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Research Paper

POWER QUALITY ENHANCEMENT IN DISTRIBUTION GRIDS USING FUZZY LOGIC-BASED SPC WITH BESS

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Abstract— Voltage sags and swells are major power quality disturbances in modern distribution systems, directly impacting sensitive loads and distributed generation sources. This paper proposes a fuzzy logic-controlled Battery Energy Storage System (BESS) integrated with a Smart Power Converter (SPC) for enhancing voltage stability and mitigating sag and swell events at both low-voltage (LV) and medium-voltage (MV) levels. The proposed scheme dynamically regulates the charging and discharging of the BESS while intelligently adapting to grid variations without requiring an exact mathematical model. A MATLAB/Simulink model of the system has been developed, and simulation results validate the effectiveness of the proposed approach in terms of improved voltage support, faster transient response, and reduced steady-state error. The results confirm that the fuzzy-controlled SPC with BESS provides a robust, adaptive, and cost-effective solution for power quality improvement in distribution networks.

*Keywords***—** BESS, SPC Converter, Fuzzy Logic Controller, AC-DC Converter, DC-AC Converter.

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I. INTRODUCTION

The global demand for reliable and high-quality electrical energy has increased significantly due to rapid urbanization, industrialization, and the widespread use of sensitive electronic devices. Modern industries, data centre's, hospitals, and commercial sectors rely heavily on uninterrupted and stable power supply. However, power quality (PQ) issues such as voltage sags, swells, harmonic distortions, and frequency fluctuations continue to challenge the operational reliability of power systems. Among these, voltage sags and swells are the most common and disruptive phenomena, directly impacting sensitive loads and reducing the overall stability of the grid.

A voltage sag is defined as a temporary reduction in RMS voltage (typically 10–90% of nominal) lasting from a few milliseconds to several seconds. It is most commonly caused by short circuits, motor startups, or sudden increases in load demand. Conversely, a voltage swell is a temporary increase in RMS voltage above the nominal value, usually triggered by sudden load disconnection, capacitor switching, or system faults. Even though these events last only for short durations, they can lead to severe consequences such as equipment malfunction, reduced lifespan of appliances, tripping of protection systems, and interruption of critical processes. In modern grids with sensitive electronics, renewable sources, and automation, the tolerance to such disturbances is very low, making voltage sag and swell mitigation a crucial area of research.

Existing Solutions

To overcome PQ issues, several custom power devices (CPDs) have been developed, including Dynamic Voltage Restorer (DVR), Distribution Static Compensator (D-STATCOM), and Unified Power Quality Conditioner (UPQC**)**. Among these, DVR has been widely recognized as one of the most effective devices for sag and swell mitigation. It operates by injecting a compensating voltage in series with the supply line through a voltage source inverter (VSI) and an injection transformer. This allows the DVR to restore load-side voltage during disturbances.

However, the performance of DVR and similar devices largely depends on the control strategies employed. Traditionally, Proportional–Integral (PI) controllers have been used to regulate the injected voltage. PI controllers are simple, easy to implement,

International Journal of Engineering Research and Science & Technology

and effective under steady-state conditions. But they suffer from significant limitations:

1. **Manual Tuning:** PI controllers require precise gain tuning, which is highly dependent on system parameters and operating conditions.
2. **Poor Adaptability:** They do not adapt well to nonlinearities or sudden system variations.
3. **Steady-State Error:** They exhibit limitations in eliminating residual errors in voltage regulation.
4. **Slower Transient Response:** Under rapidly changing grid conditions, PI controllers fail to respond effectively.

As power systems evolve toward smart grids with high penetration of renewable energy, these limitations make traditional PI-based controllers inadequate.

Whereas for the end users power quality can be considered as the feasibility of utilising the accessible power for operation of various kinds of loads. Distribution system is worst affected because of the power quality problems. Power quality becomes poor at the points where loads are connected with the distribution system. So here we'll try to upgrade the quality of power of the distribution system.

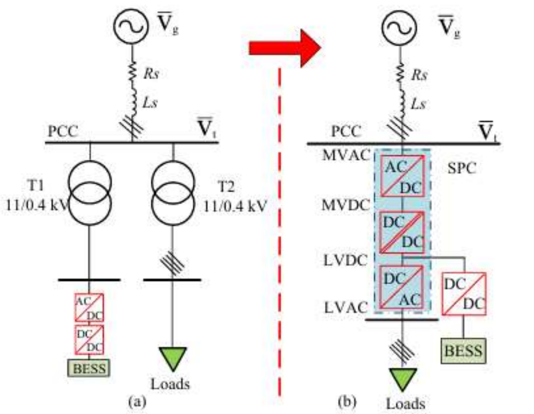

Fig. 1. Single-line diagram of considered system.
(a) Conventional power distribution system.
(b)Fuzzy controlled SPC based power distribution system

Need for Intelligent Control and Storage Integration

With the rising share of distributed generation (DG) and renewable energy sources such as solar and wind, modern distribution networks are increasingly prone to voltage fluctuations. These sources are inherently intermittent and introduce variability that conventional controllers cannot efficiently manage. Moreover, PQ devices like DVRs typically require a large energy storage system to provide active power support during sags and swells, which increases the cost and complexity of implementation.

To overcome these challenges, intelligent control techniques such as Fuzzy Logic Control (FLC) have been explored. Unlike PI controllers, fuzzy controllers do not require a mathematical model of the system and can adapt to nonlinear, uncertain, and time-varying conditions. They provide faster transient response, reduced steady-state error, and dynamic adaptability without manual tuning.

In parallel, the integration of Battery Energy Storage Systems (BESS) with PQ improvement devices has gained attention. The BESS can supply active power during voltage sags and absorb excess energy during swells, thereby reducing the stress on the grid and maintaining voltage stability. However, traditional methods often require oversized batteries, increasing system cost.

II. SYSTEM CONFIGURATION

Fig. 1(a) shows the single-line diagram of a conventional distribution system, where the medium-voltage AC (MVAC) grid supplies loads through standard distribution transformers. In this structure, the battery energy storage system (BESS) is interfaced on the low-voltage side using a combination of DC–DC and DC–AC converters, which enable charging and discharging operations. By contrast, Fig. 1(b) depicts the proposed smart power converter (SPC) based configuration, where the conventional transformers are replaced with a three-stage SPC architecture. In this arrangement, the MVAC grid is directly interfaced with the SPC, which internally establishes both a low-voltage DC (LVDC) link and a low-voltage AC (LVAC) terminal. The BESS is integrated with the LVDC link through a bidirectional DC–DC converter governed by a fuzzy logic controller, which provides intelligent charge–discharge regulation.

III. CONTROL OF POWER CONVERTERS

The smart power converter (SPC) in the proposed system is composed of three main power conversion stages: the medium-voltage (MV) converter, the bidirectional DC–DC converter, and the low-voltage (LV) converter. The SPC MV converter is implemented as a three-phase multilevel AC–DC converter, which directly interfaces with the MVAC grid, regulating power exchange and maintaining stability of the DC link. The SPC DC–DC converter is designed as a bidirectional buck–boost type and is responsible for managing the charging and discharging operations of the battery energy storage system (BESS). This converter is governed by a fuzzy logic controller, which ensures intelligent regulation of the LVDC link, adaptive charge–discharge control, and stable operation under nonlinear load and grid disturbance conditions. The SPC LV converter is realized as a standard three-phase DC–AC inverter that converts the regulated LVDC link voltage into a balanced sinusoidal AC supply, which is delivered to distributed generation (DG) loads as well as back to the grid. Together, these three stages enable seamless integration of the MV grid, the BESS, and the local DG loads, while ensuring high power quality, reliable operation, and effective voltage support under both steady-state and disturbed conditions.

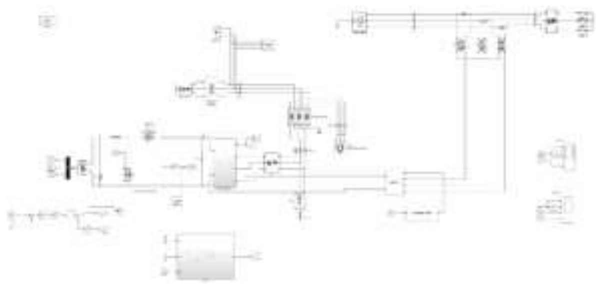

Fig. 2.proposed system matlab/Simulink model

A. SPCMV Converter

The medium-voltage (MV) converter is one of the core components of the smart power converter (SPC) architecture, providing the critical interface between the medium-voltage AC (MVAC) grid and the internal DC link. It is typically implemented as a three-phase, three-level, neutral-point clamped (NPC) voltage source converter due to its ability to handle higher voltage ratings with reduced switching stress and lower harmonic distortion compared to a two-level design. The primary role of the MV converter is to regulate the exchange of active and reactive power with the MVAC grid while maintaining the stability of the DC link voltage. Through its operation, it ensures that power can flow bidirectionally, allowing energy to be drawn from the grid under normal operation or reactive support to be injected during disturbances such as voltage sags and swells.

The control of the MV converter is based on generating appropriate current references in the synchronous dq-reference frame aligned with the grid voltage. By aligning the d-axis with the grid voltage vector, the active and reactive power components can be decoupled, which simplifies control. The instantaneous active (P) and reactive (Q) power exchanged with the grid are expressed as:

$$P=3/2(v_d i_d+v_q i_q)$$

$$Q=3/2(v_q i_d-v_d i_q)$$

where v_d,v_q are the dq-axis components of the grid voltage, and i_d,i_q are the dq-axis components of the converter current. By choosing the d-axis aligned with the grid voltage, v=0, the equations simplify to:

$$P=3/2v_d i_d,\ Q=-3/2v_d i_q$$

This shows that the d-axis current (i_d) directly controls the active power flow, while the q-axis current (i_q) controls the reactive power exchange.

To regulate the DC link voltage, a PI or intelligent controller adjusts the reference id* based on the deviation between the measured DC link voltage (V_{dc}) and its reference value (V^*_{dc}). The reactive current reference (i^*_q) is generated according to the grid voltage deviation at the point of common coupling (PCC), enabling dynamic reactive power injection or absorption. The converter switches are modulated using sinusoidal PWM or space vector modulation (SVM) to synthesize the required three-phase voltages.

The mathematical model of the MV converter in the dq-reference frame can be expressed as:

$$L_f\, di_d/dt=-R_f i_d+\omega L_f i_q+v_{cd}-v_{gd}$$

$$L_f\, di_q/dt=-R_f i_q+\omega L_f i_d+v_{cq}-v_{gq}$$

where L_f and R_f are the filter inductance and resistance, ω is the grid angular frequency, $v_{cd},$ v_{cq},are the dq-components of the converter output voltage, and v_{gd},v_{gq} are the dq-components of the grid voltage.

This model highlights the coupling between the d and q axes, which is typically compensated using decoupling feedforward terms in the control system to achieve independent regulation of active and reactive currents.

In summary, the SPC MV converter serves as the backbone of the system by maintaining the DC link voltage, managing active and reactive power exchange, and ensuring grid stability. Its mathematical control model enables precise decoupling of power components, making it well-suited for integration with intelligent control strategies. By coordinating with the DC–DC converter for BESS management and the LV converter for local load supply, the MV converter ensures smooth bidirectional power flow and effective voltage support under both normal and disturbed operating conditions.

B. SPC DC-DC Converter

The DC–DC converter in the smart power converter (SPC) framework serves as the critical interface between the low-voltage DC(LVDC) link of the SPC and the battery energy storage system (BESS). Its primary function is to regulate the charging and discharging of the BESS while maintaining the stability of the DC link voltage. Since the system requires bidirectional power flow, the converter is implemented as a bidirectional buck–boost topology, enabling it to step down the LVDC link voltage for charging the battery or to boost the battery voltage when discharging energy back into the SPC. This functionality allows the storage system to operate effectively under varying grid and load conditions, making the DC–DC converter an indispensable element of the SPC architecture.

During the charging process, when the grid supplies surplus active power, the converter operates in buck mode, reducing the LVDC link voltage to match the BESS charging level. Conversely, when the grid experiences a voltage sag, increased demand, or disturbances, the converter operates in boost mode, raising the BESS voltage to support the DC link and supply active power to the grid and local loads. This seamless transition between charging and discharging modes provides dynamic support and ensures that the battery is utilized optimally without compromising grid stability.

The control of the SPC DC–DC converter is designed to

achieve two objectives:

(i) maintain a stable DC link voltage and

(ii) regulate the state of charge (SOC) of the battery.To achieve this, a fuzzy logic controller is employed in place of a conventional PI controller. The fuzzy controller uses the error between the reference DC link voltage and the measured voltage, along with its rate of change, as inputs. Based on a set of fuzzy rules, the controller generates the duty ratio for the converter switches, thereby regulating the power flow direction and magnitude. This intelligent control approach ensures adaptive operation under nonlinear conditions, fast dynamic response to transients, and robust performance against parameter variations.

The power flow through the DC–DC converter can be expressed as:

$$P_b=V_b \cdot I_b$$

where P_b is the battery power,V_b is the battery voltage, and I_b is the charging/discharging current. In boost operation, the output DC link voltage is related to the duty cycle D as:

$$V_{dc}=V_b/1-D$$

while in buck mode (charging), the relation is:

$$V_b=D \cdot V_{dc}$$

These equations highlight the role of the duty cycle in regulating the power exchange between the DC link and the battery. The fuzzy logic controller dynamically adjusts D according to the system requirements, thereby ensuring stable and efficient operation.

In addition to stabilizing the DC link, the DC–DC converter also protects the battery from overcharging and deep discharging by monitoring the SOC. When the SOC exceeds predefined thresholds, the control strategy limits the charging or discharging current to extend the battery life. By coordinating with the MV and LV converters, the SPC DC–DC converter ensures optimal utilization of the BESS, improves voltage support during disturbances, and enhances the overall reliability of the power distribution system.

In summary, the SPC DC–DC converter acts as the power conditioning bridge between the BESS and the LVDC link. Its bidirectional nature, intelligent control, and fast response make it essential for balancing supply and demand, stabilizing the DC link, and supporting grid operation under dynamic conditions. This converter not only improves the efficiency of energy storage integration but also plays a pivotal role in ensuring resilience and reliability of the SPC-based distribution network.

C. SPCLV CONVERTER

The SPC low-voltage (LV) converter is designed to maintain a constant voltage at the SPC LVAC bus, operating in a manner similar to a grid-forming converter. At any given operating condition, the reference root-mean-square (rms) voltage (V_{lv}) for the SPC LV converter is defined as:

$$V_{lv}=n \cdot V_{lv,nom} \quad \text{where } 0.9 \le n \le 1.$$

Here, $V_{lv,nom}$ represents the nominal voltage magnitude, and the factor nnn is adjusted according to the operating scenario. Under normal steady-state conditions, the converter maintains a balanced three-phase sinusoidal voltage with nominal rms value, corresponding to n=1.

For coordinated operation, the SPC LV converter also participates in load control. By considering the connected load at the SPC LV bus as a constant impedance type, the active power drawn by the load varies proportionally with the square of the voltage. This relationship can be expressed as:

$$P_{lv} \propto V^2_{lv} / V^2_{lv,nom}$$

Where V_{lv} is the modified rms voltage reference. This implies that reducing the LVAC bus voltage leads to a corresponding reduction in the active power drawn by the load. Such a strategy is utilized during abnormal conditions like MV grid voltage sags or swells, allowing the LV converter to share the burden of voltage regulation in coordination with the MV converter and the energy storage system.

During these events, the LV converter dynamically reduces the magnitude of its reference voltage. depending on the severity of the disturbance and the control objective. This coordinated voltage reduction helps in reducing the load demand on the system, thereby easing the active power drawn from the MV grid and creating additional margin for reactive power injection. The reference voltage generated by the controller is maintained through appropriate switching modulation of the LV converter, ensuring stable and reliable operation under both normal and disturbed grid conditions.

D. BESS DC-DC Converter

The battery energy storage system (BESS) is integrated into the smart power converter (SPC) through a bidirectional DC–DC converter connected to the low-voltage DC (LVDC) terminal. The primary role of this converter is to regulate the charging and discharging of the battery while ensuring that the DC-link voltage remains stable under varying operating conditions. By enabling bidirectional power flow, the DC–DC converter allows the battery to absorb excess energy from the grid during charging periods and to inject stored energy back into the system during discharging. This capability makes the BESS DC–DC converter an essential component for balancing supply and demand, supporting the grid during disturbances, and extending the flexibility of the SPC system.

The converter is generally realized using a bidirectional buck–boost topology, which can operate in two distinct modes. During the charging mode, the converter steps down the LVDC voltage to match the charging requirements of the battery. Conversely, in the discharging mode, it operates in boost mode, stepping up the battery voltage so that energy can be delivered to the LVDC link and subsequently supplied to the AC grid or local loads through the SPC LV converter. This dual functionality ensures seamless operation of the BESS across a wide range of conditions, from surplus energy absorption to active power support during grid faults such as voltage sags or swells.

The control of the BESS DC–DC converter is based on maintaining the desired DC-link voltage while managing the state of charge (SOC) of the battery. In this system, a fuzzy logic controller is employed instead of conventional PI control, providing intelligent decision-making under nonlinear and uncertain operating conditions. The inputs to the fuzzy controller are typically the DC-link voltage error and its rate of change, which are processed through a set of predefined linguistic rules to generate the duty cycle for the converter switches. By dynamically adjusting the duty cycle, the converter regulates the direction and magnitude of power flow, thereby ensuring stable DC-link voltage and effective energy management. This control strategy also prevents overcharging or deep discharging of the BESS, which is essential for prolonging battery life.

The mathematical operation of the BESS DC–DC converter can be described as follows. The instantaneous power exchanged with the battery is given by:

$$P_b = V_b . I_b$$

where V_b is the battery terminal voltage and I_b is the charging/discharging current. In boost (discharging) mode, the DC-link voltage is related to the duty cycle D as:

$$V_b = D \cdot V_{dc}$$

These relationships demonstrate how the duty cycle directly determines the voltage conversion and thereby controls the charging and discharging process of the battery.

In summary, the BESS DC–DC converter provides the necessary power conditioning interface between the storage unit and the SPC system. Its bidirectional operation, coupled with intelligent fuzzy control, ensures stable DC-link voltage, reliable SOC management, and efficient utilization of stored energy. By coordinating with the SPC MV and LV converters, the BESS DC–DC converter enhances grid support during transients, improves power quality, and contributes to the overall stability and resilience of the distribution network.

TABLE I
SIMULATIONPARAMETERS

System quantities	Values
MVAC voltage	11kV(L-L)
LVAC voltage	0.4kV(L-L)
SPC MV converter	L_{mv}=20mH,C_{mv}=5 F,R_{mv}=30
SPC LV converter	L_{lv}=0.5mH,C_{lv}=20 F
DC link capacitor	C_{mv}dc=2000mF,C_{lv}dc=2500mF
BESS dc-dc converter	L_b=50 H,f_{sw}=10kHz

IV. SMULATION RESULTS

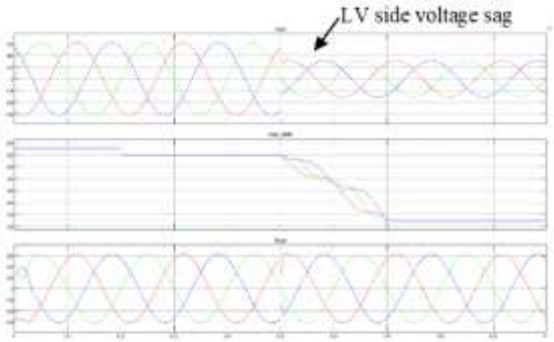

Fig.2.Voltage support during symmetrical grid voltage sag with coordinated control of SPCLV converter and BESS LVside.

The simulation results show the dynamic performance of the proposed SPC system with integrated BESS during a voltage disturbance shown in fig. 2. The grid-side RMS voltage experiences a sag at 0.05 s, while the load-side voltage remains balanced and sinusoidal due to effective compensation. The injected voltage waveform confirms that the SPC responds immediately to the disturbance, supplying the required support and restoring stability. These results validate that the fuzzy-controlled SPC ensures reliable sag mitigation and maintains power quality at the LV side.

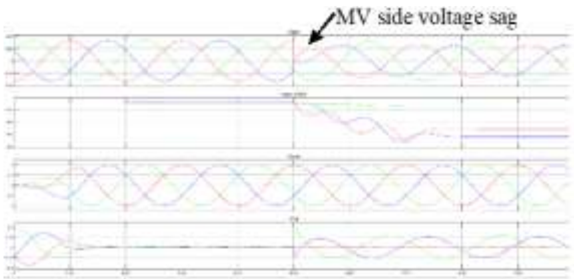

Fig.3.Voltage support during symmetrical grid voltage sag with and without coordinated control of SPC MV converter and BESS MV side.

The MV side performance of the SPC system under disturbance is illustrated in Fig.3. The three-phase grid voltage (V_{abc}) clearly exhibits a sag at around 0.05 s, which is reflected in the RMS profile (V_{abc},RMS) as a sharp drop. Despite this, the load-side voltage (V_{load}) remains balanced and sinusoidal, indicating effective compensation from the SPC system. The injected voltage waveform (V_{inj}) confirms the corrective action, as the converter immediately supplies the required voltage to counteract the sag. These results demonstrate that the SPC with fuzzy-controlled converters maintains MV side stability and ensures reliable voltage support during grid disturbances.

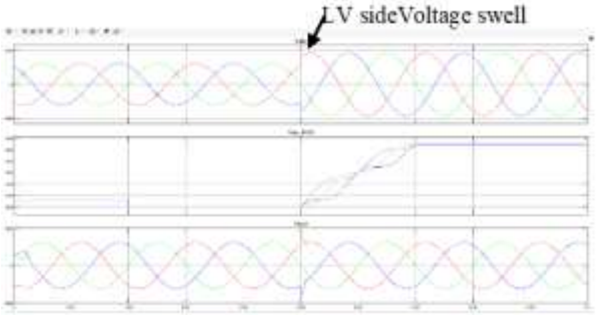

Fig.4.Voltage support during symmetrical grid voltage Swell with coordinated control of SPCLV converter and BESS LVside.

Fig.4 illustrates the LV side performance of the SPC system during a voltage swell. The three-phase supply voltage (V_{abc}) experiences a sudden rise around 0.05 s, which is clearly reflected in the RMS profile ($V_{abc,RMS}$) as the magnitude increases beyond the nominal level. Despite this disturbance, the load-side voltage (V_{load}) remains sinusoidal and well-regulated, with only minor transient deviations observed at the instant of swell. This demonstrates the effectiveness of the SPC LV converter in dynamically adjusting its control to suppress the impact of the swell and maintain stable operation. The results confirm that the proposed system not only mitigates voltage sags but also provides robust compensation against swell conditions, thereby ensuring reliable power quality at the LVAC bus.

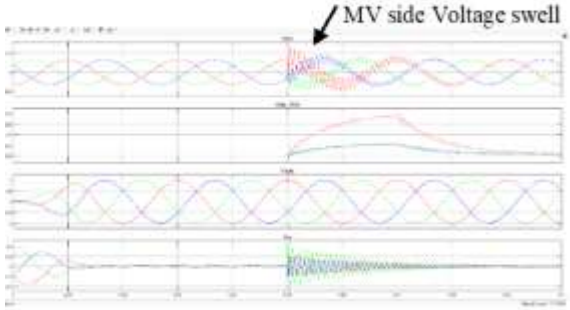

Fig.5.Voltage support during symmetrical grid voltage Swell with and without coordinated control of SPC MV converter and BESS MV side.

Fig.5 shows the response of the SPC system during an MV side voltage swell occurring around 0.05 s. The three-phase grid voltage (V_{abc}) rises significantly above the nominal level and is reflected in the RMS profile (V_{ab}c,RMS) as a clear overvoltage condition. In spite of this disturbance, the load voltage (V_{load}) remains sinusoidal and balanced, with only a brief transient observed at the instant of swell. The injected compensating voltage (V_{inj}) confirms the corrective action of the SPC, which supplies the necessary counter-voltage to limit the impact of the swell. These results verify that the SPC with fuzzy-controlled BESS effectively mitigates overvoltage disturbances at the MV side, ensuring stable operation and reliable power quality at the load end.

V. CONCLUSIONS

This research work presented the design and performance evaluation of a smart power converter (SPC) integrated with a battery energy storage system (BESS) for enhancing power quality in distribution networks. The proposed system utilizes a coordinated control approach where the MV converter ensures stable grid interfacing, the DC–DC converter regulates bidirectional energy exchange with the BESS, and the LV converter maintains sinusoidal, balanced voltage at the load terminal. A fuzzy logic controller was employed to replace conventional PI control, offering superior adaptability under nonlinear conditions and faster dynamic response during disturbances.

The simulation studies demonstrated the effectiveness of the system under various abnormal grid scenarios. During voltage sags, the SPC injected compensating voltages to stabilize the LV side while ensuring continuous supply to loads. Under swell conditions, the system dynamically reduced the impact of overvoltage and maintained power quality within permissible limits. Additionally, the results highlighted the robustness of the SPC in handling harmonic disturbances and ensuring reliable grid support.

Overall, the proposed SPC with fuzzy-controlled BESS provides seamless bidirectional power flow, improved voltage regulation, and enhanced power quality at both MV and LV sides. By effectively mitigating sags, swells, and harmonic distortions, the system improves reliability, stability, and resilience of modern distribution networks. These findings establish the SPC-based architecture as a promising solution for integrating renewable sources, distributed generation, and storage into future smart grids.

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