Enhancing voltage stability in active distribution networks through solar PV integration

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Article Info

Article history:

Received Sep 9, 2024
Revised Apr 4, 2025
Accepted May 6, 2025

Keywords:

Battery energy storage system
Decentralized control
Energy management system
Grid-connected solar power
On load tap changer

ABSTRACT

Solar PV's explosive expansion is changing distribution networks and posing new problems, such as bidirectional power flow, unstable voltage, and power quality problems, particularly in networks with low X/R ratios. Abrupt changes in voltage are difficult for conventional voltage control techniques like shunt capacitors and on-load tap changers (OLTCs) to handle. IEEE Standard 1,547 has little efficacy in such networks, despite the fact that PV inverters may provide reactive power. This paper suggests a real-time coordinated control approach to improve voltage regulation by combining PV inverters, OLTC, and battery energy storage systems (BESS). Reactive power from PV inverters is prioritized to lower operational expenses and reliance on BESS. Better voltage stability, a decrease in BESS energy processing from 9400.3 kWh to 1701.87 kWh, and a reduction in OLTC activities are the outcomes. Rural networks gain from the strategy's ability to support smaller, more affordable BESS units' voltage sensitivity analysis, and ideal BESS sizing may be investigated in future studies.

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1. INTRODUCTION

Conventional distribution networks are being rapidly transformed by solar PV integration, resulting in a change from unidirectional to bidirectional power transmission. In low X/R ratio networks in particular, this shift poses problems with voltage management and power quality. Particularly on overcast days, standard voltage regulation techniques like on-load tap changer (OLTC) and shunt capacitors find it difficult to control the sharp voltage swings brought on by fluctuating solar PV output. Coordinated control of battery energy storage systems (BESS), solar PV inverters, and OLTC has been suggested as a solution to these problems. On cloudy days, however, PV output can vary greatly, making voltage regulation more difficult and requiring sophisticated control techniques. Measuring and managing the effect of solar PV on voltage profiles requires real-time monitoring. By itself, individual regulation techniques like as BESS, OLTCs, and PV inverters are insufficient. To provide efficient, cost-effective, and standards-compliant regulation during high PV penetration, a swift, coordinated control mechanism is required [1]-[5].

Creating a sophisticated real-time data monitoring system is the aim in order to monitor grid dynamics during periods of high solar PV penetration, especially when solar production is variable. In order to do this, a coordinated voltage regulation control technique integrating all conventional devices such as solar PV inverters, BESS, and OLTCs must be designed and implemented. The goal is to provide an efficient, real-time control mechanism that reduces OLTC activities, energy cycling in BESS, and voltage regulation to maximize economic gains. Furthermore, the method has to follow utility-imposed requirements, including power factor, voltage limitations, and ramp rate constraints [6]-[10].

This work improves voltage regulation control by utilizing the phasor measurement units' (PMUs) real-time data collection capabilities. This paper presents a real-time coordinated control system for solar PV inverters, BESS, and OLTCs, in contrast to conventional approaches that rely on slower SCADA data. The suggested control method prioritizes solar PV inverters while streamlining the functioning of these devices and lowering the frequency of BESS cycling and OLTC tap adjustments. It also places a strong emphasis on economic efficiency by lowering utility expenses. Through the use of real-world implementation and MATLAB-Simulink simulations, the effectiveness of the control is verified, guaranteeing adherence to utility-imposed limits [11]-[15].

Rising solar PV installations worldwide between 2010 and 2020 (from 40,334 MW to 709,674 MW) have global solar photovoltaic capacity increased from 40,334 MW to 709,674 MW between 2010 and 2020, causing voltage oscillations to raise concerns about grid stability. Rapid variations in sunlight cause problems for traditional OLTCs and capacitor banks, which is why inverter-based control and BESS are becoming more popular. In order to decrease voltage violations, prolong equipment life, and improve economic efficiency, this study suggests a combined OLTC-BESS control approach. By reducing soil organic carbon (SOC) variability, the strategy lowers investment costs and BESS cycles. By adjusting taps more often, OLTCs improve voltage regulation [16]-[20]. For example, during periods of peak solar generation, they may change the taps from -5 to -2 instead of -5 to -4. The suggested and conventional OLTC tap operations are contrasted in Figure 1.

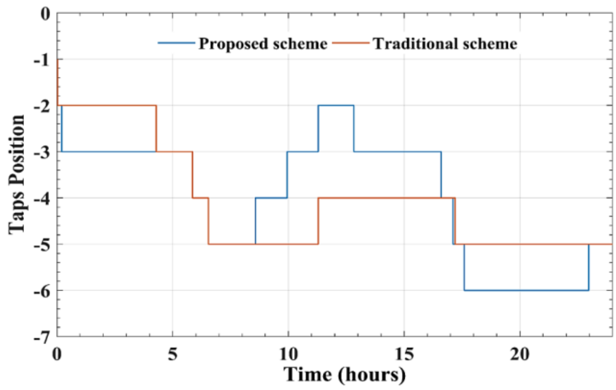

Figure 1. Comparison of OLTC taps operation in traditional and proposed control

2. METHOD

This article focuses on a 6.5-megawatt PV power plant at Aligarh Muslim University in India, which is planned to have a 1 MW, 1.5 MWh BESS. The plant's performance is studied under low load situations, where demand ranges from 2.4 MW to 4.73 MW and PV generation can surpass load by up to 2.7 times. A 3-kilometer, 33 kV feeder connects the PV facility, and an OLTC located 2.5 kilometers away from the substation regulates voltage as shown in Figure 2. In order to support voltage and manage BESS operations with traditional droop control and 5-minute cycle changes, PV inverters are controlled by PMU, SCADA, and PLC systems [21], [22]. The specs for the OLTC that is situated in the center of the 33-kilovolt feeder and provides power to the university load are listed in Table 1.

Figure 3 shows how the solar PV inverter in conventional control follows a predetermined droop curve for reactive power correction. The optimization restrictions previously discussed the power factor of the inverter, which is limited to 0.9 lagging and 0.9 leading. Four reference points for voltage control the power factor droop. In order to enable voltage regulation, the droop control uses a capacitive power factor to activate when the system voltage drops below the predetermined threshold. The inverter, on the other hand, adapts to offer inductive compensation when the voltage increases. The particular reference voltage values are V1 = 0.973 per unit, V2 = 0.983 per unit, V3 = 0.996 per unit, V4 = 1 per unit. A lower-than-average reactive power compensation for voltage regulation is shown by the 33 kV feeder's 1.12 X/R ratio. Further limiting reactive power compensation, particularly on cloudy days, are standard power factor restrictions set by the utility, which are 0.9 leading and lagging. While BESS with a 5-minute control cycle can solve voltage regulation concerns, there are significant financial and technical expenses associated with this. Different states have different point of common coupling (PCC) voltage restrictions, which are enforceable by law. As a result, voltage management is optimized under fluctuating situations. A control algorithm estimates solar PV power and BESS SOC to reduce voltage swings [23], [24]. Figure 4 shows the daily variation of solar PV power generation and load demand. Aside from variations in temperature and radiation, other factors that might cause swings in PV power generation include dust collection, inverter response time, passing clouds, and maximum power point tracking (MPPT) inefficiencies. Instability can also be caused by reactive power adjustment, abrupt changes in load, and grid voltage oscillations. Additionally, some swings may look unreasonable due to sudden changes caused by protection mechanisms like curtailment rules and overvoltage cut-off [25].

Table 1. OLTC parameters

Power rating	9 megavolt-amps	Power rating	9 megavolt-amps
Voltage rating	33 kilovolts	Tap selection time	2 seconds
Number of taps	16(+/-8)	Tap transition time	60 milliseconds
Dead band	1.25 percentage	Number of regulators	1
Step voltage	0.65% of rated voltage	Vref	0.991 per unit
Wait period	150 seconds		

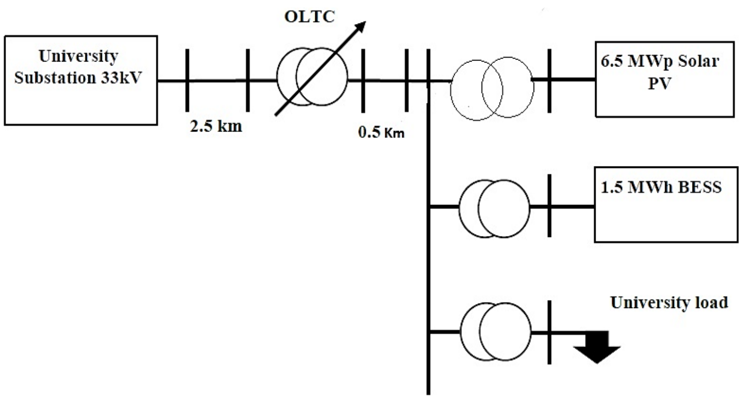

Figure 2. Distribution network diagram for Aligarh Muslim University in one line

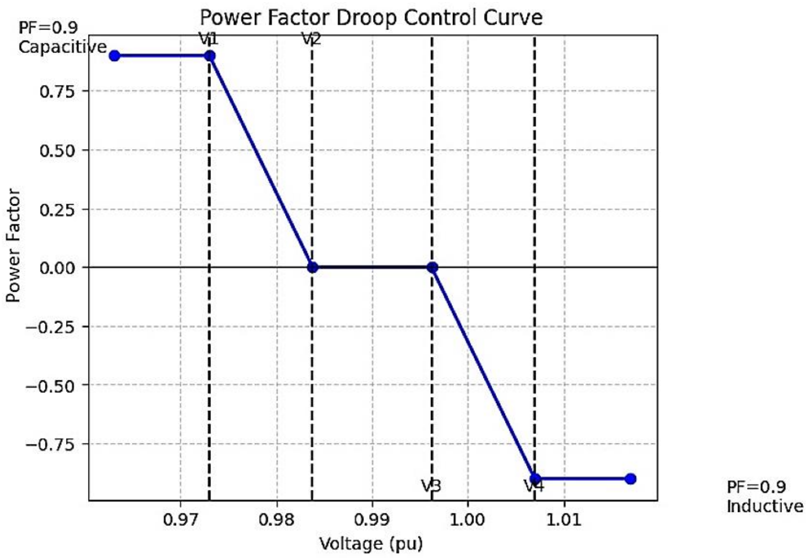

Figure 3. Graph of power factor droop

Control algorithm: System expenses are decreased by the suggested real-time coordinated control technique, which reduces voltage variations without requiring communication between inverters and OLTC. There are three primary blocks to it:

a. Data logging block: Gathers SCADA/PMU data, such as P_{PV}, Q_{PV}, P_B, Q_B, and SOC. Forecasts SOC deviation and voltage deviation (Δ_{PV}).
b. Optimization block: Makes use of gathered data to apply an optimization function to reduce voltage fluctuations. Q_{PV}, ΔP_B, and ΔQ_B are all optimized values that are generated.
c. SOC adjustment block in bi-directional brings SOC closer to its reference value by adjusting ΔP_B, guaranteeing BESS availability. Transmits updated control commands for implementation to SCADA.

This strategy guarantees that OLTC only manages mild voltage variations, avoids premature BESS depletion, and gives priority to reactive power correction. By effectively managing voltage variations by coordinating BESS, OLTC, and PV inverters, the suggested method eliminates the need for expensive communication routes. Reactive power compensation from PV inverters is given priority, and when required, BESS support is used. The technique makes sure OLTC runs efficiently and modifies voltage deviation to avoid early BESS fatigue. This method of coordinated control is illustrated in Figure 5 and (1) and (2).

$$V_{pv}^{u} = \Delta V_{pv} + |V_{ref} - (V_{DB}/2) - V_{min} - \alpha|[V_{pcc} + \Delta V_{pv} - V_{min}] \quad (1)$$

When $V_{pcc} + \Delta V_{pv} < V_{min}$.

$$V_{pv}^{u} = \Delta V_{pv} + |V_{max} - V_{ref} - (V_{DB}/2) - \alpha|[-V_{max} - V_{pcc} - \Delta V_{pv}]| \quad (2)$$

When $V_{pcc} + \Delta V_{pv} > V_{max}$.

Reactive power correction is given priority in the suggested algorithm in order to reduce voltage fluctuations and indirectly preserve BESS energy. ΔP_B is changed to ΔP_{Bu} in order to avoid premature BESS exhaustion, guaranteeing that SOC stays close to its reference value, SOC MIDDLE. With a SOC range of 40% to 80%, the BESS produces 600 kWh of usable energy. The SOC adjustment changes ΔP_B according to the SOC level, increasing charging when SOC is low and decreasing it when SOC is high. This method avoids BESS misuse or depletion while keeping SOC within reasonable bounds. Figure 6 shows the method of SOC adjustment. By keeping processed energy at 1,701.87 kWh instead of 9,400.3 kWh using traditional approaches, the suggested control scheme dramatically lowers BESS energy use. A 2.125-fold reduction in OLTC tap operations is also made, down to 32 taps. Table 2 presents specific findings.

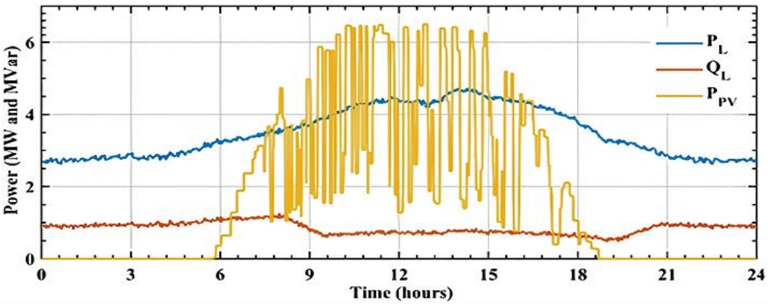

Figure 4. Daily variation of solar PV power generation and load demand

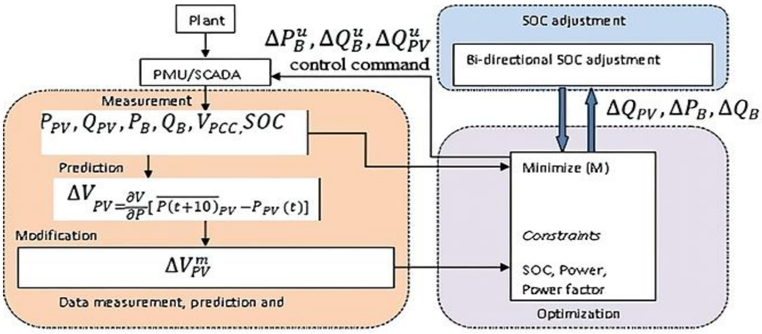

Figure 5. Suggested control plan

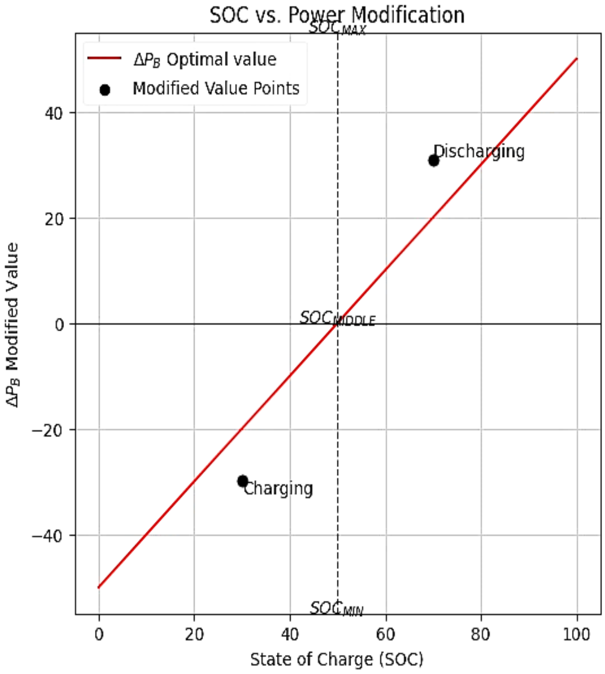

Figure 6. Method of SOC adjustment

Table 2. BESS and OLTC energy handling

Circumstances	BESS energy handling	OLTC energy handling (taps counts)
Previous PV	N/A	19
Current control	9400.3 kWh	68
Control proposed	1701.870 kWh	32

3. RESULTS AND DISCUSSION

Bi-directional SOC adjustment ensures a smoother voltage profile and keeps voltage within acceptable bounds, prolonging the life of the infrastructure. It minimizes frequent charging and discharging by optimizing reactive power adjustment, which lowers BESS energy processing from 9,400.3 kWh to 1701.87 kWh. By using solar inverters' reactive power before BESS electricity, this method also reduces OLTC procedures. Comparisons of voltage profiles and SOC are shown in Figures 7 and 8. Under two distinct control strategies, the voltage patterns are shown in Figure 7: Figure 7(a) displays the voltage profile that was obtained with the current control strategy and Figure 7(b) displays the profile that was attained utilizing the suggested method. Figure 7(b) illustrates how the suggested technique successfully reduces excessive voltage dips, resulting in a more stable voltage profile. However, there will be slight waveform distortions close to the lower clipping zone as a result. Asymmetry: The voltage profile does not mirror itself around a central reference value, likely due to the prioritization of mitigating high voltage excursions over low ones. Table 3 shows the profiles of power injection for solar PV inverters and BESS.

Figure 9 shows the profiles of power injection for solar PV inverters and BESS. A real-time voltage regulation strategy that synchronizes solar PV inverters, BESS, and OLTC is proposed in this study to control both rapid and gradual voltage variations in weak grids with significant PV penetration. To maximize economic benefits, the plan minimizes BESS active power consumption while giving priority to PV and BESS reactive power support. To increase the availability of BESS throughout the day, a novel bi-directional SOC modification technique is presented. By limiting voltages within specified bounds and smoothing out variations, the suggested approach successfully increases voltage stability. Verified by field-recorded overcast day data, the results show less BESS energy cycling, which lowers PV plant owners' operating expenses. In order to retain performance similar to pre-PV integration conditions, the method also minimizes OLTC tap procedures. Although efficient, there is a need for more study with enhancements including ideal BESS sizing and accurate voltage sensitivity testing. The results demonstrate the scheme's potential to lessen reliance on massive energy storage devices for rural networks with insufficient voltage regulation.

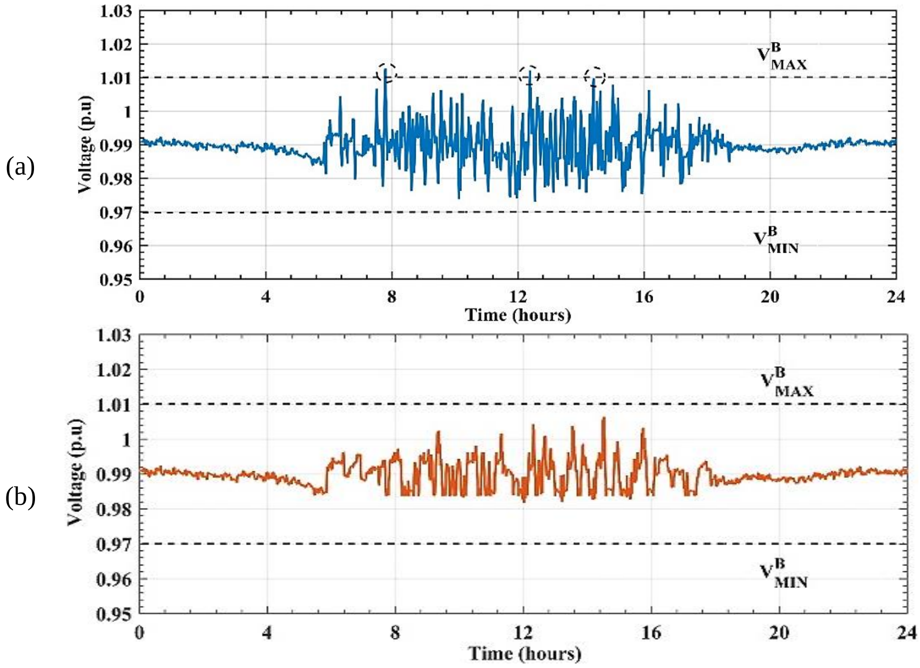

Figure 7. A solar PV-integrated distribution network's voltage profiles under various control schemes are contrasted in voltage profile with (a) existing control and (b) proposed method

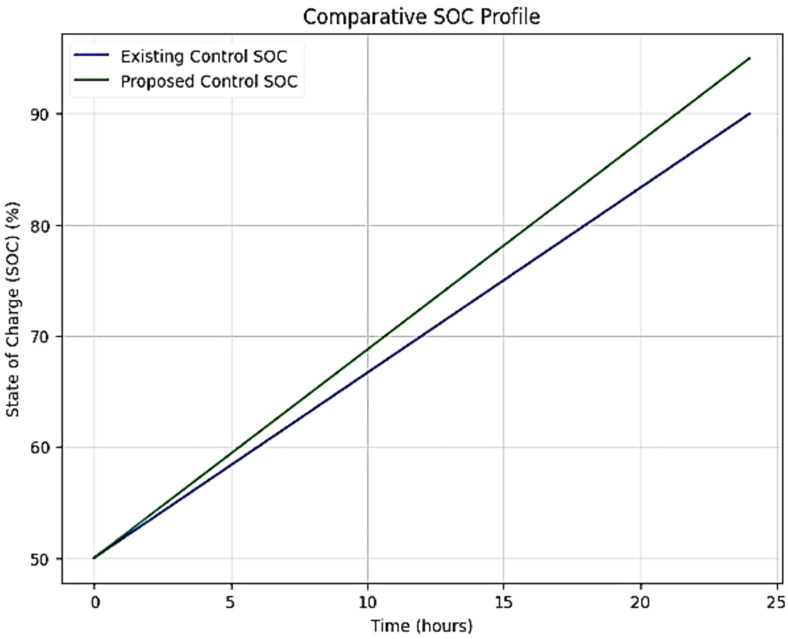

Figure 8. Comparative SOC profile

Table 3. Shows profiles of power injection for solar PV inverters and BESS

Time (hours)	P_{PV} (MW)	Q_{PV} (MVAr)	P_B (MW)	Q_B (MVAr)
0	0	0	0	0
6	1	-1	0.5	0.1
8	2.5	-2.5	0.7	0.2
10	3.5	-3	0.9	0.3
12	4	-2.8	1	0.4
14	3	-2.5	0.8	0.2
16	2	-1.5	0.6	0.1
18	0.5	-0.5	0.3	0.05

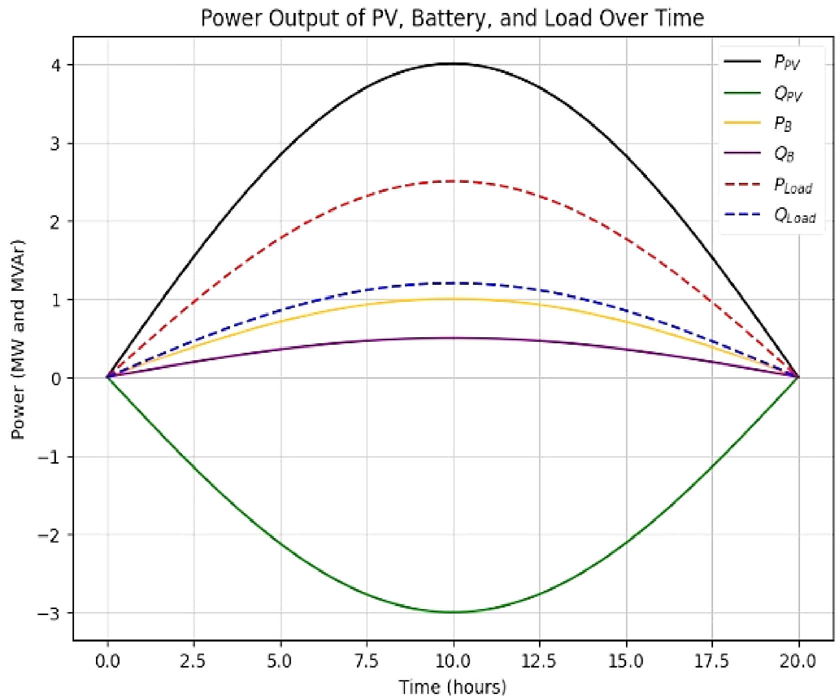

Figure 9. Profiles of power injection for solar PV inverters and BESS and load

4. CONCLUSION

In weak networks with a high penetration of solar PV, the suggested real-time coordinated voltage regulation control successfully resolves voltage fluctuation problems. Coordinating solar PV inverters, BESS, and OLTC allows the control strategy to show notable performance gains. Principal numerical findings: i) Voltage profile improvement: By efficiently mitigating voltage fluctuations, the suggested control technique guarantees that voltage levels stay within the specified ranges; ii) Reduction of BESS energy cycle: By reducing BESS energy cycling, the novel bi-directional SOC control technique prolongs battery life. The plan minimizes OLTC tap operations, which lowers maintenance expenses while preserving voltage stability; and iii) Economic benefits: By drastically lowering energy processing by BESS, the optimized control ensures solar PV plant owners can afford it. The method's practical viability is further confirmed by field application at Aligarh Muslim University, which shows better voltage regulation and less equipment wear. Future studies can concentrate on advanced energy storage integration, better voltage sensitivity assessment, and ideal BESS sizing for improved grid performance.

ACKNOWLEDGMENTS

We would like to express our heartfelt gratitude to Dr. S. Deepa for her invaluable guidance, insightful suggestions, and continuous encouragement throughout the course of our Ph.D. research. We are also deeply thankful to Dr. S. Selvi, Head of the Department, Panimalar Engineering College, for her unwavering support and kind assistance, which have been instrumental in the successful completion of this work.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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