Modified Incremental Conductance-Based Active Power Curtailment for Voltage Regulation in Highly PV-Fed Distribution Grids

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Increasing the penetration of photovoltaic (PV) systems in the distribution grid poses challenges, including voltage rise and potential violations during low load conditions or peak PV generation. This paper introduces a modified incremental conductance (IC) method to limit the active power injection from PV systems, mitigating voltage violations. A voltage-sensitive control loop is integrated into the IC method to improve its performance. This algorithm allows for the dynamic adjustment of active power output based on real-time voltage measurements from the grid, enabling precise voltage regulation while maintaining maximum power point tracking (MPPT) under normal conditions. When necessary, it shifts the operating point away from the maximum power point (MPP) to limit active power injection, ensuring voltage stays within safe limits. The proposed algorithm is less complex, cost-effective, and can be implemented in existing inverters using the IC method. The algorithm's effectiveness is validated through Simulink/MATLAB simulations, using a setup consisting of a distribution grid with two solar PV-based distributed generators (DGs), each with a capacity of 100 kW.

Keywords: Modified Incremental Conductance, PV Penetration, Voltage Violation, Active Power Curtailment, MPPT

Introduction:

The increased penetration of photovoltaic (PV) systems in the distribution grid has brought significant benefits, such as reducing dependence on traditional energy sources, lowering reliance on fossil fuels, and decreasing greenhouse gas emissions [1]. The integration of rooftop PV-based distributed generators (PVDG) into the grid has been observed globally [2]. However, despite these advantages, high PV penetration in distribution grids has introduced challenges, particularly voltage violations in low-voltage networks, often driven by bidirectional power flow [3]. Voltage violations typically occur when peak PV generation does not align with peak load, which limits further PV integration [4]. This voltage rise is mainly caused by the impedance of the feeder; in lines with higher impedance, reverse power flow can cause the voltage to exceed regulatory limits [5].

Recent studies have proposed various strategies to mitigate these issues, including feeder upgrades, on-load tap-changing (OLTC) transformers, battery energy storage systems (BESS), active power curtailment (APC), reactive power control (RPC), machine learning-based solutions, or combinations of these methods [6].

Research in [7] suggests replacing existing feeders with conductors of higher ampacity and lower impedance, as this would reduce voltage violations and allow for greater PV penetration. OLTC transformers, which dynamically adjust the turn ratio between transformer windings to regulate voltage, is another approach [8].

Battery energy storage systems (BESS) have emerged as an effective solution for managing voltage violations in high-PV grids. BESS can regulate voltage rise during peak PV generation and voltage drops during peak load periods by charging and discharging in a coordinated manner [9]. These systems are particularly effective in maintaining voltage levels within acceptable limits, even with PV penetration levels as high as 80-100% [10]. In [11], several autonomous PV inverter control techniques were compared, and a hybrid control strategy was proposed to mitigate voltage rise in low-voltage (LV) grids. A strategy combining BESS with OLTC-equipped transformers was developed in [12] to regulate voltage deviations in PV-rich distribution networks. While these methods—feeder enhancement, OLTC, and BESS—require modifications to the existing infrastructure, they are not always cost-effective or economical.

Alternatively, reactive power control has demonstrated excellent performance in voltage regulation, reducing the need for reactive power compensation [13]. A distributed Volt/Var control method, proposed in [14], minimizes the reactive power burden on substations and improves the power factor. Additionally, a local voltage control strategy based on the reactive power capability of PV inverters, using a Q-V control curve with tuning parameters for faster response, has been developed [15]. These strategies offer effective solutions to mitigate voltage violations in distribution networks with high PV penetration.
Active power curtailment (APC) is a proven strategy for mitigating voltage violations caused by high photovoltaic (PV) penetration in distribution grids [6][16]. APC can be implemented through smart PV inverters that adjust active power output based on control signals, helping to improve voltage regulation and maintain thermal feeder profiles [17]. Short-term PV power forecasts can be used to predict and prevent potential over-voltage events, enabling adaptive APC implementation.

This article presents a modified incremental conductance method designed to curtail active power flow during voltage violations, which typically occur when the peak load on the feeder does not align with peak PV power generation. The study offers a simple, cost-effective solution for power control during voltage rises. Section II details the model development, Section III introduces the proposed algorithm, Section IV presents the results and discussions, and Section V concludes the paper.

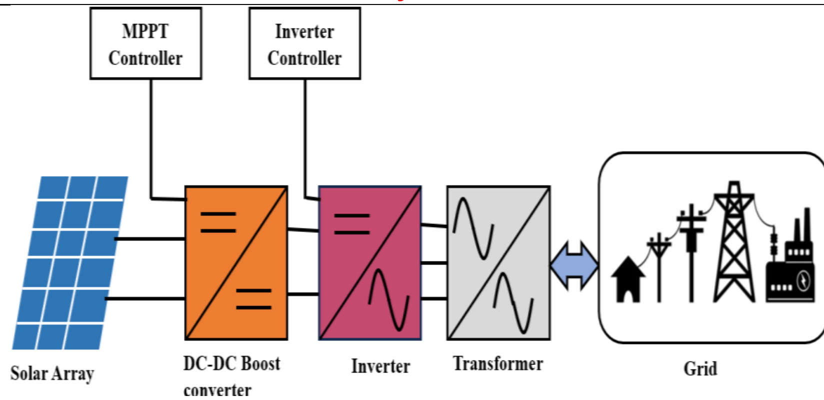


Figure 1. Block diagram microgrid integration of a PV fed with the distribution grid

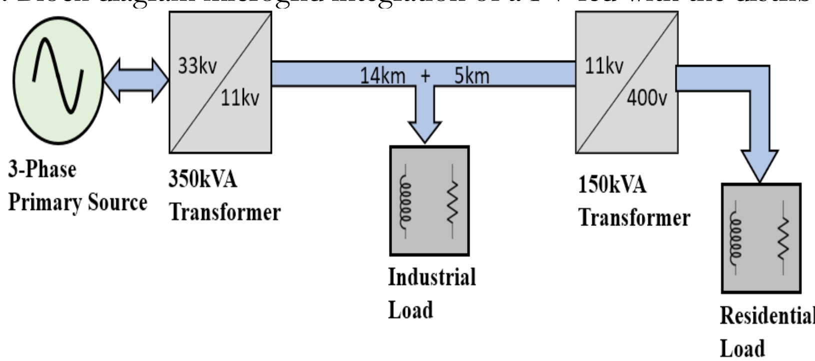


Figure 2. Block diagram of the distribution grid

Methodology:

Model Development:

The simulations were conducted in a MATLAB/SIMULINK environment, which offers a powerful and flexible platform for dynamic analysis. This setup supports the development of a detailed model that accurately reflects the real-world behavior of the system under study. The focus of this investigation was on building a comprehensive model of a grid-connected Photovoltaic (PV) system. The model captured the interaction between a PV Distributed Generation (PVDG) system and the distribution grid. A structural overview of the simulated system is shown in Figure 1.

The distribution grid model developed for this case study, shown in Figure 2, includes a primary energy source, a three-phase transformer rated at 350 kVA with a voltage rating of 33 kV/11 kV and an efficiency of 99%. The 11 kV ACSR (50 mm²) feeder being analyzed was 19 km long and terminates at an 11/0.4 kV, 150 kVA transformer. The primary energy source has an impedance of 150 ohms and an inductance of 0.75 H. This high source impedance ensures voltage violations occur when 200 kW of PV power is injected.

The total peak load of the distribution network was 200 kVA. At an economical power factor of 0.9, this corresponds to 180 kW. The load was divided into two parts:

- The first load was located 14 km from the substation along the 11 kV feeder and was rated at 104.1 kVA (94.5 kW and 43.59 kVAR). It represents a large industrial or commercial load connected directly to the 11 kV line.
- The second load was connected along the 400 V lines tapped from the end of the 11 kV feeder. It represents smaller consumers connected at the low voltage (LV) level, with a rating of 95.97 kVA (85.5 kW and 43.59 kVAR).

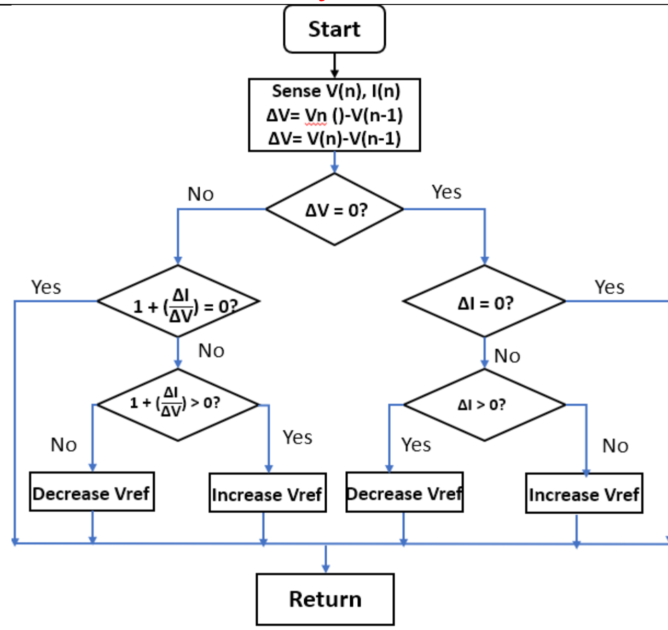


Figure 3. Traditional Incremental Conductance Flowchart

PV System:

Two 100 kW PV systems were used in the simulation, providing a combined power of 200 kW. Each PV array consists of 66 parallel strings, with 5 modules per string, and each module was made up of 96 cells. The panels used were SunPower SPR-305E-WHT-D models, each rated at 305.26 watts, resulting in a total array output of approximately 100.7 kW. SunPower panels are known for their long-term durability, with only 0.55% annual degradation over a 25-year lifespan. Each array contained 330 PV panels, producing 100 kW at the inverter output. The detailed parameters of the panels used are listed in Table 1.

Table 1. Solar Panel Parameters from Datasheet

Module Name	SunPower SPR-305E-WHT-D
Maximum power	305.226 W
Open Circuit Voltage (Voc)	64.2 V
Short Circuit Current (Isc)	5.96 A
Voltage at MPP	54.7 V
Current at MPP	5.58 A

A DC-DC boost converter regulates the DC power flow from the PV array to the inverter by tracking the Maximum Power Point (MPP) using the Incremental Conductance (IC) method combined with an integral regulator [18]. The Incremental Conductance (IC) algorithm illustrated in the flowchart in Figure 3, operates by measuring the voltage and current of the photovoltaic (PV) system and computing their increments (ΔV and ΔI) to track the Maximum Power Point (MPP). The IC method compares the instantaneous conductance (I/V) with the incremental conductance (ΔI/ΔV) to adjust the reference voltage (V_{ref}), which tracks the corresponding MPP. To enhance tracking accuracy, reducing steady-state error, and mitigating power oscillations, an integral regulator is integrated with the IC method. This regulator processes the error e according to equation (1) between the current operating point and the MPP. The resulting control signal as per equation (2) is fed to the Pulse Width Modulation (PWM) unit, which adjusts the switching of the boost converter accordingly.

$$e = \frac{dI}{dV} + \frac{I}{V} \quad (1)$$

$$U_{IR} = e.K_{pb} + \frac{K_{ib}}{S}.e \quad (1)$$

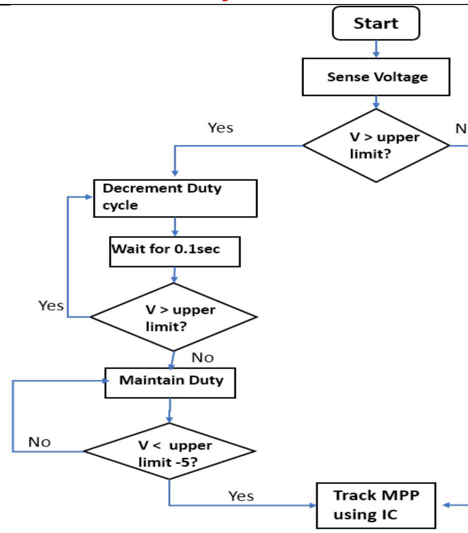


Figure 4. Flowchart of Modified Incremental Conductance method

A three-phase, three-level Voltage Source Converter (VSC) inverter was used to convert the DC power from the boost converter into 400 V, 50 Hz AC power for the grid. This inverter was designed to supply only active power. Synchronization with the grid is achieved using a combination of a current regulator, a voltage regulator, and a phase-locked loop (PLL) method [5].

Proposed IC Algorithm:

The algorithm addressed voltage violation issues by integrating a voltage regulation component into the MPPT control. This approach offers a dynamic and adaptive method for MPPT that takes into account the voltage constraints of the distribution network. The RMS voltage of the grid at the Point of Common Coupling (PCC) was continuously monitored. If it falls outside the acceptable range of ±5%, the algorithm shifts the operating point away from the Maximum Power Point (MPP) to reduce active power injection, helping to maintain the voltage within limits.

The flowchart of the algorithm is shown in Figure 4. If the sensed voltage exceeds the upper threshold (e.g., 420 V for a 400 V system), it signals a potential voltage violation. This activates the algorithm's voltage control mechanism. Recognizing that further power injection would worsen the voltage issue, the algorithm intentionally shifts the PV system's operating point away from the MPP, thereby reducing the power output. This controlled reduction helps bring the grid voltage back within acceptable limits. The reduction is carefully moderated to maintain a balance between voltage regulation and energy production; the algorithm avoids sudden large curtailments, opting instead for gradual adjustments to match the system's demand.

Before making any adjustments, the algorithm introduces a short time delay, serving two critical purposes:

1. It prevents unnecessary reactions to temporary voltage fluctuations. Since power systems can experience brief voltage dips or spikes, the delay ensures the algorithm responds only to sustained voltage deviations.
2. It helps avoid oscillations in the PV system's operation. Without a delay, continuous adjustments could destabilize the system. Allowing a brief settling time after each adjustment ensures stable and reliable voltage control.
3. Once the algorithm detects a sustained voltage violation and the time delay has elapsed, it adjusts the PV system's operating point. This was done by decrementing the duty cycle of the DC-DC converter connected to the PV array. Under normal conditions, the MPPT

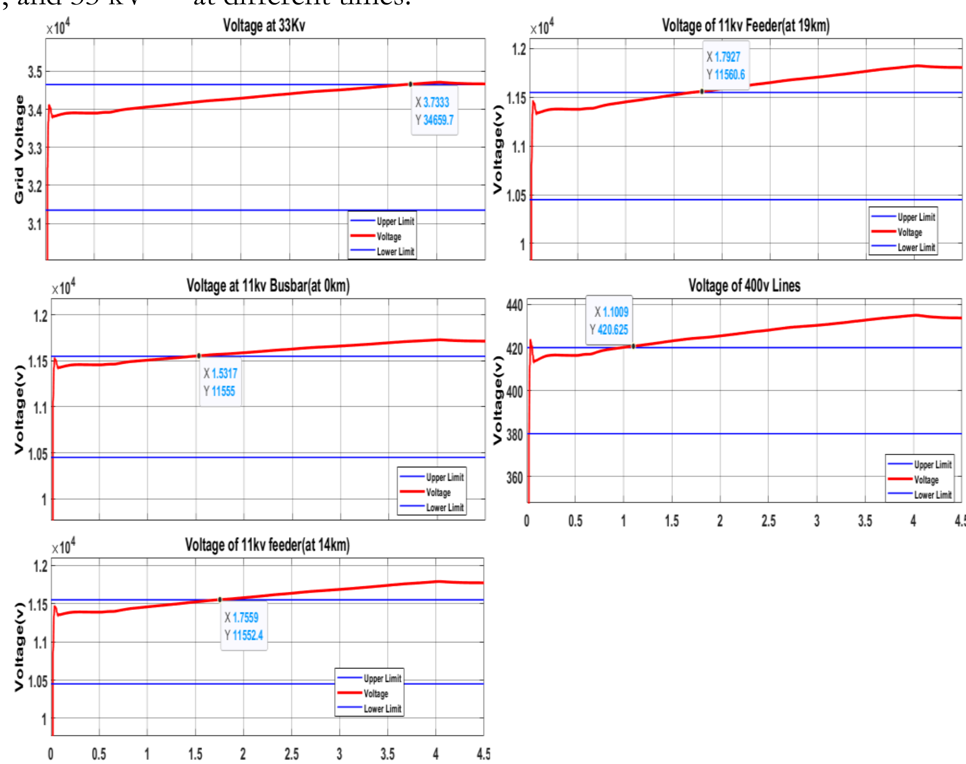
process uses the duty cycle to draw the maximum available power from the array. By reducing the duty cycle, the algorithm effectively decreases the PV system's power output.

4. The duty cycle was typically reduced in small, discrete steps of 0.01. These gradual adjustments allow for finer control of the PV power output and minimize the risk of sudden voltage fluctuations. After each adjustment, the algorithm initiates a short stabilization period of 0.1 seconds, during which the duty cycle is kept constant and no further changes are made. This stabilization period is essential for preventing oscillations and ensuring the smooth and stable operation of the PV system.

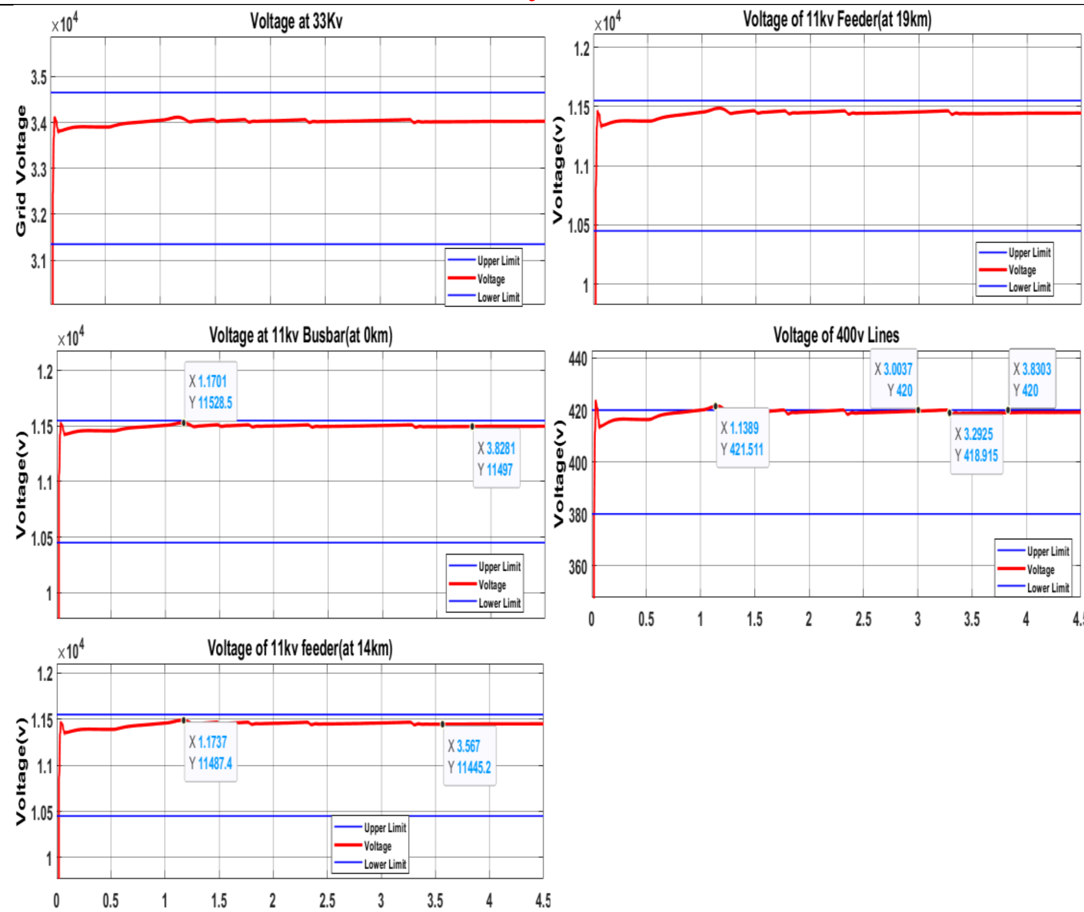
Results:

The proposed modified algorithm was simulated for PV integration at 400 V, corresponding to 40% of the peak load, while voltage levels across the entire network — 400 V, 11 kV, and 33 kV — are monitored for potential violations. During the simulation, the PV output was linearly increased from 0 kW at 0.5 seconds to 200 kW at 4 seconds, with a total simulation time of 4.5 seconds. In the results, the red lines represent the monitored voltage curves, while the blue lines indicate the upper and lower regulatory limits.

First, the system was simulated using the traditional Incremental Conductance (IC) algorithm, without the proposed modifications. The results are shown in Figure 5(a). It can be observed that voltage violations occur at all three voltage levels — 400 V, 11 kV (at 0 km, 14 km, and 19 km), and 33 kV — at different times.



5(a) With traditional IC algorithm



5(b) With the proposed IC algorithm

Figure 5. Voltage profile without and with the modified IC algorithm

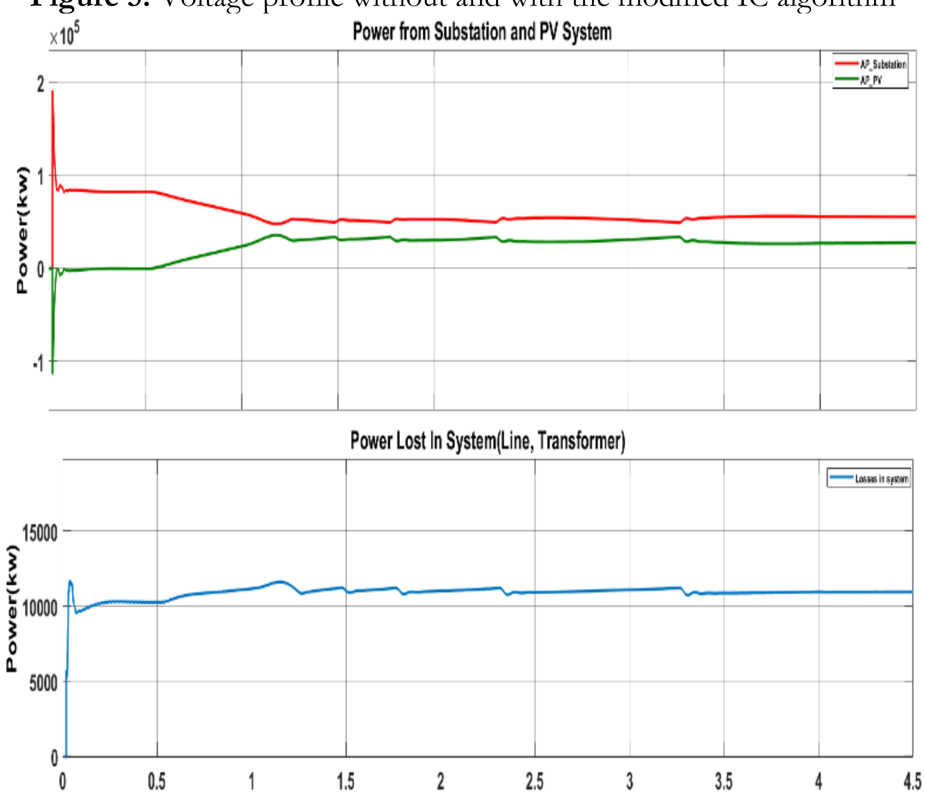


Figure 6. Power profile without the proposed IC method

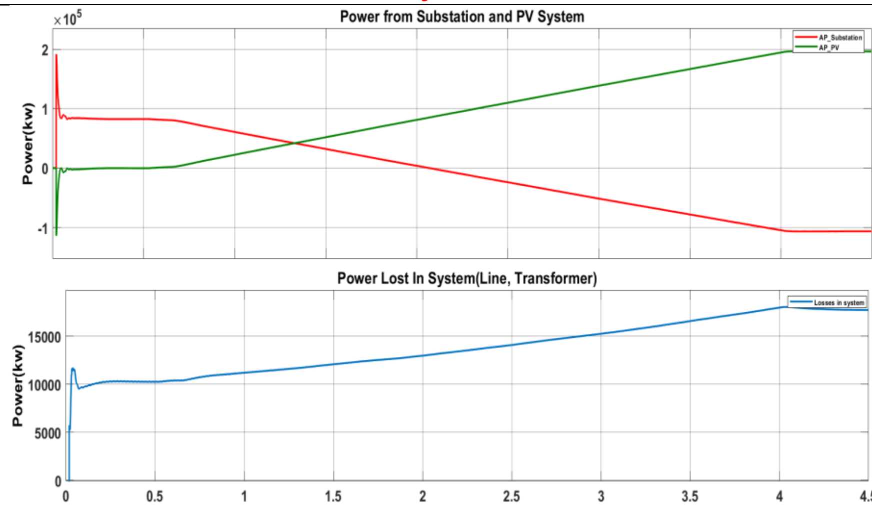
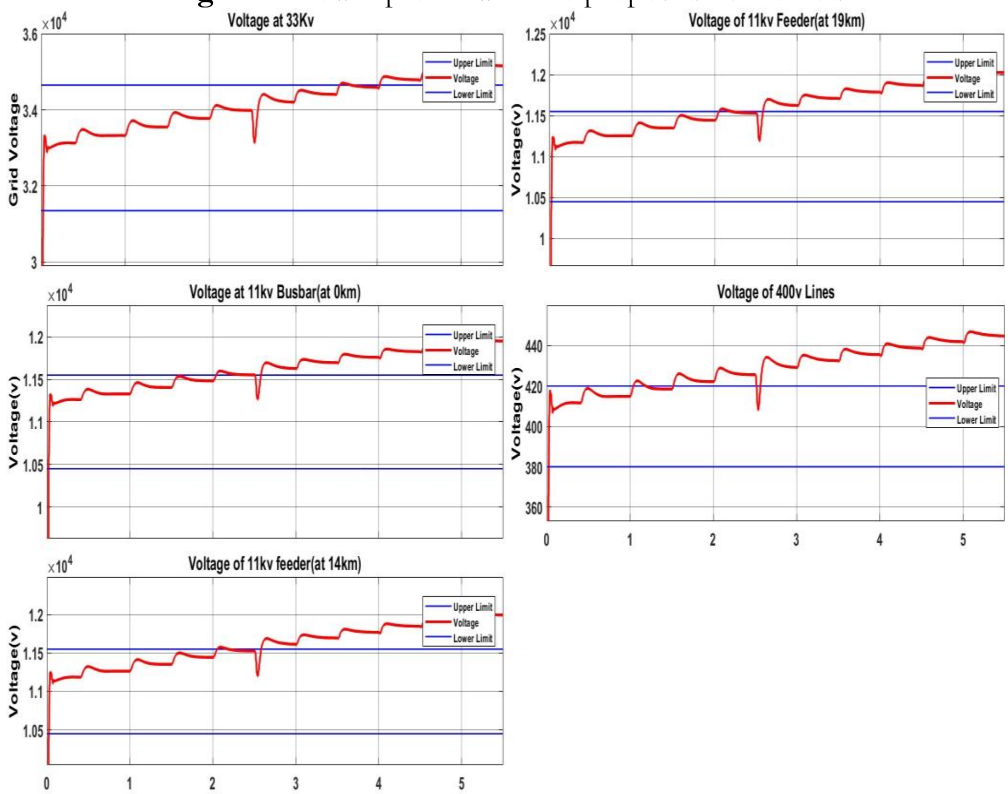
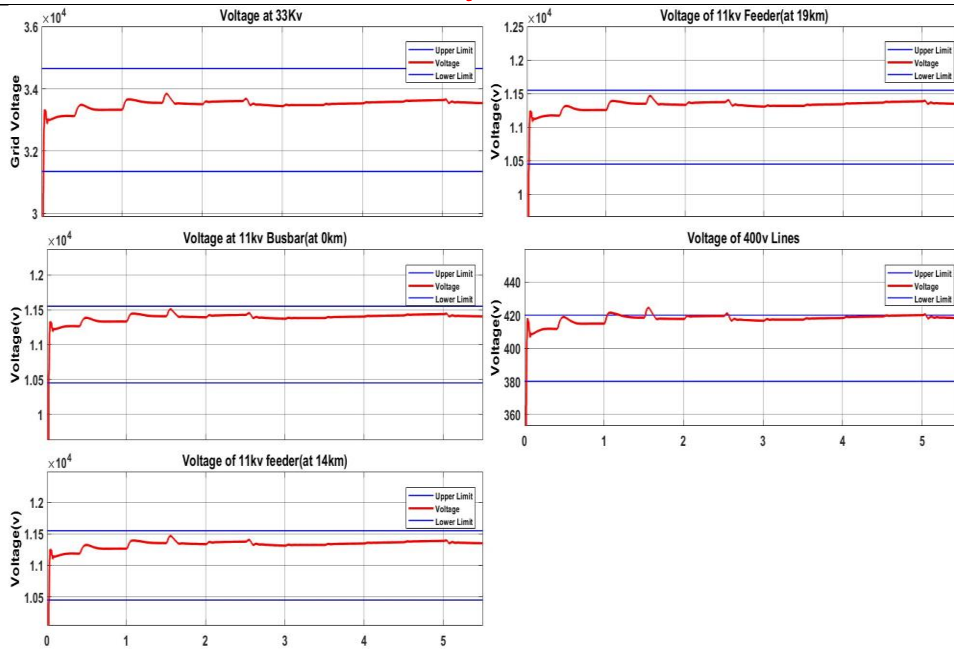


Figure 7. Power profile with the proposed IC method



8(a) With traditional IC algorithm



8(b) With the proposed IC algorithm

Figure 8. Voltage profile for step PV input without and with the modified IC algorithm

These violations happen because the PV output exceeds the penetration limit, affecting each voltage level differently. The lower voltage levels experienced violations earlier: the 400 V line exceeds the regulatory limit first at t = 1.13 s, followed by the 11 kV feeder at t = 1.53 s, 1.75 s, and 1.79 s for 0 km, 14 km, and 19 km, respectively. Finally, the 33 kV upper limit is crossed at t = 3.73 s. For a quick review, the voltage profile is summarized in Table II.

In the next phase, the proposed modified algorithm is integrated, and the simulation is repeated. The results, shown in Figure 5(b), demonstrate that the modified IC successfully maintains all three voltage levels within the specified regulatory limits. This is achieved by controlling PV power injection to prevent reverse power flow, as explained below.

Figure 6 illustrates the power flow from the primary energy source (red line) and the PV system (green line), along with the corresponding power loss curves. It is evident that as PV power injection increases, the power drawn from the primary source decreases. At t = 2.1 s, the PV output matches the load demand, and any further increase in PV generation would cause reverse power flow toward the main energy source.

Additionally, power losses in the system are directly related to voltage rise, following the relationship $p = \frac{v^2}{r}$, meaning that as voltage rises, power losses also increase. As shown in the figure, power losses escalate from 10 kW to 18 kW without the modified control. When the modified algorithm is applied, as seen in Figure 7, it curtails the active power injection after detecting a violation, thereby limiting the power losses between 10 kW and 11 kW.

The algorithm's effectiveness is further validated under a stepped PV input scenario, where sudden increases in PV output can create a high risk of voltage instability. Even moderate levels of PV penetration under low load and high solar irradiance conditions can lead to significant voltage rises.

The modified incremental conductance algorithm addresses this by proactively reducing PV power output when the voltage approaches the upper limit, preventing violations and ensuring grid stability. As a result, it allows for higher PV integration levels. Figure 8(a) and Figure 8(b) compare the voltage profiles with and without the modified control under stepped input conditions.

Table 2. Comparison of Voltage Profiles of Figure 5 (a) With and (b) Without the Proposed Algorithm

Voltage and Location	Limit Point	Without Modified IC		With Modified IC	
		Voltage Without MIC	Within Regulatory Limit?	Voltage Without MIC	Within Regulatory Limit?
400V	t=1.1s t>1.1s	420V >420V	At limit No	420V 419V	At limit Yes
11kV (19km)	t=1.7s t>1.7s	11555V >11550V	Yes Yes	11461V 11454V	No No
11kV (14km)	t=1.7 t>1.7	11550V >11550V	At limit Yes	11465V 11459V	No No
11kV (0km)	t=1.5 t>1.5	11552V >11550V	Slightly Yes	11502V 11505V	No No
Power losses in the system without the proposed algorithm linearly increase beyond the limit point at each voltage level, whereas the proposed method effectively prevents any further rise in power losses.					

Discussion:

This study presents a modified IC technique for Active APC to control voltage violation in distribution grids in case of low load and peak PV generation. The approach leverages a well-established Maximum Power Point Tracking (MPPT) technique, adapting it to limit active power injection and mitigate over-voltage. Compared to conventional complex centralized APC schemes, the proposed IC-based method offers inherent potential for low-cost implementation and simplicity, as it can be deployed through updates in existing inverters already using IC for MPPT. While all APC methods involve power curtailment, the ease of retrofitting and minimal additional hardware requirements of this modified IC approach presents a significant practical advantage over solutions requiring new hardware or infrastructure.

When contrasted with alternative voltage regulation techniques, such as feeder enhancement, OLTC, reactive power control, or Battery Energy Storage Systems (BESS), the modified IC-APC presents a different set of trade-offs. Feeder enhancement and OLTC need extra costly circuitry with maximum installation cost and time. Reactive power strategies, while avoiding active power loss, can be less effective in high R/X ratio networks and may induce thermal stress on inverters, potentially reducing their lifespan, also the complexity and cost are high as compared to the proposed APC. BESS offers comprehensive voltage support without curtailment but has high upfront costs and other concerns like degradation of the battery. The proposed method aims for a cost-effective and readily implementable solution, though it shares the common APC challenge of energy loss and, if implemented purely locally, may not inherently address fairness in curtailment distribution without further coordination. Future work should validate its dynamic performance for other MPPT algorithms, and explore potential integrations for diverse penetration and load scenarios with coordination mechanisms to balance simplicity with systemic needs.

Conclusion:

Most existing solutions to the voltage rise problem caused by widespread PV deployment rely on reactive power control. This paper addresses the issue through active power curtailment, by introducing a distinct approach to achieving active power curtailment via a modification of the incremental conductance (IC) algorithm: under normal conditions, it tracks maximum power, but when the feeder voltage exceeds regulatory limits, it reduces the active power output. This is achieved by decreasing the duty cycle, which shifts the PV system's operating point away from the maximum power point (MPP), thereby limiting active power injection. The proposed method is simple, cost-effective, and has the additional advantage of being easily implementable in existing PV systems, as many already employ IC for maximum power point tracking.

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