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Advanced Technology for Sustainable Power Quality: Open UPQC Control Strategies from Developed Grid Frameworks

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Abstract: In this study, we investigate the integration of thin-film-based voltage sensing concepts with an Open-type Unified Power Quality Conditioner (Open-UPQC) controlled by Model Predictive Control (MPC) to mitigate voltage sag and swell disturbances in renewable-integrated distribution networks. Recent advances in thin-film sensing technologies have enabled compact, high-sensitivity voltage monitoring elements suitable for smart power systems. This work explores how such sensing principles can support fast and accurate disturbance detection within a UPQC compensation scheme. The proposed Open-UPQC is implemented in the Matlab simulation platform to mitigate voltage magnitude disturbances in a 230 V single-phase AC distribution system. An MPC strategy regulates the series and shunt voltage source converters of the Open-UPQC, enabling rapid and precise voltage compensation during sag and swell events; the controller predicts system behaviour over a finite horizon and generates optimal switching actions to restore the load voltage to its rated value under dynamic grid conditions, with the underlying sensing layer informing the accuracy of these predictions. Simulation studies are performed for typical sag and swell scenarios to validate the compensation effectiveness of the proposed controller. Results confirm that the MPC-based Open-UPQC, supported by thin-film sensing principles, achieves rapid voltage restoration, stable transient performance, and strong robustness against load variations. The proposed approach offers a sustainable and reliable solution for improving voltage stability in 230 V renewable-supported distribution networks, with particular relevance to power-sensitive industrial applications such as thin-film manufacturing systems.

Keywords: Open-UPQC; Model Predictive Control (MPC); Voltage Sag; Voltage Swell; 230 V Distribution System; Thin-Film Engineering; Power Quality Enhancement; Renewable Energy Integration.

1. Introduction

The rapid integration of renewable energy sources such as solar photovoltaic and wind generation into modern electrical distribution systems has increased the complexity associated with maintaining stable voltage conditions [1]. In India, a large portion of domestic and light commercial consumers are supplied through a 230 V single-phase AC network, wherein voltage stability is critical for reliable operation of sensitive loads including household electronics, medical devices, automation equipment, and small industrial drives [2]. However, the intermittent nature of renewable generation, together with switching operations and sudden load variations, frequently introduces voltage disturbances in low-voltage distribution systems, particularly in the form of voltage sag and voltage swell [1]. Among various voltage disturbances, sag and swell are considered the most critical because they directly influence the load-side voltage magnitude and may cause malfunction of sensitive equipment, interruption of industrial processes, and reduction in system reliability, leading to considerable economic losses [3].

A voltage sag comprises a temporary reduction in RMS voltage magnitude to approximately 10%–90% of its nominal value for durations ranging from half a cycle to one minute, typically caused by short-circuit faults, motor starting currents, or feeder switching events [5]. Conversely, a voltage swell comprises a temporary rise in RMS voltage magnitude beyond the nominal value, generally within the range of 110%–180%, which may occur due to sudden load removal, unbalanced faults, or grounding issues [6]. Therefore, effective mitigation of sag and swell disturbances is essential for maintaining stable operation of low-voltage 230 V distribution systems [6].

To mitigate these disturbances, compensation devices comprising Dynamic Voltage Restorers (DVR) and Distribution Static Compensators (DSTATCOM) have been utilized in distribution networks [7], [8-9]. A DVR operates as a series compensation device configured to inject a controlled voltage into the feeder, thereby restoring the load voltage during sag conditions. In contrast, a DSTATCOM operates as a shunt compensation device configured to regulate voltage through reactive power support and current control. Although each device individually addresses specific voltage regulation requirements, effective mitigation of both sag and swell disturbances in modern distribution networks requires coordinated operation of both series and shunt

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compensation structures [10].

In this study, the Unified Power Quality Conditioner (UPQC) comprises a combined configuration of a DVR and a DSTATCOM operating simultaneously through series and shunt converters to provide comprehensive voltage regulation and power quality improvement. A particular configuration known as the Open-type Unified Power Quality Conditioner (Open-UPQC) comprises a structure in which the series and shunt converters operate without a common DC-link connection. In this arrangement, the series converter performs voltage injection to compensate sag or swell disturbances, while the shunt converter provides current regulation and reactive power support to maintain system stability. The absence of a common DC link enables flexible power exchange between the converters and simplifies structural implementation in low-voltage distribution networks. Accordingly, the Open-UPQC configuration provides an effective solution for mitigating voltage sag and swell disturbances in 230 V distribution systems while maintaining stable load-side voltage under dynamic operating conditions.

2. Literature Review

Voltage sag and voltage swell are among the most critical voltage disturbances in low-voltage distribution systems, particularly in renewable-integrated networks where intermittent generation and rapid load variations frequently affect voltage stability. In India, most residential and light commercial consumers operate on a 230 V single-phase AC distribution supply, making sag and swell mitigation highly essential for ensuring uninterrupted operation of sensitive loads such as electronic appliances, automation systems, and small industrial drives [11]. Maintaining a stable 230 V supply is therefore a major requirement in modern distribution networks, especially under increasing renewable penetration [12].

Traditional voltage compensation devices such as Dynamic Voltage Restorers (DVR) have been widely researched for voltage sag and swell mitigation. Wang et al. [4] presented DVR operation and control principles and demonstrated that series voltage injection is an effective approach to restore load voltage during sag conditions. Vilathgamuwa et al. [6] introduced techniques for compensating sags in multi-line distribution systems and highlighted the effectiveness of series compensators for voltage stability enhancement. Similarly, Kwan et al., [13] proposed fast transient DVR control methods for sag compensation without external DC sources, emphasizing the need for rapid controller response during short-duration voltage disturbances.

Ghosh and Ledwich [5] also demonstrated DVR-based sag compensation methods and reinforced the importance of series voltage injection in distribution systems. Although DVR systems provide effective voltage correction, their performance can be constrained by limited energy support and the need for coordinated control under repeated sag/swell events. To provide improved voltage compensation capability, Unified Power Quality Conditioner (UPQC) based solutions have been introduced as advanced power quality enhancement devices. The UPQC combines a series converter and a shunt converter to provide coordinated voltage regulation and distribution system support [14]. Early work by [15] demonstrated that combined series and shunt compensation offers improved performance compared to individual compensators. Study of [16] further provided detailed explanations of UPQC principles and converter coordination methods, establishing UPQC as a strong solution for voltage regulation in distribution networks. Later, Brenna et al. [12] proposed an Open-UPQC configuration and showed that open-type arrangements can effectively improve voltage profiles and load performance under voltage disturbance conditions. These foundational contributions established Open-UPQC as a flexible topology suitable for voltage sag and swell mitigation in low-voltage systems.

Barros et al. proposed one of the most recognized Open-UPQC concepts, demonstrating its ability to improve distribution system voltage stability and enhance load-side voltage quality through coordinated converter operation [13]. Their work highlighted the importance of control strategies capable of ensuring rapid voltage restoration during sag and swell conditions, making Open-UPQC an attractive solution for modern distribution applications.

With the increasing complexity of renewable-supported distribution networks, recent studies have focused on advanced controller design to enhance UPQC and Open-UPQC performance. In particular, the use of Model Predictive Control (MPC) has gained strong attention due to its predictive nature, ability to optimize control actions, and capability to handle system constraints explicitly. Kwan et al. presented one of the early and important contributions by implementing MPC for UPQC applications and demonstrated that MPC provides effective voltage regulation and improved power quality performance through predictive system modelling and optimized control action selection [14]. This work confirmed that MPC is suitable for converter-based compensators due to its fast dynamic response and ability to handle switching-based systems effectively.

Kazemi-Robati et al. [15] proposed a dynamic reference voltage adjustment strategy for Open-UPQC to improve distribution network hosting capacity under high distributed generation penetration. Their results demonstrated strong voltage restoration capability under sag and swell events, proving Open-UPQC as a practical solution for renewable-integrated networks. Their study also highlighted that controller selection plays a major role in ensuring fast transient response and stable voltage recovery in distribution systems experiencing frequent voltage fluctuations.

Babaei et al., [16] investigated UPQC-O placement and system-level optimization in renewable-rich distribution networks and showed that UPQC-O can significantly reduce voltage deviation during disturbance conditions. Their work reinforced that Open-UPQC is an effective device for maintaining voltage stability under sag and swell disturbances, especially in systems with distributed renewable generation. Although their approach was optimization-based, it indicated the need for fast real-time control strategies such as predictive controllers for improved practical implementation.

Several alternative control methods have also been explored in literature for voltage regulation under sag and swell conditions. Gomathi [17] investigated sliding mode-based controllers for power quality improvement and reported strong robustness and rapid recovery during voltage disturbances; however, chattering effects were noted as a practical limitation due to switching stress. Gopal [18] proposed fuzzy-based voltage sag and swell controllers and demonstrated stable performance under uncertain operating conditions, although the tuning of membership functions and rule bases remained a key challenge for maintaining consistent performance under varying disturbance depths. These studies confirm that intelligent and robust controllers provide improved performance compared to classical PI regulators, but their practical effectiveness can still be limited under fast transients or repeated sag and swell conditions.

From the reviewed works, it is evident that Open-UPQC provides a strong technical solution for voltage sag and swell mitigation in distribution systems. However, controller selection is the most critical factor in achieving fast voltage restoration and stable transient response. Conventional controllers may require extensive tuning and may not guarantee optimal performance under changing load conditions or renewable intermittency. In contrast, Model Predictive Control (MPC) offers superior benefits due to its predictive capability, optimized switching selection, and explicit handling of operational constraints, making it highly suitable for Open-UPQC systems operating in 230 V low-voltage networks.

Therefore, based on the research gap identified from the existing literature, this work focuses exclusively on the design and MATLAB/Simulink simulation of an MPC-controlled Open-UPQC for a 230 V single-phase AC distribution system, targeting only voltage sag and swell disturbance mitigation. The proposed study contributes toward developing an effective and modern voltage compensation strategy suitable for renewable-supported Indian distribution systems.

Unified Power Quality Conditioner (UPQC) based solutions have emerged as advanced custom power devices that integrate both series and shunt converters to achieve improved voltage regulation performance [19]. Further, study [20] showed that combined series–shunt compensation provides superior voltage restoration capability compared to individual compensators. In study [21] presented detailed UPQC principles and control approaches, establishing UPQC as an effective device for voltage regulation in distribution systems. Later, Brenna et al. [12] introduced the Open-UPQC concept and demonstrated that open-type configurations can improve voltage performance under disturbance conditions. Study of [22] proposed one of the most recognized Open-UPQC topologies, confirming that Open-UPQC offers improved flexibility and coordinated operation for voltage disturbance mitigation. The Open-UPQC is particularly suitable for low-voltage distribution applications because it enables effective voltage restoration using series injection and shunt support, without requiring complex transformer-based arrangements. Additionally, Open-UPQC systems can support distribution networks with distributed generation where voltage disturbances occur frequently due to renewable penetration and fluctuating loads [19].

3. Methodology

The proposed methodology follows a systematic MATLAB/Simulink-based simulation procedure for evaluating an MPC-controlled Open-UPQC under 230 V voltage sag and swell disturbances as shown in Fig. 1. Initially, system parameters such as grid voltage, feeder impedance, load characteristics, and converter ratings are defined, and the Open-UPQC model is developed with series and shunt compensating units. A discrete-time MPC controller is then implemented using a fixed sampling time Ts, and the reference load voltage is set to 230 V. Voltage sag and swell disturbances are generated by varying the grid voltage magnitude, and the grid and load voltages are continuously measured. The MPC algorithm computes the voltage error, predicts the future system response, and selects the optimal converter switching state by minimizing the cost function. Based on this decision, switching pulses are generated and applied to the converters, enabling the series unit to inject the required compensating voltage. Finally, waveform results such as grid voltage, load voltage, injected voltage and grid current are recorded and analyzed to validate the sag and swell compensation performance of the proposed Open-UPQC system.

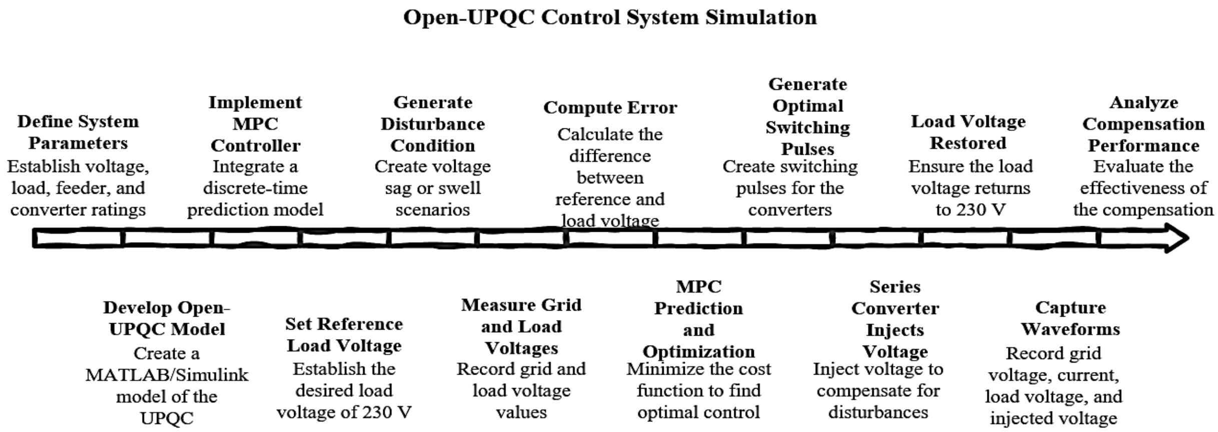

Fig. 1: Flowchart of the proposed MATLAB/Simulink-based methodology for MPC-controlled Open-UPQC simulation under 230 V voltage sag and swell conditions

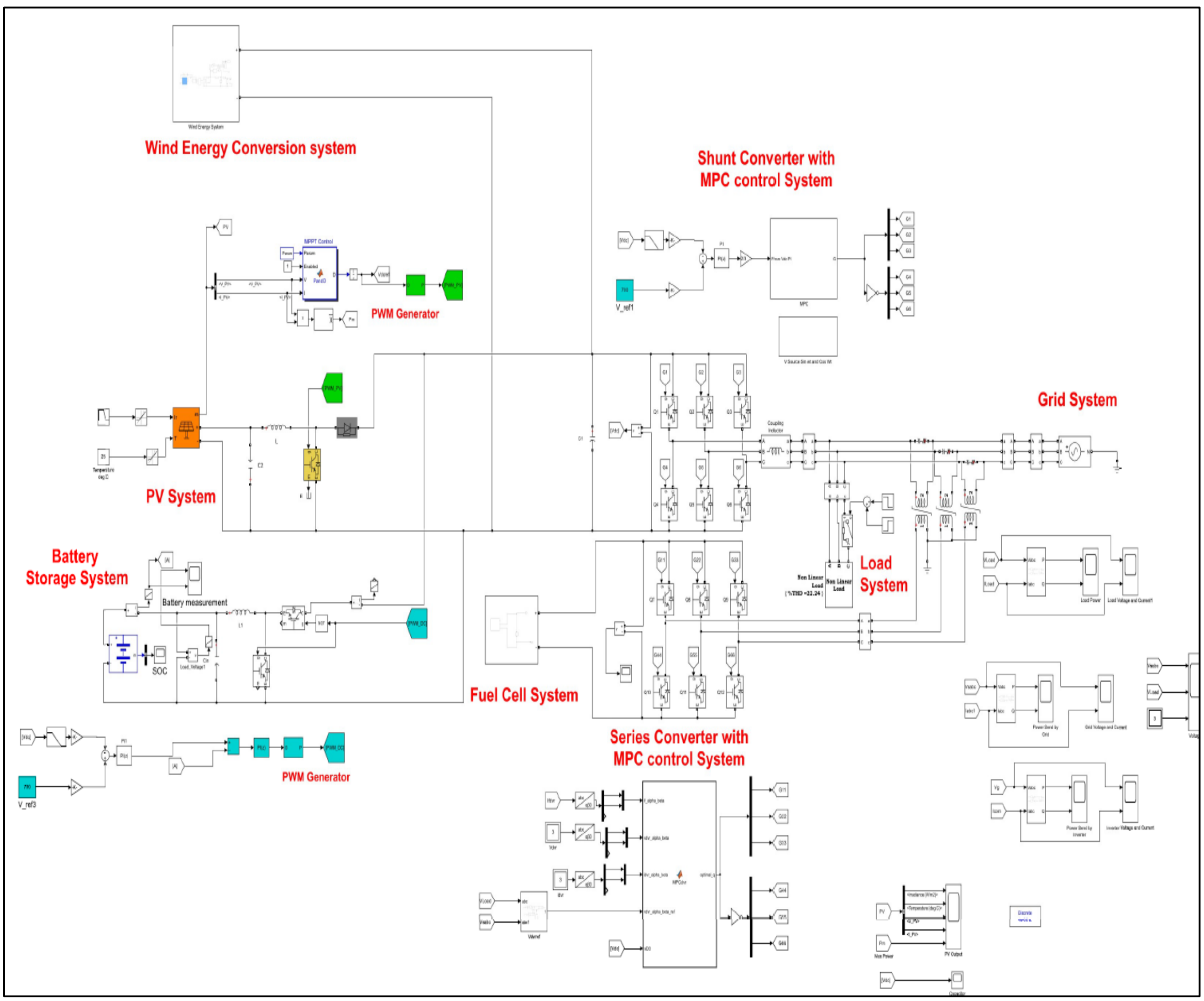

Fig. 2: MATLAB/Simulink model of the proposed MPC-controlled Open-UPQC system with renewable energy sources (wind, PV, battery, fuel cell) for voltage sag and swell compensation in a 230 V distribution network.

3.1 Experimental work on Simulation of MPC-Based Open-UPQC Model

The proposed open unified power quality conditioner (Open-UPQC) system is designed to mitigate voltage sag and voltage swell disturbances in a 230 V distribution network using coordinated series and shunt compensation. The overall circuit configuration consists of a grid/source connected to a nonlinear load through a distribution feeder, where the Open-UPQC is integrated at the point of common coupling (PCC), as shown in Fig. 2. The Open-UPQC comprises two main compensating units: The Series Active Power Filter (SEAPF) and the Shunt Active Power Filter (SHAPF). The SEAPF is connected in series with the feeder through an injection transformer arrangement and is responsible for generating and injecting the compensating voltage V_{inj} during sag and swell events. This injected voltage ensures that the load-side voltage is maintained close to its rated reference value. In addition, the SHAPF is connected in parallel at the PCC and supports the compensation process by regulating the current exchange required during dynamic voltage disturbance conditions, thereby improving overall system stability.

The complete Open-UPQC system is modeled and simulated in the MATLAB/Simulink environment for performance validation under sag and swell disturbances. The simulation is executed in discrete mode using a fixed sampling time Ts , enabling implementation of the Model Predictive Control (MPC) switching logic. Voltage measurement blocks are incorporated to monitor the grid voltage V_s, load voltage V_L, and injected voltage V_{inj}. These measured signals are provided as inputs to the MPC controller, which predicts the future voltage behavior of the system and determines the optimal converter switching state required to achieve effective compensation. The corresponding output waveforms, including grid voltage, load voltage, injected voltage, and grid current, are captured through scope blocks for detailed performance evaluation. This simulation framework ensures accurate validation of the Open-UPQC operation and confirms stable load voltage regulation during dynamic sag and swell conditions.

3.2 Mathematical Modelling and MPC Control Strategy

The primary objective of the proposed MPC-based Open-UPQC is to maintain the load voltage V_L at the rated reference value V_{ref}(t) (230 V RMS equivalent) even when the supply/grid voltage $V_s(t)$ experiences sag or swell disturbances. The injected compensating voltage $V_{inj}(t)$ is produced by the series converter such that:

$$V_L(t) = V_s(t) + V_{inj} \tag{1}$$

Therefore, the required injected voltage is computed as:

$$V_{inj}(t) = V_{ref}(t) - V_s(t) \tag{2}$$

During sag, Vs(t) decreases and $V_{inj}(t)$ becomes positive in phase with the supply. During swell, $V_s(t)$ increases and $V_{inj}(t)$ becomes negative (opposite polarity), thereby maintaining the load voltage constant.

To implement the MPC algorithm in discrete-time form, the system is represented with a sampled model where the control action is updated at each sampling instant. The controller predicts the future behavior of the load voltage based on present measurements and selects the optimal switching state of the Open-UPQC converters to minimize the deviation from the reference voltage. The voltage tracking error is defined as:

$$e(t) = V_{ref}(t) - V_L(t) \tag{3}$$

The MPC objective is to minimize this error by selecting the switching state that produces the required injected voltage. Therefore, the optimization function can be expressed in simplified form as:

$$J = (V_{ref}(k+1) - V_L(k+1))^2 \tag{4}$$

where k represents the discrete sampling instant. At every sampling step, the controller evaluates the predicted load voltage for all possible switching combinations and selects the switching state that results in minimum cost function value. The selected switching state is then applied to the series and shunt converter switches of the Open-UPQC. Thus, the MPC controller ensures that the injected voltage is dynamically adjusted during sag and swell events such that;

$$V_L(t) \approx V_{ref}(t) \tag{5}$$

This predictive approach enables fast compensation and stable voltage restoration under transient grid disturbances.

4. Results and Discussion

4.1 Voltage Sag Condition Analysis

Fig. 3 presents the simulation results of the proposed MPC-controlled Open-UPQC under a voltage sag disturbance occurring between 0.7 s and 0.8 s. Fig. 3(a) shows the three-phase grid voltage, in which a clear reduction in magnitude is observed for all three phases during the sag interval, representing a typical disturbance caused by short-circuit faults or sudden load variations. Fig. 3(b) shows the corresponding injected voltage generated by the series converter. During the sag period, the injected voltage rises sharply in phase with the grid voltage, reaching approximately 70-80 V, indicating that the MPC controller actively compensates for the reduced supply magnitude. Fig. 3(c) presents the load voltage waveform, which remains nearly constant in magnitude and waveform shape throughout the sag interval, confirming that the Open-UPQC successfully isolates the load from the grid-side disturbance. These results validate that the MPC-controlled Open-UPQC achieves fast and accurate compensation during voltage sag conditions with minimal distortion at the load terminals.

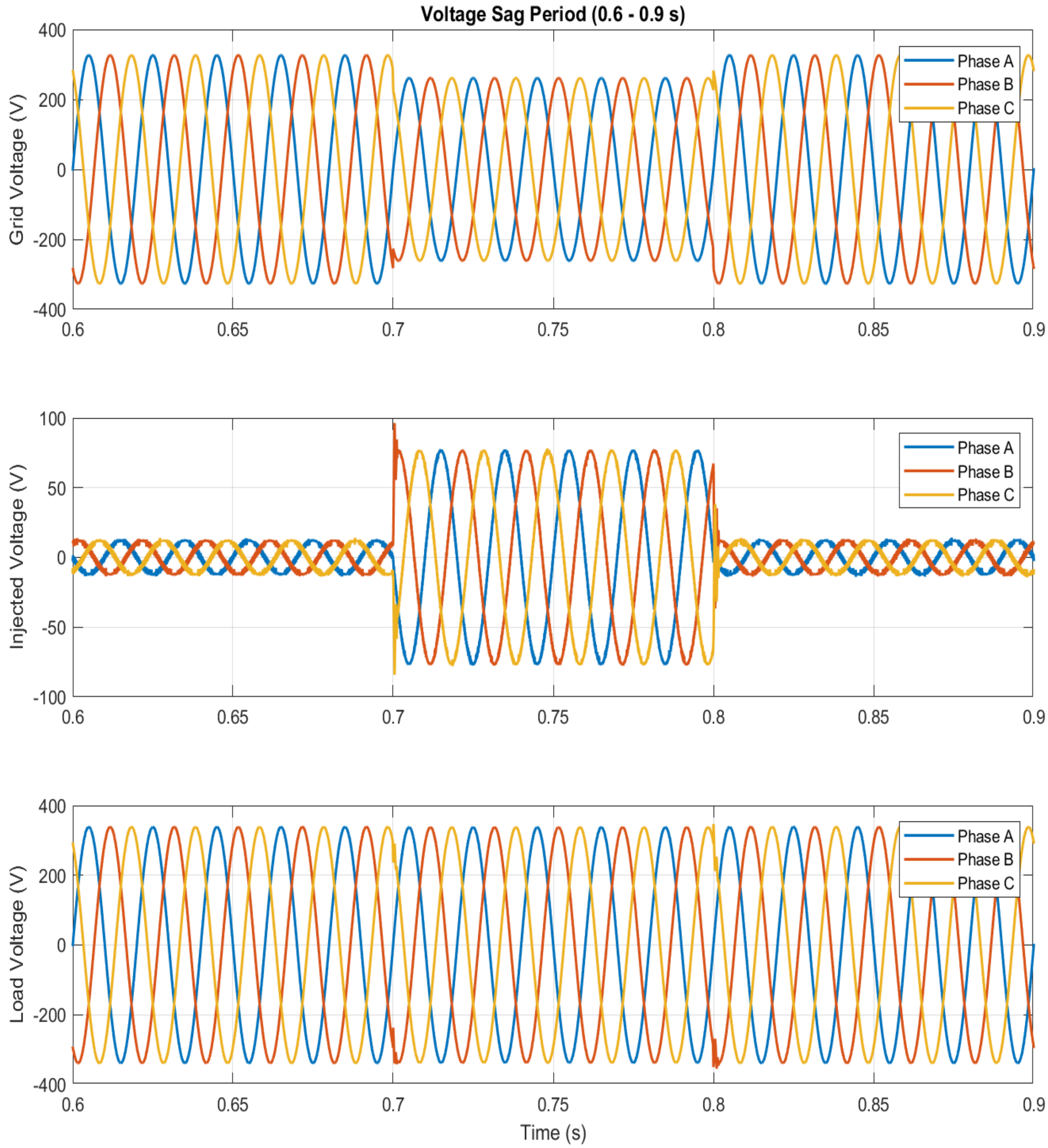

Fig. 3: Three-phase grid voltage, injected voltage, and load voltage waveforms of the MPC-controlled Open-UPQC during the voltage sag period (0.6 s-0.9 s).

4.2 Voltage Swell Condition Analysis

Fig. 4 illustrates the corresponding waveform results for a voltage swell disturbance occurring between 1.0 s and 1.1 s. Fig. 4(a) shows the three-phase grid voltage increasing sharply above its nominal magnitude during the swell interval, representing a typical overvoltage condition caused by sudden load rejection or switching events. Fig. 4(b) presents the injected voltage response, which is generated with opposite polarity relative to the sag case, reaching approximately 50-55 V, thereby subtracting the excess voltage from the supply. Fig. 4(c) shows the load voltage, which remains regulated close to its rated magnitude throughout the swell interval despite the disturbance on the grid side. These results confirm that the MPC controller correctly identifies the swell condition and generates the appropriate compensating polarity and magnitude in real time.

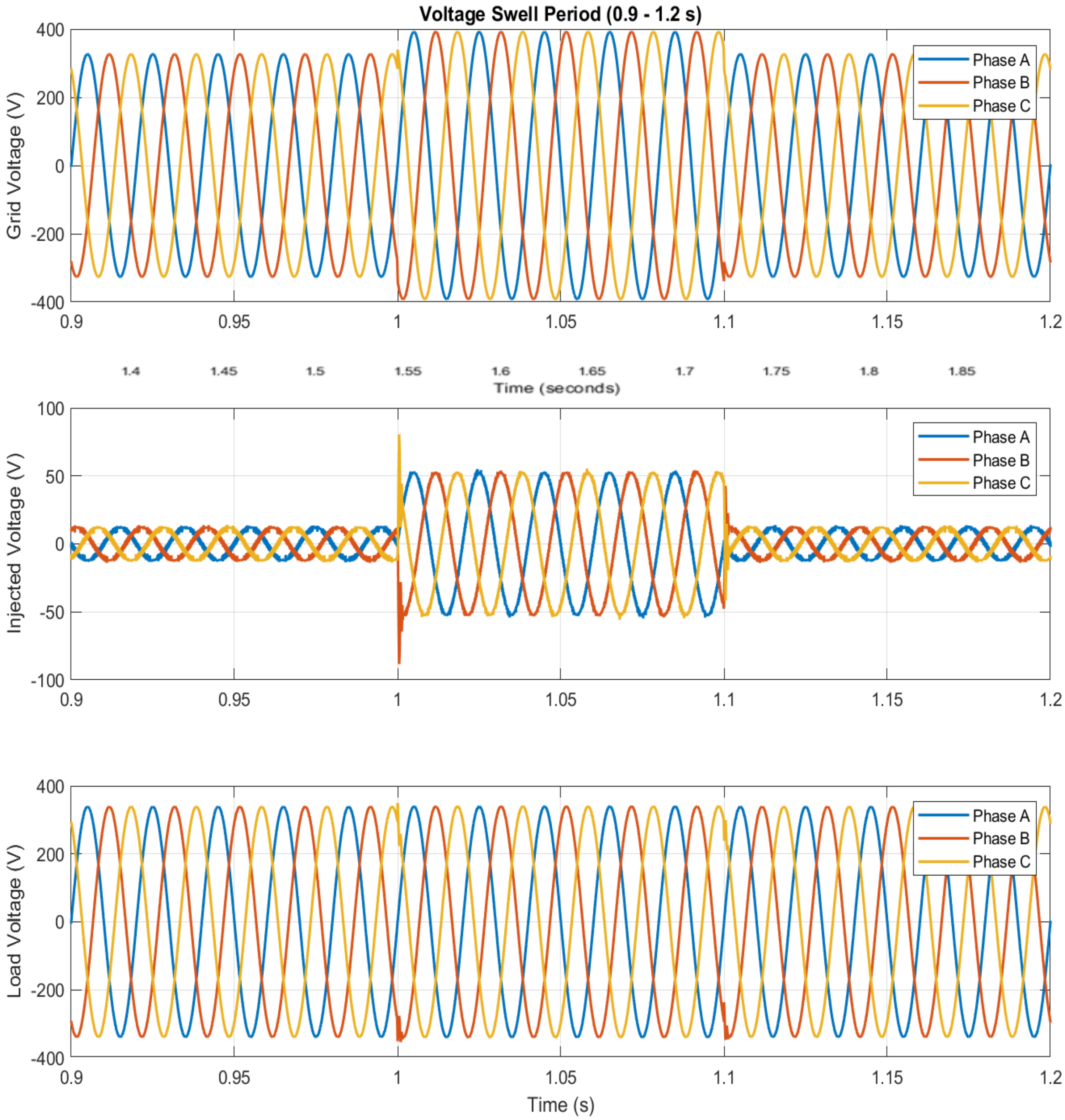

Fig. 4: Three-phase grid voltage, injected voltage, and load voltage waveforms of the MPC-controlled Open-UPQC during the voltage swell period (0.9 s-1.2 s).

4.3 Grid-Side Voltage, Current, and Power Analysis

Fig. 5 presents an extended analysis of the grid-side electrical quantities over the full simulation interval (0.1 s-1.5 s), encompassing both the sag and swell events. Fig. 5(a) shows the three-phase grid voltage, in which the sag interval (0.7 s-0.8 s) and swell interval (1.0 s-1.1 s) are both clearly visible as reductions and increases in voltage magnitude, respectively. Fig. 5(b) shows the corresponding three-phase grid current, which exhibits a transient response immediately after the simulation start but stabilizes into a periodic waveform with relatively low sensitivity to the sag and swell events, indicating that the Open-UPQC compensates primarily through voltage injection rather than imposing significant current disturbance on the supply side. Fig. 5(c) and Fig. 5(d) show the real power (P_grid) and reactive power (Q_grid) drawn from the grid, respectively. Both quantities display an initial transient settling period before stabilizing to near-constant values, with only minor deviations corresponding to the sag and swell intervals. This behaviour confirms that the Open-UPQC maintains stable power exchange with the grid even during voltage disturbance events.

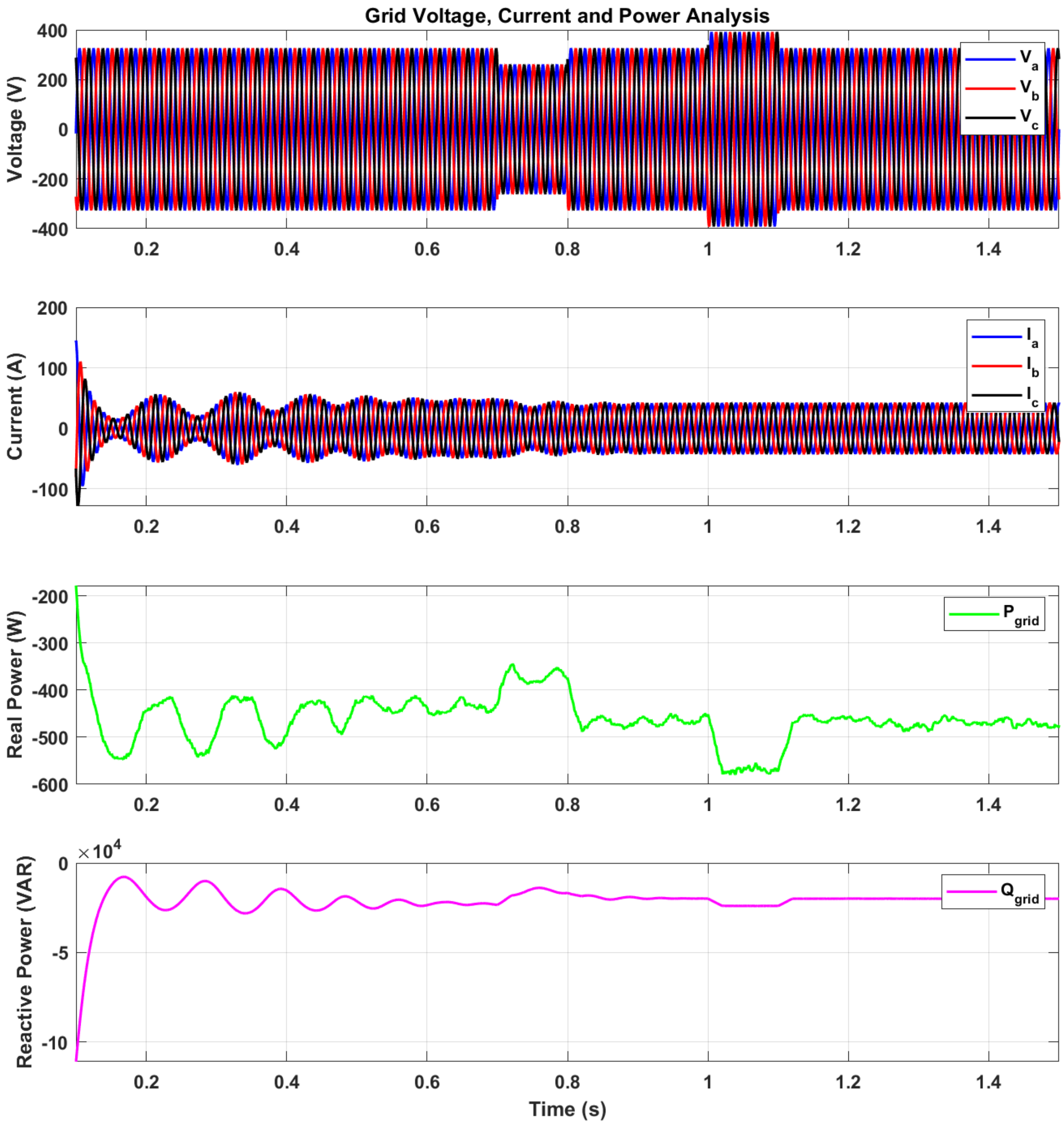

Fig. 5: Grid voltage, current, real power, and reactive power analysis of the MPC-controlled Open-UPQC system over the complete simulation period, including sag and swell disturbance intervals.

4.4 Combined Grid, Injected, and Load Voltage Response

Fig. 6 presents the combined waveform results of grid voltage, injected voltage, and load voltage over the full simulation period, enabling direct comparison of compensation behaviour across both disturbance events. Fig. 6(a) shows the three-phase grid voltage with the sag (0.7 s-0.8 s) and swell (1.0 s-1.1 s) intervals clearly visible. Fig. 6(b) shows the injected voltage generated by the series converter, which remains near zero under normal conditions and activates only during the disturbance intervals, with positive-polarity injection during sag and reduced-magnitude injection of opposite character during swell. Fig. 6(c) shows the resulting load voltage, which remains consistently regulated near its rated magnitude throughout the entire simulation, including during both disturbance intervals. This confirms that the MPC-controlled Open-UPQC provides continuous and reliable voltage regulation across multiple, sequential disturbance events without requiring controller re-initialization or exhibiting degraded performance on repeated operation.

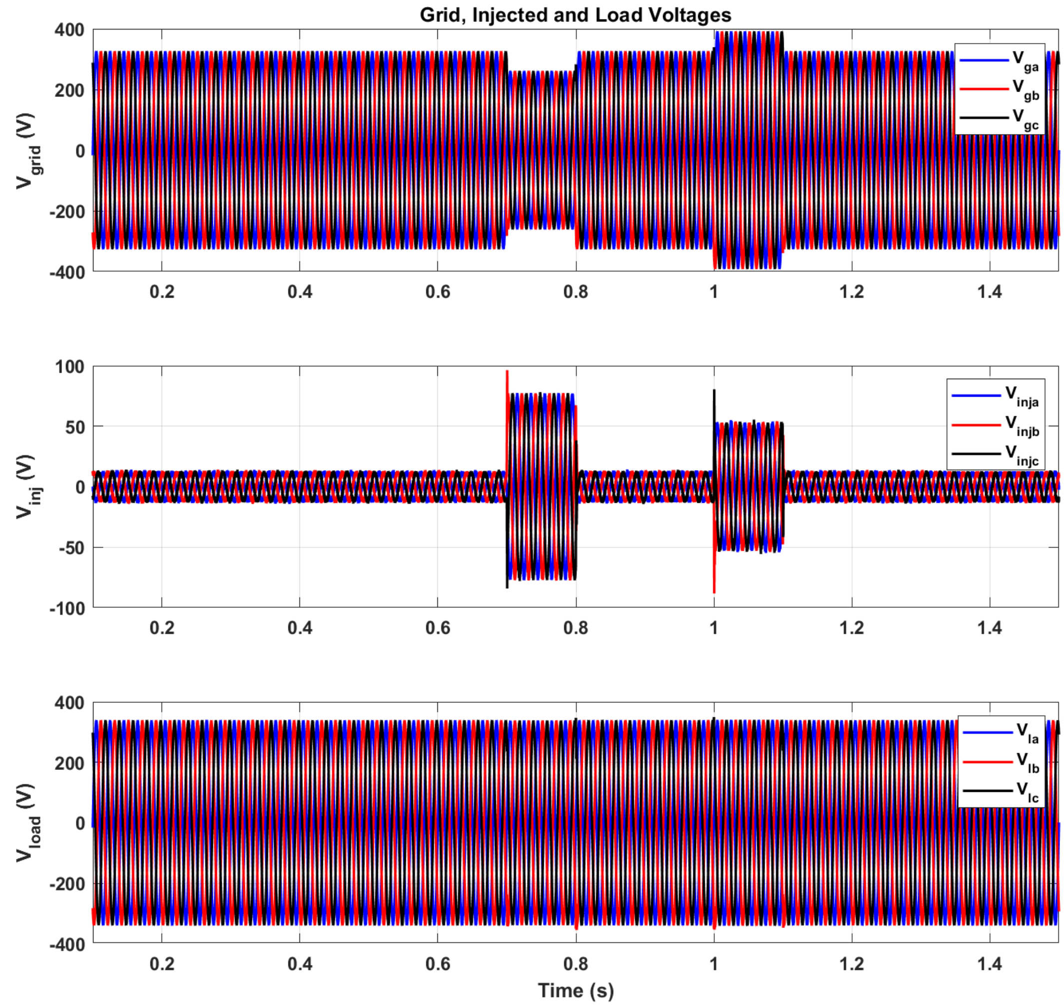

Fig. 6: Combined grid voltage, injected voltage, and load voltage waveforms of the MPC-controlled Open-UPQC across the full simulation period, illustrating coordinated compensation during sequential sag and swell events.

4.3 Injected Voltage Response Analysis

Fig. 7 presents the combined waveform results of the MPC-controlled Open-UPQC system under voltage sag and swell conditions for a 230 V distribution network. Fig. 7(a) shows the grid voltage waveform, where voltage disturbances are intentionally introduced to evaluate the performance of the compensation strategy. It is observed that a voltage sag occurs approximately between 0.90 s and 1.00 s, during which the grid voltage magnitude reduces significantly below the nominal value. Similarly, a voltage swell is observed approximately between 1.60 s and 1.70 s, where the grid voltage magnitude increases above the rated value. These variations indicate abnormal supply conditions which typically lead to poor power quality and malfunction of sensitive loads.

Fig. 7(b) shows the corresponding load voltage waveform. Even though the grid voltage experiences a sag (reduction) and swell (increase), the load voltage remains nearly constant throughout the entire simulation interval, maintained close to the rated 230 V reference level. During the sag period (0.90 s to 1.00 s), the load voltage does not drop along with the grid voltage, and during the swell period (1.60 s to 1.70 s), the load voltage does not rise above the nominal value. This confirms that the Open-UPQC successfully isolates the load from supply disturbances, thereby ensuring stable voltage regulation.

Fig. 7(c) illustrates the injected voltage waveform generated by the series converter. It is clearly observed that the injected voltage remains nearly zero under normal conditions and becomes active only during disturbance intervals. During the sag event (0.90 s to 1.00 s), the injected voltage is produced with positive polarity and a magnitude of approximately +80 V to +100 V, which adds to the reduced grid voltage and restores the load voltage. During the swell interval (1.60 s to 1.70 s), the injected voltage is generated with negative polarity in the range of approximately −80 V to −100 V, thereby subtracting the excessive grid voltage and preventing overvoltage at the load terminals. This confirms that the MPC controller generates the correct compensation magnitude and polarity in real time.

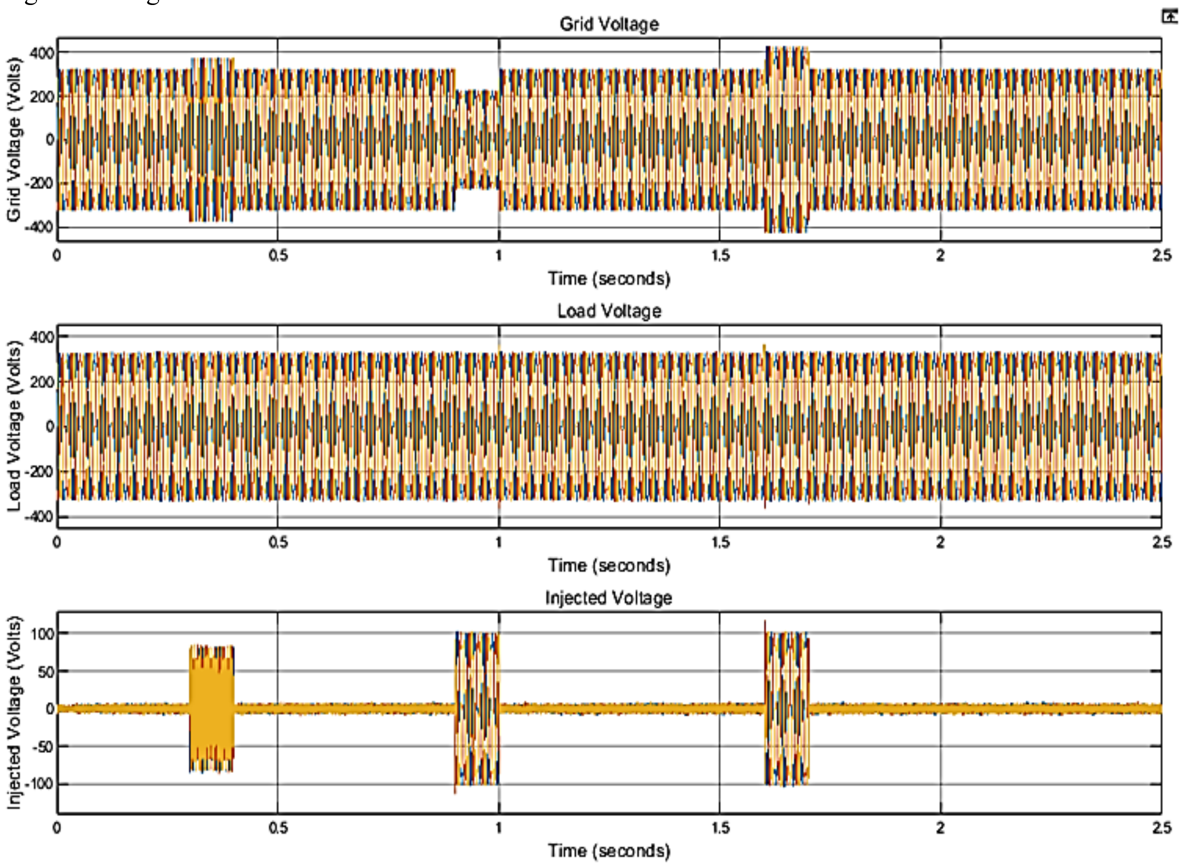

Fig. 7(a): Grid voltage waveform of the 230 V system under sag and swell disturbances. **Figure . 7(b).** Load voltage waveform of the MPC-controlled Open-UPQC under sag and swell disturbances (230 V system). **Figure. 7(c).** Injected voltage waveform generated by the series converter during sag and swell compensation (230 V system)

4.4 Performance Comparison of Control Strategies

Table 1: Comparative Performance of Controllers for Voltage Sag and Swell Compensation.

Parameter	**Conventional PI**	**FLC (Fuzzy Logic Controller)**	**ANN Controller**	**SMC (Sliding Mode Control)**	**Proposed MPC**
Sag Recovery Time	40–60 ms (slower dynamic response due to fixed gains)	25–35 ms (rule-based fast response)	20–30 ms (data-driven adaptive action)	15–25 ms (fast switching dynamics)	< 20 ms (predictive compensation before peak sag)
Swell Recovery Time	~40 ms	20–30 ms	20–25 ms	15–20 ms	< 15 ms (pre-emptive voltage injection)
Overshoot in DVR-Link Voltage	Moderate (5–10%)	Low (3–6%)	Low (2–5%)	Very Low but chattering may occur	Minimal (<2%)
Settling Time DVR-Link	50–80 ms	30–50 ms	25–40 ms	20–35 ms	< 25 ms
Reactive Power Compensation	Acceptable steady-state support	Fast and adaptive response	Highly adaptive response	Very fast response	Instantaneous and optimal regulation
Predictive Action	Not provided	Not provided	Limited learning-based adaptation	Reactive control only	Explicit predictive control capability
Robustness to Parameter Variation	Medium (sensitive to gain	High	High	Very High	Very High (model-based control)

	tuning)				
Computational Complexity	Very Low	Low–Medium	Medium	Medium	High (online optimization per sampling interval)
Controller Design Complexity	Simple gain tuning	Rule-base design required	Training process required	Sliding surface design required	System model formulation with constraint optimization
Adaptability to Nonlinear Loads	Limited	Good	Excellent	Excellent	Excellent
Overall Performance Rank	Basic	Improved	Advanced	Robust	Best Overall

The comparative performance of different control strategies for voltage sag and swell mitigation is summarized in Table 1. The results indicate that the proposed Model Predictive Control (MPC) approach provides superior dynamic response when implemented in the Open-UPQC structure. In comparison with conventional PI control, which typically exhibits sag recovery times of 40–60 ms and swell recovery of approximately 40 ms, the MPC strategy achieves significantly faster compensation with recovery times below 20 ms for sag and below 15 ms for swell disturbances. Intelligent controllers such as FLC and ANN demonstrate improved response compared to PI control; however, their performance may depend on rule design or training accuracy. Sliding Mode Control (SMC) also provides fast transient response but may introduce implementation challenges due to switching chattering effects. In contrast, the MPC controller utilizes predictive system modeling and cost-function optimization to determine the optimal converter switching state at each sampling instant. This predictive capability enables the Open-UPQC to respond rapidly to sudden voltage disturbances while maintaining stable system operation. The results further indicate faster settling behavior and strong robustness under varying system conditions. Overall, the comparison demonstrates that the MPC-controlled Open-UPQC provides more effective sag and swell compensation and improved voltage regulation performance for a 230 V distribution network.

4.5 Discussion

Overall, the waveform results demonstrate significant improvement in power quality because the load voltage is maintained constant despite the presence of sag and swell faults in the grid voltage. The regulation of load voltage eliminates the risk of voltage-related equipment malfunction, process interruption, and insulation stress. The injected voltage waveform also confirms that the Open-UPQC operates dynamically, injecting voltage only when required, which reduces unnecessary switching and improves system efficiency. Hence, Fig. 7(a)–7(c) validates that the proposed MPC-controlled Open-UPQC effectively reduces fault impact and enhances voltage stability in a 230 V distribution system.

The simulation results validate that Model Predictive Control (MPC) provides superior compensation performance due to its predictive and optimization-based nature. At every sampling instant, the MPC controller predicts the future voltage response and selects the optimal switching state that minimizes the voltage tracking error, enabling fast response to sudden sag and swell disturbances while maintaining the load voltage close to the reference value. Unlike conventional controllers that depend on gain tuning and may exhibit delay during transient conditions, MPC directly generates converter switching pulses through an optimization process, resulting in faster voltage restoration and improved disturbance handling capability in a 230 V distribution network. Overall, the MATLAB/Simulink results confirm that the proposed MPC-controlled Open-UPQC effectively mitigates both sag and swell disturbances, as the injected voltage waveform exhibits correct compensation polarity and the load voltage remains stable near its rated value, demonstrating that MPC is a suitable control strategy for Open-UPQC based voltage regulation in 230 V distribution systems.

5. Conclusions

This research work presented a MATLAB/Simulink-based analysis of an MPC-controlled Open Unified Power Quality Conditioner (Open-UPQC) for improving voltage stability in a 230 V distribution system under voltage sag and swell disturbances. The Open-UPQC was implemented using coordinated series and shunt compensating converters, where the series converter injects the required compensating voltage to restore the load voltage during abnormal grid conditions. Simulation results confirm that during voltage sag, the injected voltage is produced in-phase with the grid voltage to compensate the reduced supply magnitude, whereas during voltage swell, the injected voltage is generated in opposite polarity to suppress overvoltage conditions. The waveform results clearly demonstrate that the load voltage remains regulated close to its rated value during both sag and swell intervals, validating the effectiveness of the proposed MPC strategy. Due to the predictive nature of MPC, fast and optimal switching decisions are achieved, ensuring stable transient response and rapid voltage restoration. Therefore, the proposed MPC-based Open-UPQC provides a reliable and efficient solution for sag and swell mitigation in low-voltage distribution networks, and future work may focus on hardware implementation and real-time validation to confirm its practical feasibility.

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References

[1] P. Kumar, D. S. Chand, R. K. Gupta, A. B. Singh, "Impact of Renewable Energy Integration on Power Quality- Challenges and Solutions", International Journal of Innovative Research in Engineering and Management (IJIREM), Vol-11, Issue-4, Page No-95-99, 2024. Available from: https://doi.org/10.55524/ijirem.2024.11.4.12.

[2] A. Agustoni, E. Borioli, M. Brenna, G. Simioli, E. Tironi and G. Ubezio. LV DC distribution network with distributed energy resources: Analysis of possible structures, in: CIRED 2005 – 18th International Conference and Exhibition on Electricity Distribution, (2005). https://doi.org/10.1049/cp:20051292

[3] W. E. Brumsickle, D.M. Divan, G.A. Luckjiff, J.W. Freeborg and R.L. Hayes. Operational experience with a nationwide power quality and reliability monitoring system, in: Proceedings of the 38th IAS Annual Meeting of the Industry Applications Conference, (2003), 1063–1067. https://doi.org/10.1109/IAS.2003.1257679

[4] B. Wang and M. Illindala. Operation and control of a dynamic voltage restorer using transformer-coupled H-bridge converters, IEEE Transactions on Power Electronics, 21(4), (2006), 1053–1061. https://doi.org/10.1109/TPEL.2006.876836

[5] A. Ghosh and G. Ledwich. Compensation of distribution system voltage using DVR, IEEE Transactions on Power Delivery, 17(4), (2002), 1030–1036. https://doi.org/10.1109/TPWRD.2002.803839

[6] D. Vilathgamuwa, H.M. Wijekoon and S.S. Choi. A novel technique to compensate voltage sags in multiline distribution system—The interline dynamic voltage restorer, IEEE Transactions on Industrial Electronics, 53(5), (2006), 1603–1611. https://doi.org/10.1109/TIE.2006.882017

[7] C. N. Ho and H.S. Chung. Fast transient control of single-phase dynamic voltage restorer (DVR) without external DC source, in: Proceedings of the 2006 IEEE Power Electronics Specialists Conference, (2006), 1–7. https://doi.org/10.1109/pesc.2006.1712085

[8] M. K. Mishra, K. Karthikeyan and P.K. Linash. Development and implementation of DSP-based DSTATCOM to compensate unbalanced nonlinear loads, in: Proceedings of the 2006 IEEE Power India Conference, (2006). https://doi.org/10.1109/POWERI.2006.1632501

[9] B. Singh, A. Adya, A.P. Mittal and J.R.P. Gupta. Analysis, simulation and control of DSTATCOM in three-phase four-wire isolated distribution systems, in: Proceedings of the 2006 IEEE Power India Conference, (2006). https://doi.org/10.1109/POWERI.2006.1632556

[10] J. Jianjun, X. Dianguo, L. Hankui and G. Maozhong. Unified power quality conditioner (UPQC): The principle, control and application, in: Proceedings of the Power Conversion Conference-Osaka 2002, (2002), 80–85. https://doi.org/10.1109/PCC.2002.998518

[11] R. S. Faranda, E. Tironi, I. Valadè and D. Zaninelli. “Power quality improvement using series electronic reactor shunt power conditioner,” in Proc. Int. Symp. and Exhib. Electric Power Engineering at the Beginning of the Third Millennium, Capri, Italy, May 12–18, 2000.

[12] M. Brenna, R.S. Faranda and E. Tironi. "A New Proposal for Power Quality and Custom Power Improvement: OPEN UPQC," in IEEE Transactions on Power Delivery, vol. 24, no. 4, pp. 2107-2116, Oct. 2009, doi: 10.1109/TPWRD.2009.2028791.

[13] K. H. Kwan, Y.S. Png, Y.C. Chu and P.L. So. Model predictive control of unified power quality conditioner for power quality improvement, in: Proceedings of the 2007 IEEE International Conference on Control Applications, (2007), 916–921. https://doi.org/10.1109/CCA.2007.4389350

[14] E. Kazemi-Robati, H. Hafezi, R. Faranda, B. Silva and M.S. Nasiri. A dynamic reference voltage adjustment strategy for Open-UPQC to increase hosting capacity of electrical distribution networks, Sustainable Energy, Grids and Networks, 39, (2024), 101503. https://doi.org/10.1016/j.segan.2024.101503

[15] A. Babaei, M.H. Babaei and M.A. Fatideh. Optimization of maximum photovoltaic absorption with energy loss reduction and UPQC-O placement in distribution networks using firefly algorithm, in: Proceedings of the 2024 28th International Electrical Power Distribution Conference (EPDC), (2024), 1–8. https://doi.org/10.1109/EPDC62178.2024.10571751

[16] S. Gomathi. Power quality enhancement in a power system using active filter with sliding mode controller, in: Proceedings of the 2025 8th International Conference on Trends in Electronics and Informatics (ICOEI), (2025), 128–132. https://doi.org/10.1109/ICOEI65986.2025.11013485

[17] M. V. Gopal. A fuzzy voltage sag/swell controller employing a dynamic voltage restorer with a lower rating, Journal of Computational Intelligence and Secure Systems of Artificial Intelligence, 1(02),

(2025), 23–28. https://creativecommons.org/licenses/by-nc-nd/4.0/

[18] G. Wang, Z. Wu and Z. Liu. Predictive direct control strategy of unified power quality conditioner based on power angle control, International Journal of Electrical Power & Energy Systems, 156, (2024), 109718. https://doi.org/10.1016/j.ijepes.2023.109718

[19] N. Kumar, V. Kumar and R. Kumar. Effect of high demand AI applications on power quality and enhancement techniques using series compensation, SAF, and FLC-I, in: Proceedings of the 2025 International Conference on Electronics and Renewable Systems (ICEARS), (2025), 281–287. https://doi.org/10.1109/ICEARS64219.2025.10940239

[20] Y. Priyanka and A.R. Ram. A novel LSO-PI open-left UPQC for dual load harmonic mitigation and voltage correction, International Journal of Renewable Energy Research, 15(1), (2025), 118–127.

[21] G. Wang, Z. Wu and Z. Liu. Predictive direct control strategy of unified power quality conditioner based on power angle control, International Journal of Electrical Power & Energy Systems, 156, (2024), 109718. https://doi.org/10.1016/j.ijepes.2023.109718