Voltage Coordination Control Strategy for Low Voltage Distribution Networks in Western Rural Areas under Photovoltaic Storage Access

Zhimin Lei, Qing Xu, Guojie Hao, Chunyu Wei*, Mingle Yang

Abstract—**The low-voltage distribution network (LVDN) in western rural areas covers a large area and has long power supply lines, so the access of photovoltaic (PV) system will solve the problem of unstable or insufficient power supply. But PV access to LVDN will produce many problems, such as harmonic pollution, and trigger voltage fluctuations. Voltage overruns significantly impact the performance of PV systems and are considered a critical factor affecting their overall energy consumption. This study conducts an initial analysis of the impact mechanism associated with the access of PV systems into LVDN. It further examines the diverse implications of PV access on the original distribution lines, considering various perspectives. Furthermore, building upon the aforementioned analysis, this study introduces a voltage coordination control strategy designed to alleviate voltage fluctuations in low-voltage distribution networks (LVDN) in rural areas of western regions during the integration of PV and energy storage systems (ESS). The proposed approach achieves accurate voltage control and dynamic regulation at the point of common coupling (PCC) by leveraging the residual reactive power regulation capability of the inverter and the direct voltage regulation capability of the ESS. Lastly, the simulation results validate the efficacy and dependability of the proposed control strategy.**

Index Terms—**Photovoltaic Access, Energy Storage System, Voltage Overruns, Inverter Residual Reactive Power Capacity**

I. INTRODUCTION

THE rural western regions of China have witnessed rapid economic development and surging energy demand in recent years, leading to an increased need for electricity supply. Energy poverty in western rural areas not only limits the improvement of the quality of life of farm households, but also leads to a series of serious problems. Traditional biomass fuels, such as straw and firewood, while being the main energy source for local farmers, are marked by an unstable traditional biomass fuels also places tremendous pressure on the ecological environment. Frequent logging of trees and burning of biomass fuels in rural areas have led to increasingly serious problems such as the reduction of forest supply and low efficiency. At the same time, overreliance on resources, soil erosion, and water pollution [1]. Therefore, it is crucial to address energy poverty in western rural areas. The promotion and utilization of renewable energy sources can effectively deliver a dependable and environmentally friendly energy supply to farmers.

At the same time, in the western rural areas, the stability and quality of the electricity supply still suffer from a series of problems due to the relative lag in infrastructure and the limitations of the size of the grid. The planning and layout of power supply lines face certain challenges due to the relative lag in the level of distribution network construction and limited investment funds. The decentralized distribution of power loads in rural areas makes it necessary for power supply lines to cross long distances, which leads to the power supply radius of low-voltage power supply lines of 10kV and below exceeding the requirements of economic power supply radius stipulated by relevant national standards. Western rural areas have vast land resources and good sunshine conditions, so access of PV systems will solve the problem of unstable or insufficient power supply, and decentralized power supply loads, and can effectively promote agricultural production and rural economic development.

As a result of the quick functioning of power electronic devices, the integration of PV systems into low-voltage distribution networks (LVDN) introduces harmonic pollution, which in turn affects network reliability. The inconsistency of PV power generation causes voltage variations in the grid and to a certain degree, intensifies the problem of three-phase imbalance. Among the various risks mentioned above, voltage overruns are significantly influenced by the consumption of PV systems, making it one of the most crucial factors [2]. This issue becomes particularly prominent when accessing PV power generation systems into LVDN, leading to pronounced voltage fluctuations. About [3], a study focused on addressing the challenges associated with residential PV access into LVDN proposes an enhanced voltage regulation control strategy. By regulating the exchange of reactive power between PV inverters and the LVDN, this strategy aims to improve voltage distribution and mitigate voltage imbalances. The proposed approach utilizes a distributed consensus-based voltage regulation algorithm to maintain the three-phase bus voltages within acceptable limits. Nonetheless, it is crucial to recognize that the control strategy that depends solely on inverter reactive power regulation possesses certain constraints and cannot

Manuscript received December 18, 2023; revised April 22, 2024. This work was supported in part by Research on integrated power supply technology of Source-Grid-Load-Storage for new power system terminal grid under Grant 40730926.

Zhimin Lei is an engineer at Baiyin Power Supply Company, State Grid Gansu Electric Power Company, Baiyin Gansu 730900, China (e-mail: 198931@sina.com).

Qing Xu is an engineer at Baiyin Power Supply Company, State Grid Gansu Electric Power Company, Baiyin Gansu 730900, China (e-mail: xuqing_yx@163.com).

Guojie Hao is an engineer at Baiyin Power Supply Company, State Grid Gansu Electric Power Company, Baiyin Gansu 730900, China (e-mail: 406285744@qq.com).

Chunyu Wei is a postgraduate student at School of New Energy and Power Engineering, Lanzhou Jiaotong University, Lanzhou Gansu 730070, China (corresponding author e-mail: 12222139@stu.lzjtu.edu.cn).

Mingle Yang is an engineer at Baiyin Power Supply Company, State Grid Gansu Electric Power Company, Baiyin Gansu 730900, China (e-mail: 403946255@qq.com).

completely eradicate voltage fluctuations in the LVDN. In reference to [4], the study proposes a method that collects real-time voltage measurements at the point of common coupling (PCC, hereinafter referred to as PCC) and utilizes the voltage magnitude to determine the reference value for reactive power control. The voltage at the PCC can be regulated by modulating the PV inverter's reactive power output according to the reference value provided. Nevertheless, this approach involves a specific amount of active power loss from the PV system output and is highly dependent on the functioning of the communication system. The local reactive power control strategy proposed in the literature [5] and [6] considers the electrical distance, building upon the strategy presented in the literature [4], and literature [5] proposed a more specific principle of boundary parameter adjustment, and a coordinated design method of boundary parameters and threshold parameters compared with the literature [6]. With a focus on electrical distance, the local reactive power control strategy provides enhanced capabilities for precise voltage regulation. This strategy achieves rapid control without being dependent on communication infrastructure by efficiently utilizing the available inverter's reactive power capacity. Due to the significant R/X ratio in transmission lines, active power regulation plays a crucial role in ensuring voltage stability in LVDN. Based on the PV inverter's output range, if the reactive capacity margin in the aforementioned strategy is insufficient to mitigate voltage fluctuations at the PCC, literature [7] proposes a method to release additional reactive capacity margin by cutting the active power output from the distributed PV systems. This approach effectively suppresses overvoltage occurrences in the low-voltage feeder. Implementing this strategy would impose limitations on the output of distributed PV systems, thereby affecting the economic efficiency of distributed PV, especially when the residual reactive capacity of the PV out-put inverter is sufficient to meet the voltage requirement of the PCC. Building upon this, literature [8] introduces an enhanced strategy. The reactive voltage control strategy, employing active adaptive adjustment, enables swift transitions between the maximum power tracking control mode, active curtailment control mode, and reactive sag control mode based on real-time acquisition of voltage, current, and distributed PV output power data at the PCC. This approach ensures the maximization of economic benefits while preventing voltage overruns. However, it is worth noting that this strategy does not consider the role of ESS in regulating the PCC voltage.

This paper will analyze the impact mechanism of PV access into LVDN in rural western areas, and submit a voltage coordination control strategy grounded on inverters and the energy storage system (ESS). Through the regulation of this control strategy, the inverter and energy storage system can collaboratively suppress voltage fluctuations, to minimize the negative impact of PV access into LVDN in rural western areas as much as possible.

II. Mechanism Analysis of Voltage Impact of PV Access to Western Rural LVDN

Western rural areas are sparsely populated, and the loads of electricity consumption are relatively decentralized, and their types and access methods are relatively complex. At the same time, due to the long power supply distance, and insufficient power supply capacity, with the growing demand for electricity in the region, the quality of electricity and power supply reliability of rural residents is seriously affected. While access of a PV system can offer assistance to the distribution network, it also has a certain impact on the power supply line's voltage level. Figure 1 shows the load distribution of a western rural terrace area, in which $P_i + \mathrm{j}Q_i (i = 1, 2, \ldots, 70)$ is the load consumed by the ith user.

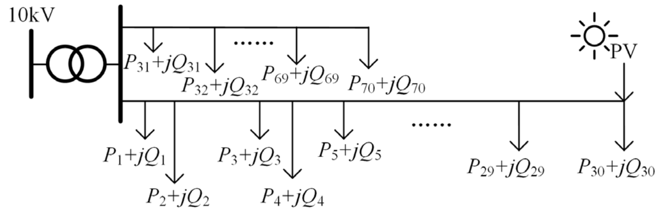

Fig. 1. Load distribution in a western rural station area.

A. Voltage fluctuation analysis for PV system access at the end of the feeder line

In a single-supply radial LVDN, the access of a PV system leads to a gradual reduction in voltage along the feeder line, starting from the powerpoint and extending towards the end [9]. In the scenario of a radial LVDN line with N nodes, the PV system is connected at the feeder line's end for analysis. The voltage at the beginning of the line is U_0, U_N denotes the voltage at the PCC of the PV system accessed by the Nth node. P_{LN} is the active power consumed by the Nth user, Q_{LN} is the reactive power consumed by the Nth user. The line impedance between the two access points is $R_N + \mathrm{j}X_N = l_n(r + \mathrm{j}x)$. P_{pv} is the PV system's active power output, while Q_{pv} is the PV system's reactive power output. Figure 2 illustrates the specific structure:

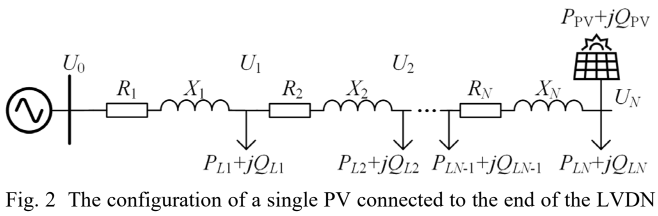

Fig. 2 The configuration of a single PV connected to the end of the LVDN line.

Based on the provided illustration, the voltage at node m within the distribution network in the absence of PV system connection is [10]:

$$U_m = U_{\mathrm{N}} - \frac{\sum_{j=1}^{m}\left[R_j \sum_{i=j}^{n} P_{\mathrm{L}.i} + X_j \sum_{i=j}^{n} Q_{\mathrm{L}.i} \right]}{U_{\mathrm{N}}} \tag{1}$$

When the PV system is coupled to the end of the feeder line, the voltage at the customer node prior to the access point is set as follows:

$$U_m = U_0 - \sum_{k=1}^{m} \frac{\left(\sum_{n=k}^{N} P_n - P_v\right) rl_k + \sum_{n=k}^{N}\left(Q_n - Q_v\right) xl_k}{U_{k-1}} \tag{2}$$

When the power factor (PF, hereinafter referred to as PF) of the user is high, the feeder's R/X impedance ratio tends to be larger. The voltage is more significantly affected by the active power of the line, while the impact of the reactive power on the feeder can be disregarded as a result. Also, when the PV system's output PF is 1, the voltage difference between the two nodes before the access point is:

$$\Delta U = U_m - U_{m-1} = -\frac{\left(\sum_{n=m}^{N} P_n - P_v\right) rl_m}{U_{m-1}} \tag{3}$$

Based on the given equation, if the loads' total active power consumption at node *m* and all the loads at the feeder's end surpass the PV system's active power output, the voltage along the feeder line gradually decreases. Alternatively, if the cumulative active power consumption of the loads at node m and all the loads at the end of the feeder is less than the active power output of the PV system, the voltage along the feeder line incrementally rises.

B. Simulation analysis of PV influence mechanism on feeder line voltage

The simplified topology of the distribution network is depicted in Figure 3, focusing on the access of a PV system at the feeder 2's end within the distribution line. The study investigates the effects of various grid-connected capacities, fluctuations in feeder load, and the PF of the grid-connected inverter. A typical radial distribution line comprising 14 users is analyzed, and the corresponding parameters are presented in Table I.

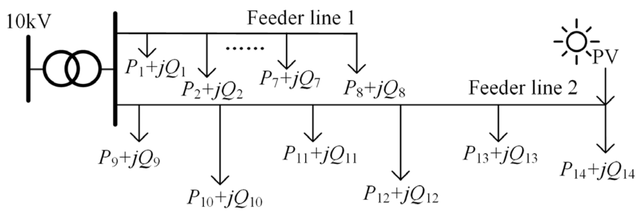

Fig. 3 Simplified distribution line load distribution.

TABLE I
PARAMETERS RELATED TO DISTRIBUTION LINES

Items	Numerical Value
Line resistance	0.38Ω/km
Line inductors	4.12×10^{-3}H/km
Feeder 1 line length	8km
Feeder 2 line length	16km
Feeder voltage level	220V
User load	1 kW×14

Initially, while keeping other operating conditions constant, the impact of varying PV system access capacities on the voltage of the distribution system is examined. The PV system is connected at the feeder 2's end, with access capacities of 0 kW, 15 kW, 25 kW, and 35 kW. The voltage amplitude changes of each node in the two feeders are plotted collectively, and the simulated voltage values for each node are presented in Figure 4:

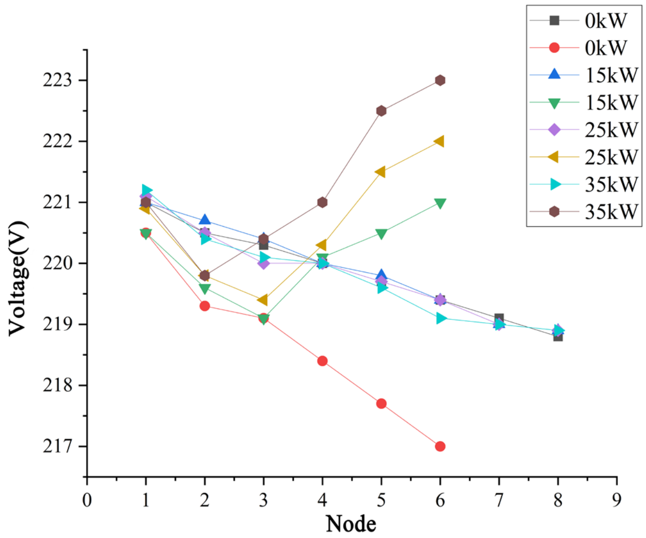

Fig. 4 Voltage distribution at each node with different capacity of PV connected to the feeder 2's end.

The analysis of the above figure reveals that the voltage level of the two feeders gradually decreases from the first section to the line's end before the PV access. When 15 kW PV is accessed at the feeder's end, the active power transmitted at the PV access point and the nodes before it will decrease accordingly, the line voltage loss decreases, and the voltage at the PV access point will be raised. When the PV is connected at the feeder's end, the feeder 2's voltage level undergoes a gradual reduction from the initial end of the line and subsequently experiences a gradual increase due to the influence of PV access. As the PV access capacity keeps escalating, the voltage of Feeder 1 stays primarily unaltered, the comprehensive voltage trajectory of Feeder 2 remains constant, and the voltage levels at each individual node escalate along with the increase in PV capacity.

Set the PV access capacity to 15 kW, and the access location is the feeder 2's end. Without changing other operating conditions, the user load at each node is increased by 0.5 kW, used to simulate the user peak power consumption. A simulation of the node voltage is shown in Figure 5:

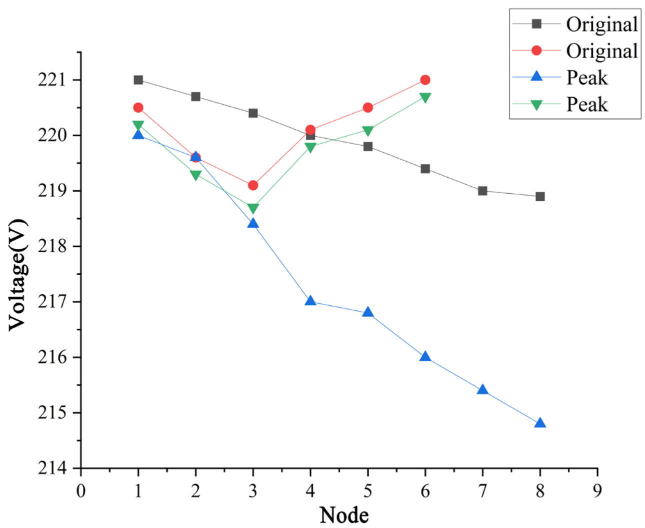

Fig. 5 Distribution of voltage at each node during the highest peak of consumer power consumption.

From the examination of the preceding figure, it is noticeable that during the users' peak electricity consumption period, as the load escalation occurs at each node, the comprehensive voltage level of both feeders descends. Meanwhile, the increase in user load does not affect the trend of feeder voltage levels after PV access.

The set PV access capacity is 15 kW, and the access location is the feeder 2's end. While keeping other operating conditions unchanged, the output PF of the PCC inverter is varied to 1, 0.98, 0.96, and 0.94, respectively. The simulated voltage values at each node are presented in Figure 6:

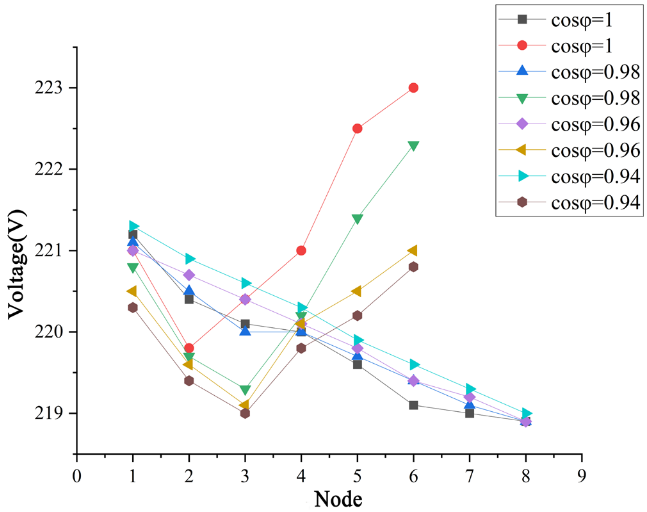

Fig. 6 Voltage distribution at each node with different output PF.

From the examination of the above figure, one can observe that as the PF of the inverter progressively diminishes, the voltage level at each node of Feeder 1 maintains itself mainly unchanged, whereas the voltage level at every node of Feeder 2 displays an overall descending trajectory. However, the decrease in output PF does not influence the trend of feeder voltage levels following PV access.

III. Voltage Coordination Control Strategy Based on Inverter and Energy Storage

The access of PV systems to LVDN and the access of energy storage can facilitate several benefits. These include increasing the self-sufficiency of PV systems, improving the reliability of the power supply, mitigating power fluctuations, balancing energy peaks and troughs, and providing ancillary services. Such access facilitates the transition to cleaner and greener energy sources, increases the use of renewable energy, improves energy efficiency, and supports sustainable development goals. The PV system's active power output is heavily influenced by environmental factors such as light intensity and temperature, resulting in significant randomness and volatility. The active power that the PV system produces, which fluctuates, can lead to disturbances, flickering, and possible voltage violations at different points when accessed into the LVDN. However, the access of ESS can effectively smooth out PV power fluctuations and regulate voltage violations at the PCC.

The actual power injection of the PV inverter can be restrained by storing power in ESS, thus the issue of the voltage upper limit will be alleviated to a certain extent. In particular, during peak load periods when PV power generation is typically lower, the energy stored in the ESS can be used to compensate for voltage dips on the bus at the feeder's end [11]. In essence, energy storage plays a role in regulating the voltage at the PCC. In cases where the PCC voltage surpasses the upper threshold, active energy is absorbed by the ESS to reduce the voltage. On the other hand, if PCC voltage falls below the lower threshold, active energy is discharged to elevate the voltage. The ability of the ESS to both charge and discharge can be employed to maintain the PCC voltage within the desired range. Figure 7 illustrates the energy storage access approach:

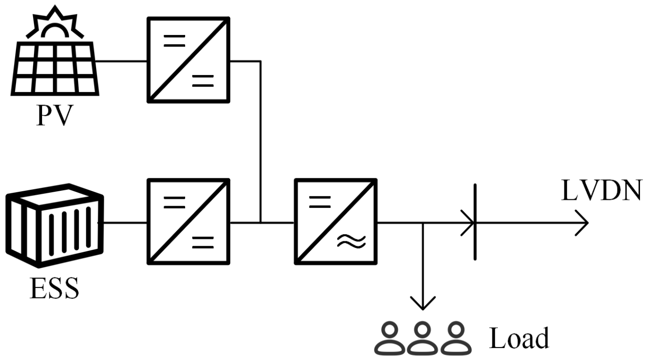

Fig. 7 Energy storage access to western rural LV distribution network topology.

Incorporating an ESS into weak and underdeveloped LVDN in rural areas of western regions can address the challenge of growing electricity demand and inadequate distribution and substation infrastructure. By reducing the imbalance between peak and off-peak power supply, the addition of ESS can reduce the load on the grid. It can also help reduce feeder losses to some extent.

This paper introduces a voltage coordination control strategy that encompasses the design of both a PCC inverter and an ESS. Figure 8 shows the overall topology of the proposed strategy:

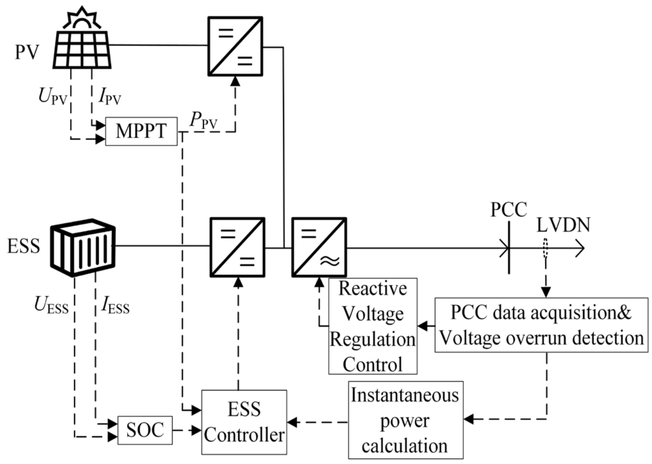

Fig. 8 Overall topology of voltage coordination control strategy.

In the above topology, the DC side is connected to the PV and ESS. The PV controls a Boost circuit through a maximum power tracking controller to achieve maximum power output. The ESS controls the bidirectional DC-DC circuit through the energy storage controller to realize the bidirectional flow of energy. By collecting data from the PCC, over-voltage is detected and commands are sent to either the grid inverter or the energy storage controller to effectively suppress voltage fluctuations at the PCC.

A. Residual reactive power regulation control strategy based on PCC inverter

Maintaining power system stability in LVDN involves balancing the injected power with the consumed power to ensure normal operation. It is also critical to regulate the voltage level of each network node within a normal range using the system's reactive power capability. When PV is connected to the LVDN, a specific level of reactive power capacity is typically allocated to handle voltage fluctuations and ensure system stability. Overvoltage situations at the PCC can be classified as exceeding the upper limit or exceeding the lower limit [12]. Instances of exceeding the upper threshold occur when the active power of the PV system increases and user load decreases. Conversely, breaching the lower threshold is observed when the active power of the PV system decreases, user load increases, and there is an extended transmission span within the station area.

In power systems, maintaining the normal voltage level requires the appropriate supply of reactive power to distribution system loads. Common reactive power compensation devices include series capacitors and static reactive power generators. As in the literature [13], a multivariable polynomial approach is used to design the control of an SVC. SVC can compensate for PF better than APF. By controlling SVC, compensation for the power factor on the user side can be achieved more effectively than APF. While capacitor-based compensation devices are less expensive, their reactive power capacity is fixed, resulting in intermittent compensation. On the other hand, high-capacity static reactive power generators are more expensive and not economically viable for LVDN in rural areas.

The available residual reactive power capacity of the PCC inverter varies based on the fluctuation of the PV output and the absorption and release of active power by the ESS. The maximum reactive power output (i.e. residual reactive power capacity) of the PCC inverter available for voltage control is [14]:

$$Q_{left}=\sqrt{S_{VSC}^2-(P_{pv}+P_{ess})^2} \tag{4}$$

The formula for the inverter's maximum reactive power, represented by Q_{left}, can be derived from the grid inverter rated power (S_{VSC}), the PV system's active power (P_{pv}), and the active power released or absorbed by the ESS (P_{ess}).

When the PF of the PV system is less than 1, the PCC voltage can be obtained from the analysis in chapter two:

$$\begin{aligned} U_{\text{pcc}} &= U_0-\sum_{k=1}^{p}\frac{\left(\sum_{n=k}^{N}P_n-P_{\text{pv}}\right)rl_k-\sum_{n=k}^{N}Q_{\text{pv}}xl_k}{U_{k-1}} \\ &= U_0-\sum_{k=1}^{p}\frac{\left(\sum_{n=k}^{N}P_n-P_{\text{pv}}\right)rl_k}{U_{k-1}}+\sum_{k=1}^{p}\frac{\sum_{n=k}^{N}Q_{\text{pv}}xl_k}{U_{k-1}} \end{aligned} \tag{5}$$

In the above formula, U_{pcc} represents the PCC voltage. The equation shows that the inverter absorbs or injects inductive reactive power. This capability allows the PCC voltage to be regulated. The intermittent and random nature of PV system output results in the PCC inverter often operating below its rated power. By fully utilizing this residual capacity, the PCC inverter of the PV system can effectively support the LVDN's voltage level, thereby maximizing economic benefits. As a result, the inverter retains a specific amount of residual reactive power capacity. Voltage regulation can be achieved by continuously monitoring the real-time voltage data of the PV system when a minor deviation occurs above the desired voltage level. Based on the reactive power sag curve, reactive power's reference is generated for the PCC inverter, enabling effective voltage regulation [15]. The specific functional expression for the reactive power setpoint follows a first order function [16]:

$$Q_{\text{ref}}=\begin{cases} Q_{\max} \quad , \quad U_{\text{pcc}}<U_1 \\ \frac{Q_{\max}}{U_1-U_2}\left(U_{\text{pcc}}-U_1\right)+Q_{\max} \quad , \quad U_1<U_{\text{pcc}}<U_2 \\ \frac{Q_{\max}}{U_3-U_4}\left(U_{\text{pcc}}-U_3\right) \quad , \quad U_3<U_{\text{pcc}}<U_4 \\ -Q_{\max} \quad , \quad U_{\text{pcc}}>U_4 \end{cases} \tag{6}$$

In the above equation, Q_{ref} is the reactive power's reference value, while $Q_{\max}$ is the maximum residual reactive power capacity. U_1, U_2, U_3 and U_4 correspond to voltage levels of 0.95p.u., 0.98p.u., 1.02p.u. and 1.05p.u. respectively. If the PCC voltage exceeds the upper threshold, the PCC inverter is instructed to absorb reactive power, thereby reducing the voltage level [12] . Conversely, when the PCC voltage exceeds the lower threshold, the PCC inverter is commanded to release reactive power, resulting in an increase in the voltage level. Through aggregating the PCC voltage and current data and deriving the reactive power reference value using equation (6) in the power calculation module, the inverter's residual reactive power capacity can autonomously regulate the PCC voltage, even under subpar communication conditions. In addition, the PCC inverter's output PF must be considered to ensure that the reactive power control is performed while maintaining the PF at the user side.

If the PCC voltage remains in an overvoltage state and the inverter's residual reactive power alone cannot regulate it back to the normal level, an alternative approach is required. Equation (4) shows that the inverter can obtain additional regulated reactive power by cutting its active power output. In the case of western rural LVDN, where the feeder's R/X ratio is higher, regulating the active power output of the inverter becomes more important to mitigate voltage fluctuations. Conventionally, reducing the active power output of the PCC inverter denotes a direct reduction of the active power output from the PV system, hence augmenting the adjustable range for residual reactive voltage regulation. However, in western rural LVDN, for maximum economic benefit, the PV output to be reduced is absorbed by the ESS. This approach ensures that the PV system utilization rate is maintained while still providing maximum voltage regulation capability. The block diagram illustrating the specific control strategy is shown in Figure 9 below:

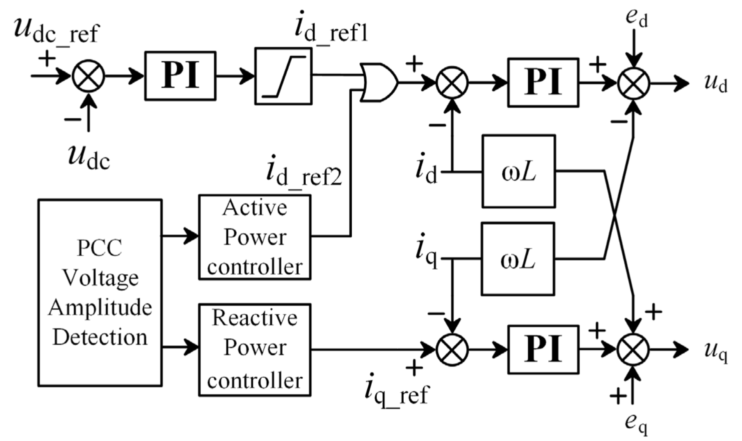

Fig. 9 Block diagram of a control strategy based on the PCC inverter's reactive capacity.

In the figure, u_{dc} is the DC bus voltage at the PV access side, and u_{dc_ref} is its reference value. i_d and i_q are the d- and q-axis current values of the grid inverter, and i_{d_ref1}, i_{d_ref2} and i_{q_ref} are its reference values. e_d and e_q are the d- and q-axis filter output voltages of the grid inverter. u_d and u_q are the d- axis and q-axis output voltages of the grid inverter, and L is the filter inductance.

B. Direct voltage regulation control strategy based on ESS

Figure 10 illustrates the specific configuration of the PV storage access to the LVDN:

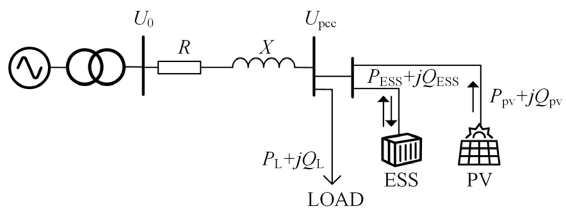

Fig. 10 PV and ESS access to rural LVDN.

In the above figure, U_S is the voltage at the first of the feeder. $R+\mathrm{j}X$ is the line impedance, P_L and Q_L are the active and reactive power absorbed by the user loads, respectively, P_{ESS} is the active power output or absorbed by the ESS, and P_{pv} is the PV system's active power. Therefore, the difference between the voltage at the first of the feeder and the voltage at the PV storage access point can be obtained as [17]:

$$\Delta U = U_{pcc} - U_S = \frac{\left(P_{pv} - P_L + P_{ESS}\right)R}{U_{pcc}} \tag{7}$$

The value of P_{ESS} is adjustable within certain limits imposed by the PF of the grid inverter output. Consequently, the control strategy based on the reactive power control of the grid inverter cannot freely reduce the active power output without restrictions. In order to maintain the PF at the user side, when a significant voltage surge occurs, the required active power value for the ESS to interact with the distribution grid can be directly calculated. By directly absorbing or releasing power at the PCC, the ESS ensures that the grid voltage remains within a stable range.

Define the voltage stabilization range at the PCC as:

$$U_{MIN} \le U_{pcc} \le U_{MAX} \tag{8}$$

where U_{MIN} is the lower limit of the PCC voltage and U_{MAX} is the upper limit of the PCC voltage. The energy storage device remains inactive when the voltage falls within the defined stabilization range. However, if the voltage at the grid point exceeds the upper limit, U_{pcc} is set to U_{MAX}. Equation (7) indicates that the active power, which the ESS must ingest to restore the voltage at the network point to the normal range, is:

$$P_{ess} = P_{pv} - P_L - \frac{U_{MAX}^2 - U_S U_{MAX}}{R} \tag{9}$$

If the PCC voltage falls below the lower limit, U_{pcc} is set to U_{MIN}. To return the PCC voltage to the normal range, the ESS must release the following amount of active power:

$$P_{ess} = P_{pv} - P_L - \frac{U_{MIN}^2 - U_S U_{MIN}}{R} \tag{10}$$

Based on the above analysis, it is clear that when the voltage amplitude detector at the PCC detects a significant deviation from the limit, the energy storage controller is activated. Consequently, the ESS is instructed to absorb or release the appropriate amount of active power based on the signal received from the power calculator. This control mechanism effectively prevents the PCC voltage from significantly exceeding the limit.

C. Voltage coordination control strategy

The PCC inverter's control strategy, grounded on the regulation of residual reactive power, facilitates accurate control of the PCC voltage. This strategy offers high flexibility and quick response, allowing for effective voltage stabilization within an appropriate range. Maintaining stable PCC voltage yields several benefits, including improved grid voltage stability, reduced impact of voltage fluctuations on user equipment, and ensuring smooth operation of the power system.

By adjusting the inverter's reactive power output, it effectively compensates for the reactive power demand at the load side, quickly adapting to changes in grid load demand and providing optimal reactive power support. This is particularly important when accessing renewable energy sources such as PV into the grid, especially during periods of high load.

In addition, the use of a direct voltage regulation control strategy based on the ESS enables peak shaving and suppression of significant voltage fluctuations at the PCC. The ESS can flexibly absorb or release reactive power as part of its regulation process. This approach plays a key role in facilitating higher penetration of renewable energy, optimizing power system operations, and promoting the transition to a more sustainable energy ecosystem.

This paper presents a voltage coordination control strategy that addresses the problem of insufficient control capacity of the residual reactive power inverter. The proposed strategy combines the advantages of both reactive power regulation and direct regulation using energy storage. When the PCC voltage exceeds a small margin, specifically in the range of 0.95p.u. < U_{pcc} < 1.05p.u., the regulation is performed based on the inverter's residual reactive power capacity. However, when the PCC voltage exceeds a larger margin, i.e. U_{pcc} > 1.05p.u. or U_{pcc} < 0.95p.u., regulation is performed using the direct regulation capability of the ESS. The specific control flow is shown in Figure 11 below:

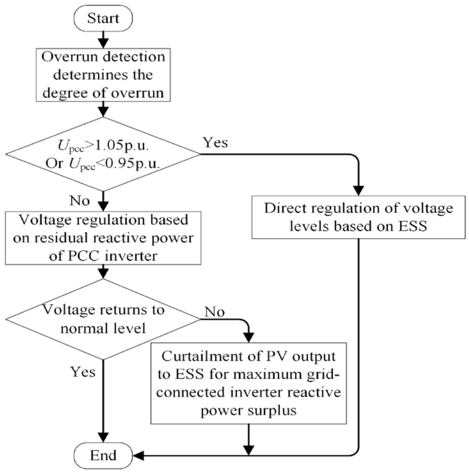

Fig. 11 Specific control flow chart of voltage coordination control strategy.

IV. Simulation and Result Analysis

To authenticate the accuracy of the theoretical analysis and evaluate the efficiency of the suggested control strategy, a simulation model tying a PV and ESS to a LVDN is built using MATLAB/Simulink, demonstrated in Figure 12. Table 2 lists the simulation parameters, including a grid voltage level of 380 V, a rated output voltage frequency of f = 50 Hz, a switching frequency of 20 kHz, a DC bus voltage level of 700 V, and a PV access capacity of 15 kV·A.

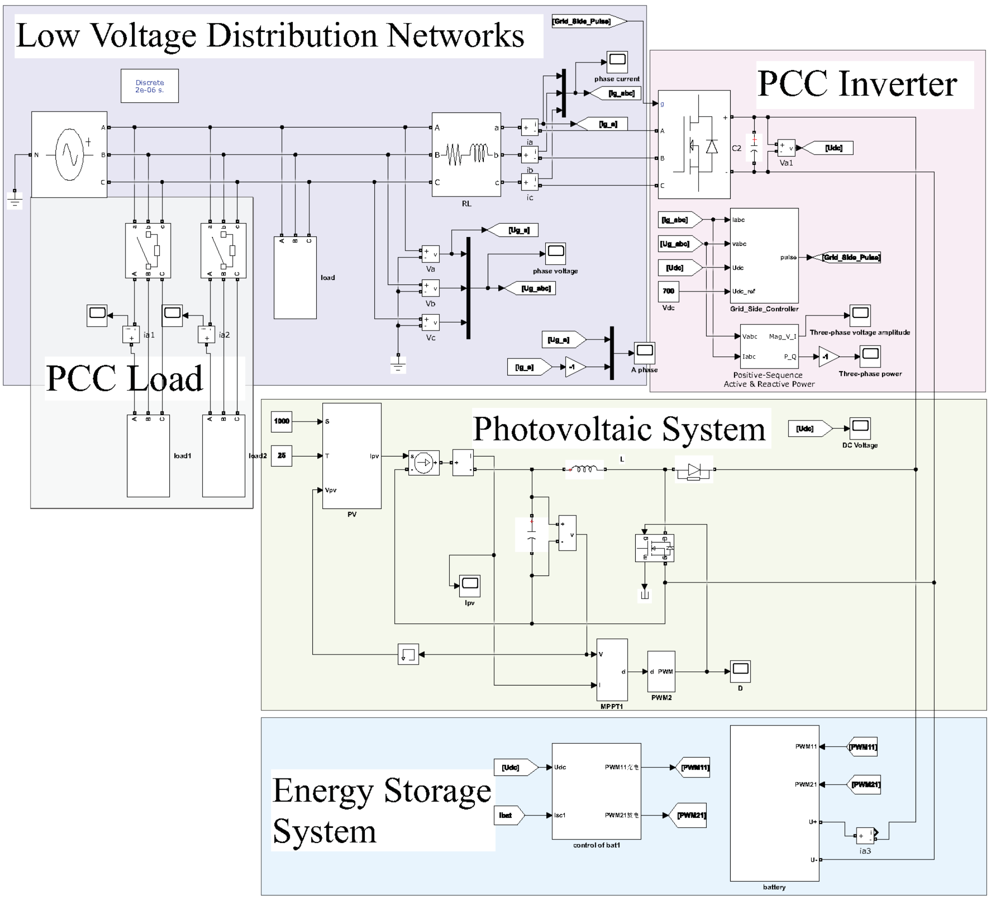

Fig. 12 PV and ESS connected to LVDN model in MATLAB/Simulink.

TABLE II
SIMULATION SPECIFIC PARAMETERS

Structure	PARAMETERS	Numerical Value
PCC inverter	Filter Inductors L/mH	10
	Voltage loop scaling factor	0.16
	Voltage Loop access factor	6
	Current loop scaling factor	48
	Current loop access factor	4
Boost Circuit	PV Side Inductors L_{pv}/mH	0.12
	PV Side Capacitance C_{pv}/mF	0.11
Bidirectional DC-DC Circuit	Energy Storage Inductors L_b/mF	0.8
	Energy Storage Capacitors C_b/mH	0.5

When the load at the PCC increases at 0.6s and the voltage at the PCC occurs to cross the lower limit by a small margin (0.95p.u.<U_{pcc}<1.0p.u.), the simulation results are shown in the following Figs. 13, 14, and 15:

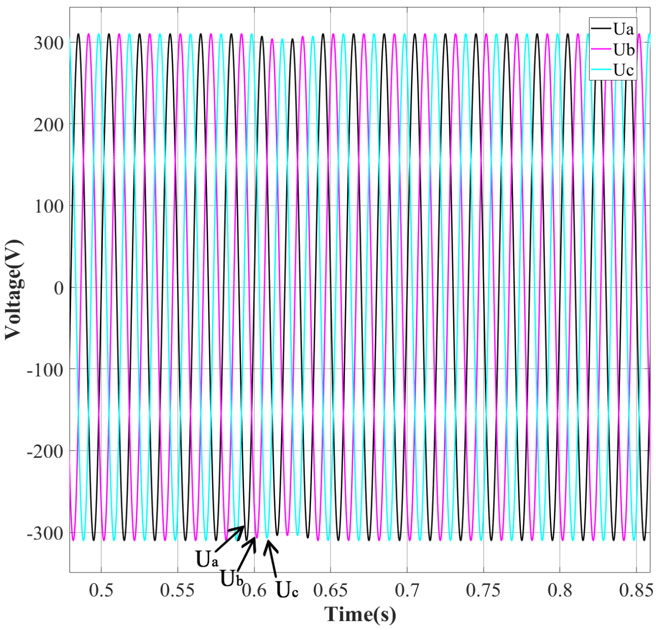

Fig. 13 Simulation waveforms of voltage exceeding the lower limit with small amplitude at the PCC.

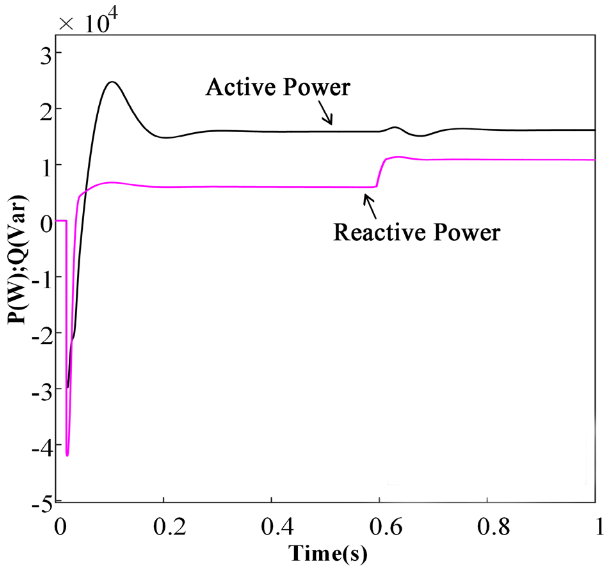

Fig. 14 Inverter's active and reactive power output waveforms based on residual reactive power control strategy of PCC inverter.

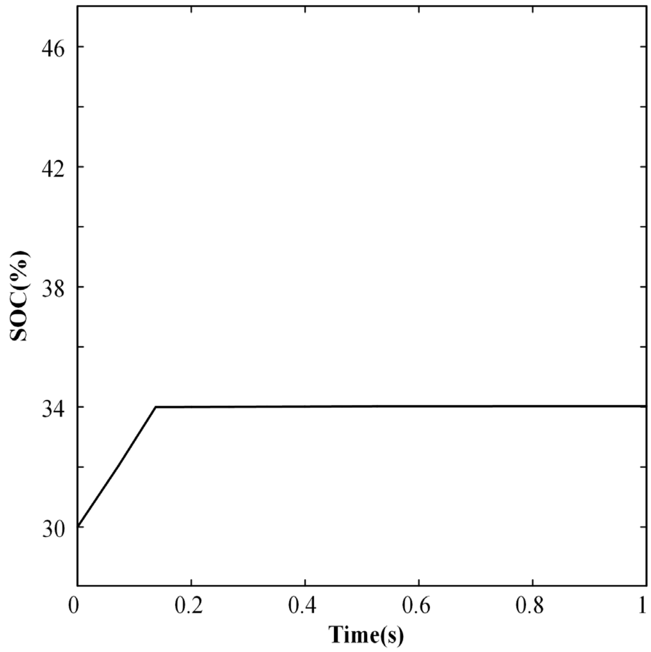

Fig. 15 Waveform of SOC change in ESS.

The simulation duration is 1 second. At the very beginning of the simulation, the load at the PCC is small and the voltage at the PCC is maintained in the normal range with the joint support of the PV output and the grid. However, at 0.6 seconds into the simulation, a sudden increase in load at the PCC occurs, leading to a decrease in the amplitude of the three-phase PCC voltage, as depicted in Figure 13. By collecting the amplitude information of the voltage at the PCC, the reactive power controller generates the reference value of reactive power, based on the control strategy of the PCC inverter's residual reactive power regulation.

As shown in Figure 14, the capacitive reactive power output of the PCC inverter increased from 5.9 kVar to 10.5 kVar. In 0.04s, it was able to raise the voltage at the PCC, which exceeded the lower limit, back to the normal level, thus resolving the voltage over-limit issue. Simultaneously, it did not interfere with the active power output of the PCC inverter. The ESS continued in its charging state, preserving the stability of the DC bus voltage.

Given the confinements of the limited residual reactive power capacity of the PCC inverter, there might occur scenarios where solely escalating the inverter's reactive power output falls short of elevating the PCC voltage. To address this, the controller collects information regarding the voltage amplitude at the PCC and transfers it to the storage controller. Following this, the active power output of the PCC inverter is lessened, and the excess power gets saved into the ESS. By varying the magnitude of load increase at the PCC, the voltage can be raised above the lower limit. When the voltage amplitude at the PCC is equal to or greater than 0.95p.u., the simulation results are presented in Figures 16, 17, and 18 below:

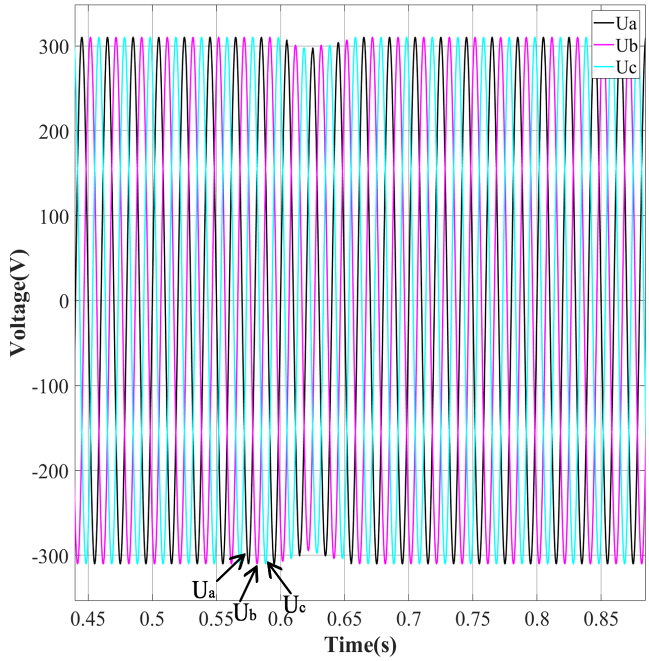

Fig. 16 Simulation waveform of significant under-limit voltage at the PCC (U_{pcc}>0.95p.u.).

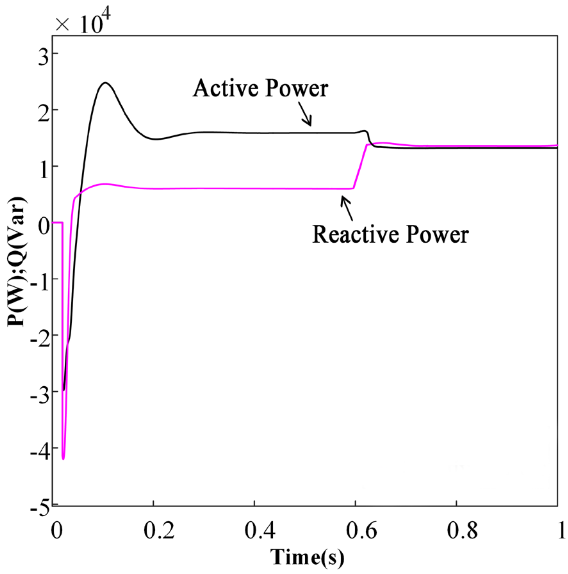

Fig. 17 Inverter's active power and reactive power output when the active output of the PCC inverter is curtailed.

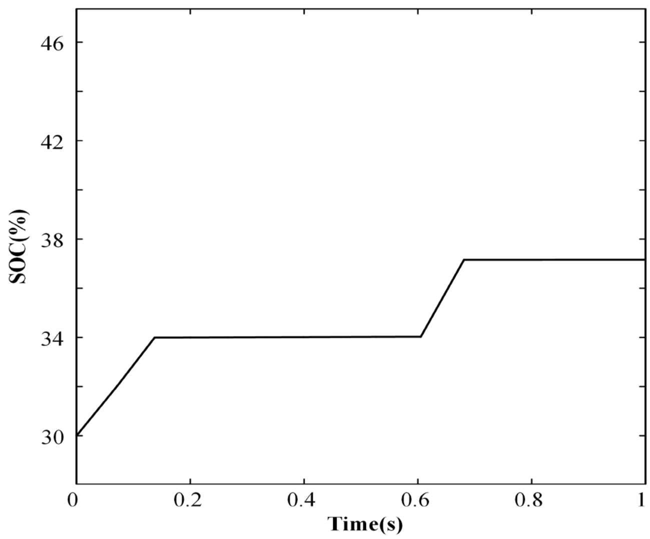

Fig. 18 Waveform of SOC change in ESS.

The simulation duration is 1 second, and at the very beginning of the simulation, the load at the PCC is small. Initially, the PCC voltage remains within the normal range due to the combined support from the PV output and the grid voltage. The simulation sets a sudden increase the PCC load at 0.6s, at which time it is impossible to raise the PCC voltage to within the normal range just by relying on the residual reactive power of the inverter. The controller collects voltage amplitude information and transmits control signals to the energy storage system. By commandeering the energy storage system to operate in charging mode, at 0.6s, the inverter's active power output dwindles from 15.8 kW to 12.8 kW, and the capacitive reactive power output from the inverter escalates from 6 kVar to 12.9 kVar. Owing to the decrease in the active power output of the inverter, the inverter garnered more residual reactive power capacity. As a result, the amplitude of the PCC voltage returned to the normal level, effectively solving the voltage over-limit problem. The ESS integrates the inverter's active power. This power would have otherwise been reduced by dismissing light, consequently preserving the economic benefits of PV access in western rural areas.

When a significant under-limit case occurs at the PCC voltage, i.e. U_{pcc}<0.95p.u., the PCC inverter cannot support the voltage merely through reactive power capacity. The controller collects the amplitude information of the PCC voltage and transmits it to the energy storage controller. According to Equation (10), the active power that the energy storage system needs to release is calculated. This allows the PCC voltage to be raised to a normal range. The simulation results can be seen in Figures 19, 20 and 21.

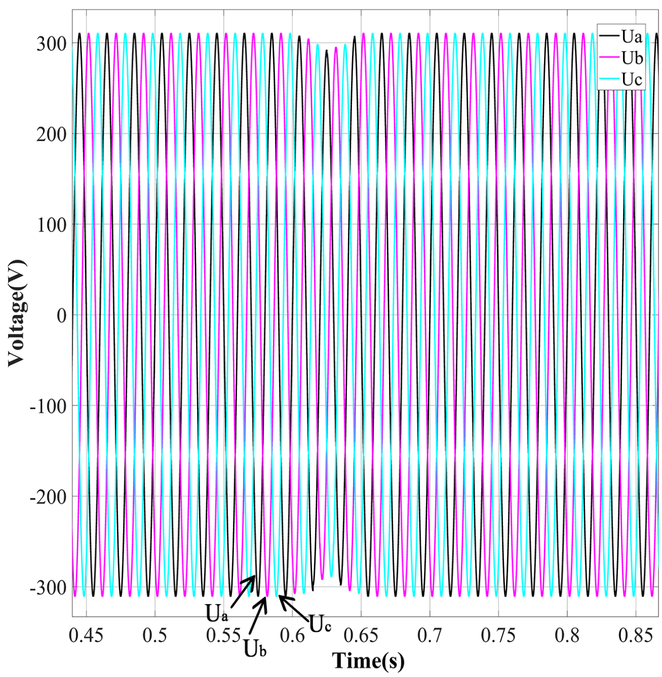

Fig. 19 Simulation waveforms of the PCC voltage exceeding the lower limit significantly.

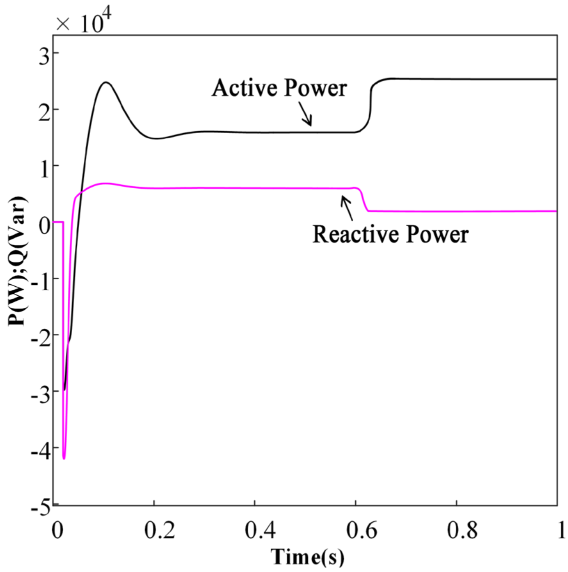

Fig. 20 The active power and reactive power output of the PCC inverter are directly controlled by ESS when the voltage significantly exceeds the lower limit.

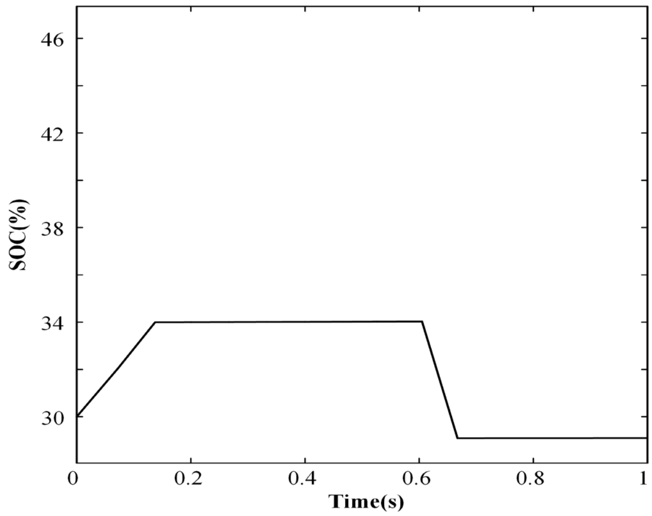

Fig. 21 Waveform of SOC change in ESS.

The simulation results indicate that when neither the residual reactive power of the PCC inverter nor the reduction in the inverter's active power output is adequate to restore voltage within its normal boundaries, directing the ESS to actively discharge power prevents the PCC voltage from significantly falling below its lower limit. Thus, directly controlling the energy storage system will compensate for the situation where relying solely on the residual reactive power adjustment ability of the PCC inverter is insufficient.

The above simulation analysis is based on the situation where the PCC point voltage exceeds the lower limit. As the load connected to the PCC diminishes and the voltage of the PCC surpasses the lower limit, it can be segmented into the scenario where the voltage marginally topples above the upper limit, the scenario where the voltage considerably tops over the upper limit (1.0p.u.<U_{pcc}<1.05p.u.), and the scenario where the voltage massively exceeds the upper limit (U_{pcc}>1.05p.u.). Through simulation, the first two cases (1.0p.u.<U_{pcc}<1.05p.u.) are similar to the discussed under-limit situation, and the PCC inverter can pull the PCC voltage back to the normal range by outputting inductive reactive power. No description is made here. When the PCC voltage significantly exceeds the upper limit, the simulation results are shown in the following Figures 22, 23, and 24:

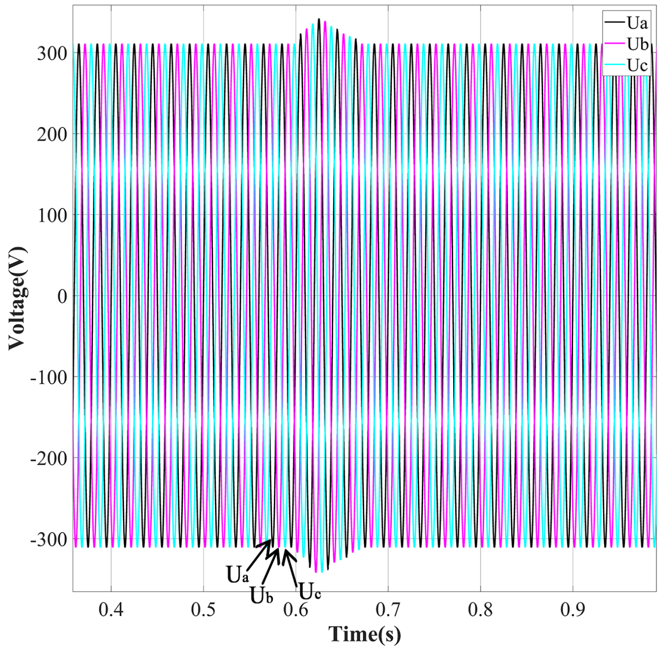

Fig. 22 Simulation waveform of significant over-limit voltage at the PCC.

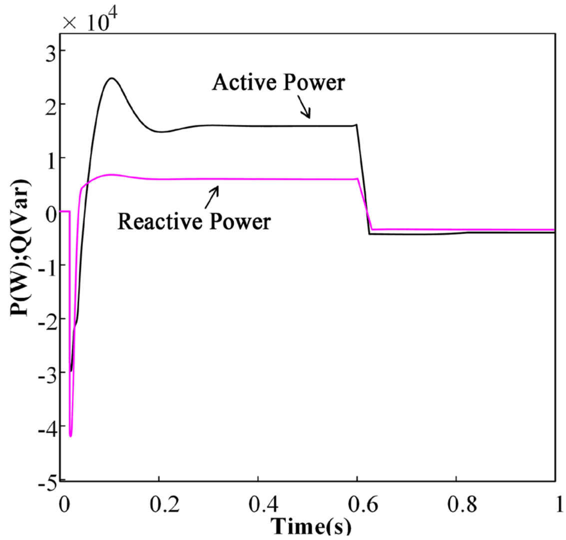

Fig. 23 The active power and reactive power output of the PCC inverter are directly controlled by ESS when the voltage massively exceeds the upper limit.

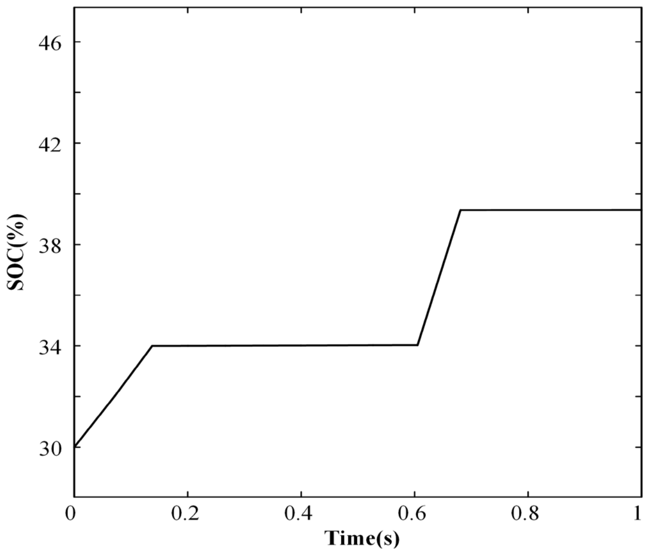

Fig. 24 Waveform of SOC change in ESS.

The simulation results show that when the PCC voltage greatly exceeds the upper limit and the inductive reactive power output by the inverter cannot pull the voltage back to a normal level, directly controlling the ESS to absorb active power can suppress the occurrence of a significant over-limit voltage at the PCC, thus solving the voltage over-limit problem.

In summary, the voltage coordination control strategy has the ability to calibrate the PCC voltage within the regular range when it oversteps the limit to varying degrees. This article verifies the correctness and effectiveness of the proposed control strategy through simulation analysis of the voltage coordination control strategy in LVDN in the western rural areas under photovoltaic storage access. Simulation outcomes demonstrate that the voltage coordination control strategy, which is proposed in this paper, can substantially alleviate the issue of surpassing the limit of the PCC voltage and uplift the reliability and stability of the voltage between the grid and the access points of PV and ESS. By controlling the ESS through the controller, the active power that would have been lost due to light abandonment is absorbed, ensuring the economic benefits under the access of PV in the western rural areas.

V. Conclusion and Prospect

This paper presents a comprehensive investigation into the voltage coordination control strategy for LVDN in western rural areas, considering the access of PV and ESS. The study aims to address the issue of voltage overrun at the PCC by utilizing the PCC inverter's residual reactive capacity and implementing coordinated control with the ESS. The following conclusions are drawn:

1. In the face of PCC voltage slightly exceeding the limit, we can design voltage regulation strategies based on the residual reactive power capacity of the PCC inverter. It can provide strong voltage support for each node in the LVDN. More precisely, by reducing the active power output of the inverter, we can provide a greater reactive margin for the voltage regulation strategy. At the same time, the active power that originally needed to be reduced by discarding light can now be effectively absorbed by the ESS. This approach considerably amplifies the utilization efficiency of solar energy resources and guarantees the economic gains of the LVDN in the western rural areas that are interconnected with PV and ESS. This coordinated control strategy can greatly reduce the adverse effects of PV on LVDN, thereby enhancing the stability and reliability of the PV and ESS connected to the LVDN in the rural western region.

2. The introduction of ESS is of significant importance in voltage coordination control. ESS can not only effectively alleviate the adverse effects of PV access on LVDN, but also serve as an important pillar for power interaction with LVDN. Indeed, if the voltage variation at the PCC outstrips the pre-set normal range, the ESS is equipped to swiftly execute charging and discharging operations, responding to the PCC voltage over-limit scenario and load access condition. ESS adjusts the voltage at the PCC by absorbing or releasing active power, gradually returning it to the normal range. This flexible and efficient voltage regulation method maximizes the benefits of voltage management. Therefore, voltage coordination control based on ESS can not only ensure grid operation stability, but also improve the economic benefits and energy utilization efficiency of the grid.

Considering the above discussions, we can conclude that: the voltage coordination control strategy proposed in this article for PV and ESS access, whether in practicality or feasibility, performs very well. This research focuses on how to optimize the use of the residual reactive power capacity of the inverter and the ESS, effectively suppress the over-limit situation of the PCC voltage, and design a set of voltage coordination control strategies. This control strategy can be smoothly implemented in the existing PV and ESS access LVDN without requiring large-scale reconstruction of the current system. This not only reduces the implementation cost, but also greatly lowers the technical threshold. Therefore, in the LVDN of the western rural area with PV and ESS access, this strategy has great prospects and can effectively guarantee the operation of the local power system and the quality of the power supply. However, despite the many positive advantages of this voltage coordination control strategy, further research and practice are still needed to verify and improve its effectiveness and feasibility. By continuous optimization and improvement, we hope to further promote its widespread application in actual situations, to fully exploit its potential in energy management of power systems.

References

[1] G. Luo, and T. Liu, "The Exposition of Non electricity Customers, Renewable Energy Power Poverty Problems of the Aural areas of Western China," Journal of North China Electric Power University (Social Sciences), no. 6, pp 6-12, 2013.

[2] W. Jin, B. Xu, J. Ding, L. Wang, and J. Pan, "Research on Power Quality Integrated Control Technology for Photovoltaic Poverty Alleviation Rural Grid Based on Coordination and Autonomy," Power Capacitor & Reactive Power Compensation, vol. 38, no. 3, pp 0157-0161, 2017.

[3] M. Zeraati, M. Golshan, and J. Guerrero, "Voltage Quality Improvement in Low Voltage Distribution Networks Using Reactive Power Capability of Single-Phase PV Inverters," IEEE Transactions on Smart Grid, vol. 10, no. 5, pp 5057-5065, 2019.

[4] L. Zhou, Y. Chao, B. Liao, P. Chao, and M. Yang, "A Voltage Regulation Strategy by Grid-Connected PV Inverters in Low-Voltage Networks," Power System Technology, vol. 37, no.9, pp 2427-2432, 2013.

[5] Y. Cai, L. Zhang, W. Tang, O. Xu, J. Wang, and Q. Song, "A Voltage Control Strategy for LV Distribution Network With High Proportion Residential PVs Considering Reactive Power Adequacy of PV Inverters," Power System Technology, vol. 41, no. 9, pp 2799-2808, 2017.

[6] Y. Zhang, H. Yi, H. Zhang, Q. Wang, Z. Yang, and F. Zhuo, "Coordinated Reactive Power Margin Management of Multiple Photovoltaic Inverters for Voltage Regulation in Distribution Networks," 2022 IEEE International Power Electronics and Application Conference and Exposition (PEAC), 04-07 November, 2022, Guangzhou, Guangdong, China, pp 1598-1602.

[7] R. Tonkoski, L. Lopes, and T. El-Fouly, "Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention," IEEE Transactions on Sustainable Energy, vol. 2, no. 2, pp 139-147, 2011.

[8] Z. Yu, Y. Tang, J. Dai, and J. Yi, "Voltage/var Control Strategy of PV Plant Based on Adaptive Adjustment of Active Power," Power System Technology, vol. 44, no. 5, pp 1900-1907, 2020.

[9] Y. Wang, K. Tan, X. Peng, and P. So, "Coordinated Control of Distributed Energy-Storage Systems for Voltage Regulation in Distribution Networks," IEEE Transactions on Power Delivery, vol. 31, no. 3, pp 1132-1141, 2016.

[10] J. Yang, W. Tushar, T. Saha, M. Alam, and Y. Li, "Prosumer-Driven Voltage Regulation via Coordinated Real and Reactive Power Control," IEEE Transactions on Smart Grid, vol. 13, no. 2, pp 1441-1452, 2022.

[11] M. Zeraati, M. Golshan, and J. Guerrero, "Distributed Control of Battery Energy Storage Systems for Voltage Regulation in Distribution Networks With High PV Penetration," IEEE Transactions on Smart Grid, vol. 9, no. 4, pp 3582-3593, 2018.

[12] Y. Zhang, X. Wang, and Y. Li, "PV reactive voltage regional autonomy control strategy for Q(U) improvement in distribution network," 2019 4th International Conference on Intelligent Green Building and Smart Grid (IGBSG), 06-09 September, 2019, Hubei, China, pp 497-501.

[13] J.J Marulanda-Durango, A. Escobar-Mej´ıa, and E. Giraldo, "Multivariable Coupled Control of a Static Var Compensator to Improve the Power Factor of a Steel Plant with an Electric Arc Furnace Load," Engineering Letters, vol. 29, no. 2, pp 365-372, 2021.

[14] D. Li, C. Ho, L. Liu, and G. Escobar, "Reactive Power Control for Single-Phase Grid-Tie Inverters Using Quasi-Sinusoidal Waveform," IEEE Transactions on Sustainable Energy, vol. 9, no. 1, pp 3-11, 2018.

[15] B. Craciun, D. Sera, E. A. Man, T. Kerekes, V. A. Muresan and R. Teodorescu, "Improved voltage regulation strategies by PV inverters in LV rural networks," 2012 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 25-28 June, 2012, Aalborg, Denmark, pp 775-781.

[16] S. Zhao, J. Wang , H. Wang, and A. He, "Control Strategies of Microgrid at Micro-source Level and System Level," Engineering Letters, vol. 28, no. 1, pp 155-167, 2020.

[17] J. Gao, C. Shih, C. Lee, and K. Lo, "An Active and Reactive Power Controller for Battery Energy Storage System in Microgrids," IEEE Access, vol. 10, pp 10490-10499, 2022.