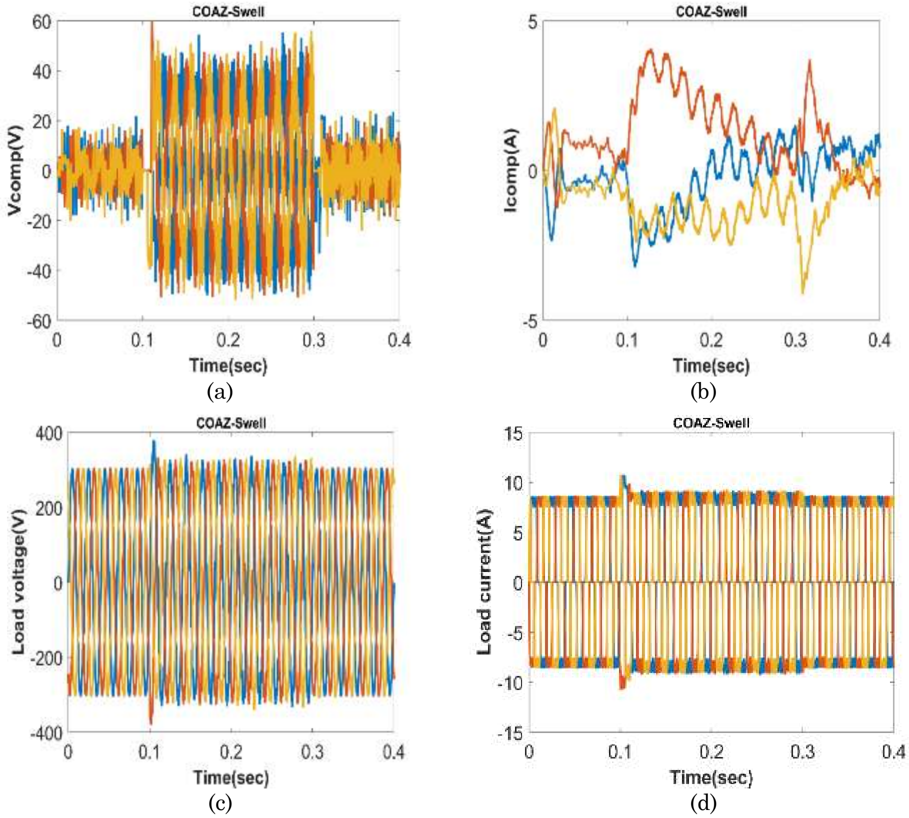

Fig. 3 *Analysis during swell condition including (a) Voltage Compensation, (b) Current Compensation, (c) Load Voltage, (d) Load Current*

4.3 Comparative Analysis

Table 1 shows the analysis of optimal solutions for the proposed COAZ optimized UPQC with a PID controller and the conventional models of HRES-based distribution system using different metrics.

Table 1. *Analysis of optimal parameters of the conventional vs proposed COAZ optimized UPQC with PID controller for HRES*

Metrices	PI	ASO	COA	ZOA	COAZ
Kp	1	0.25	10.223	23.02	1
Ki	1	0.36565	5.232	10.323	0.5
Kd	0	0.1	1.2323	2.3323	0.1

Table 2 shows the analysis of DC link voltage stability for the proposed COAZ optimized UPQC with PID controller and the conventional models of HRES-based distribution system using different metrics. For risetime, the proposed PID-optimized COAZ model obtained values of 0.36345 which is lower than that of existing model of COA with 0.36398, ZOA with 0.3637, ASO with 0.36406, respectively, however, for settling time, the proposed PID-optimized COAZ model obtained values of 0.38624 which is lower than that of existing model of COA with 0.39627, ZOA with 0.3962, ASO with 0.39628, respectively. This indicates that the proposed method achieves faster dynamic response and stability compared to other algorithms. The reduction in risetime and settling time reflects improved real-time performance, essential for maintaining PQ in fluctuating renewable environments. In addition, the smaller delay in stabilization contributes to less energy loss and reduced stress on connected equipment. Thus, the proposed PID optimized COAZ-based UPQC model for HRES could accurately enhance the PQ of the model. Therefore, the integration of COAZ not only improves compensation accuracy but also enhances the overall resilience and responsiveness of the HRES distribution system.

Table 2. *Stability Analysis for DC Link Voltage of the conventional vs proposed COAZ optimized UPQC with PID controller for HRES*

Metrices	PI	COA	ZOA	ASO	COAZ
RiseTime	0.36371	0.36398	0.3637	0.364	0.3634
SettlingTime	0.39632	0.39627	0.3962	0.3962	0.3862
SettlingMin	148.79	147.73	148.71	147.72	149.65
SettlingMax	165.3	164.14	165.19	164.12	166.24
Peak	165	164.14	165.19	164.12	166.24
PeakTime	0.4	0.4	0.4	0.4	0.4

5. Conclusion

This work proposed a COAZ optimized UPQC with a PID controller for HRES to enhance the PQ of the model. The hybrid sources, including wind, solar, and battery, were used to produce power for the system. In this model, the UPQC was utilized to control several PQ problems in distribution systems, such as negative sequence current, voltage imbalance, and voltage sags and swells. The proposed COAZ algorithm was obtained by the combination of COA and ZOA, respectively. In the HRES, a COAZ-based PID controller regulates the PID controller's settings to enhance system performance, especially when temperature, wind speed, and solar radiation fluctuate. The suggested technique produced better efficiency, decreased oscillations, and quicker response compared to conventional methods. The COAZ algorithm significantly outperformed traditional optimization strategies like ASO, GA, and standalone ZOA/COA in terms of risetime, settling time, and response stability. Its adaptive control capability allowed the PID controller to respond more effectively to dynamic changes in generation and load conditions. Additionally, the UPQC's dual compensation worked harmoniously with the COAZ optimizer, ensuring harmonics suppression and voltage regulation across diverse grid conditions. The results confirm that the model is resilient and flexible, making it a suitable solution for practical situations. Future work may explore hardware implementation and real-time validation of the proposed model to further assess its performance under real-world disturbances and renewable intermittencies.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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