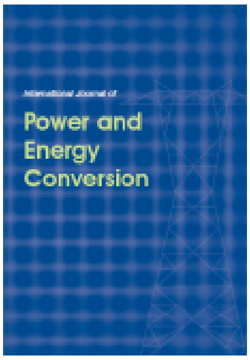

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Control strategy of battery inverter for voltage profile improvement in low voltage networks with high PV penetration level

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Abstract: This paper presents a control strategy for grid-connected inverter interfaces with a battery storage system (BSS) to enhance PV penetration level in a low voltage (LV) grid. The strategy involves determining the optimal inverter set points that regulate the output of active and reactive power based on grid voltage, with considering battery specifications and state of charge (SoC). A LV grid consisting of 19 buses and 12 houses was used as a case study to test the proposed strategy. The simulation results show that the proposed control strategy successfully sets the power references to control the battery inverter, resulting in an increase in the PV penetration level to 50% while keeping voltage rise and drop within permissible limits. The strategy shows promising results in optimising the set points of battery inverters to improve the voltage profile and increase the PV penetration level in LV PV-grid tied distribution grids.

Keywords: voltage profile improvement; battery inverter; reactive power control; RPC; PV penetration level.

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1 Introduction

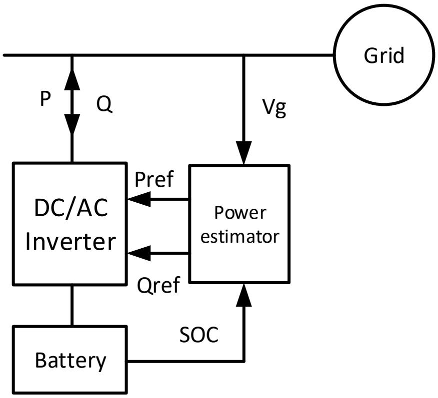
Solar photovoltaic (PV) technology is widely adopted due to its economic and environmental benefits. However, the high integration of PV systems may lead to power quality issues in distribution systems, such as voltage instability, system reliability, and protection (Roy and Pota, 2015; Mosobi and Gao, 2021). Maintaining acceptable voltage levels is crucial in high-penetration PV systems, where voltage fluctuations can occur due to the intermittent nature of PV generation (Ismail et al., 2020). This ensures uninterrupted power supply to consumers and prevents frequent disconnection of PV inverters. The voltage variation occurs depending on the power flow passing into electrical feeders, which is affected by PV power generation that is highly dependent on variable solar radiation based on seasons and times of day. High PV power generation coupled with low power demand leads to reverse power flow, resulting in voltage rise. Conversely, periods of low PV power generation alongside high power demand can introduce voltage drops (Tonkoski et al., 2012). To address this concern, conventional methods for enhancing voltage profiles, such as series voltage regulators (SVR), switched capacitor banks, and on-load tap changers (OLTCs), are no longer adequate (Zhu et al., 2018; Khan et al., 2022). The reason for this is that these methods operate at a relatively slow speed, making them less effective in compensating for the rapid changes in PV output power. Therefore, a new approach to voltage regulation is required beyond these conventional schemes (Li et al., 2020). Numerous approaches for improving voltage profiles in distribution networks in the presence of PV systems have been explored in existing literature. Following the revision of the IEEE 1547 standard (IEEE, 2018), PV inverters can contribute to voltage regulation by injecting or absorbing reactive power as needed. In the case of a voltage drop, the inverter can inject reactive power into the grid to compensate for the drop and help raise the voltage level back up to the desired level. This is known as reactive power injection. On the other hand, if the voltage rises above the desired level, the inverter can absorb reactive power to help lower the voltage back down to the desired level. This is known as reactive power absorption. However, schemes involving reactive power control (RPC) of PV inverters, as discussed in references Guo et al. (2019) and Jung et al. (2014), are not deemed cost-effective solutions for distribution networks with high R/X ratios. This is because reactive power has a minor effect on voltage fluctuations within low voltage grids, necessitating a substantial amount of reactive power to enhance the voltage. This, in turn, leads to the requirement for oversized inverters (Demirok et al., 2009). Instead, active power control (APC) is a more effective to improve the voltage in low voltage grid. In order to tackle the issue of voltage rise, Ghosh et al. (2017) proposes curtailment active power to restrict PV-generated power. However, it is crucial to knowledge that while this approach may be effective in resolving voltage rise in the short term, it is not a sustainable long-term solution due to the associated high energy losses, which render it economically impractical. Additionally, Chamana and Chowdhury (2018) proposes voltage regulation in medium voltage distribution systems by a multistage volt-var method. The last proposed method ensures optimal utilisation of traditional devices and minimises solar PV power curtailment. However, with decreasing costs and increasing life-cycles of batteries, utilising a battery storage system (BSS) for real power control in conjunction with solar PV has become a viable option (Zhao et al., 2023). In Emarati et al. (2021), two-level strategy addresses over-voltage in low voltage grid with high PV penetration. Level one optimises OLTC, battery storage. Level two fine-tunes voltage using reactive power compensation of PV inverters. In other hand, in Zhang et al. (2023) authors address a scheme combines local and central control methods, optimising inverter settings and utilising battery energy storage and OLTC for enhanced voltage regulation. Zeraati et al. (2018) proposes a control strategy for BSS based on local droop-based control to ensure that feeder voltages remain within desired limits, even with changing power of PV systems and loads. Additionally, Kabir et al. (2014) and Wang et al. (2018) demonstrate the use of coordinated control of solar PV reactive power output and BSS for voltage regulation. In their study, Zeraati et al. (2018) proposed a coordinated control approach for BSS, which involves local droop control to maintain the voltage levels of the feeder within specified limits. Nonetheless, the authors did not take into account the maximum active power absorbed or delivered by the battery, and also did not utilise the battery inverter to inject or absorb reactive power to the power grid based on the SoC of the battery. This paper proposes a control strategy for a battery inverter used to increase PV penetration level in a low voltage network. This strategy enables the battery inverter to interact with the measured grid voltage and improve the voltage profile by either absorbing or delivering active and reactive power, depending on the state of charge of the battery. The novelty of this work lies in prioritising the control of active power, especially in grids with a high R/X ratio, where effective voltage regulation is achieved through APC rather than reactive power. Furthermore, this prioritisation takes into account the maximum power can battery charging and discharging, as well as the battery SoC. In order to fully utilise the capabilities of the battery inverter, the RPC is initiated. This involves using the battery inverter to inject or absorb reactive power, thereby enhancing voltage levels, particularly when the SoC approaches its maximum or minimum thresholds.

2 Materials and methods

2.1 Control of battery inverter

The battery inverter is proposed for the purpose of voltage regulation and to increase the penetration level of the PV system. Therefore, the inverter is controlled to deliver or absorb active power (P) and reactive power (Q) based on the measured grid voltage (Vg), battery SoC, and power estimator reference values P_{ref} and Q_{ref} for active and reactive power respectively as shown in Figure 1. This ensures that the inverter can maintain a stable voltage level in case the voltage rises when the PV penetration level increases. The primary goal of the battery inverter is to deliver or absorb active and reactive power based on the grid voltage measurement.

Figure 1 The scheme of battery inverter



Mainly, the inverter absorbs active power if the battery is not fully charged; otherwise, reactive power can be absorbed to reduce the voltage rise. In case the voltage drops, this commonly occurs at low power generation from the PV system. The battery delivers active power if the battery is not depleted or fully discharged; otherwise, reactive power can be delivered from the battery inverter.

Additionally, keeping the battery from being fully charged helps to ensure that it can be used in the next day and it is available to be charged in case of a voltage rise.

2.2 Active power control

In low voltage networks, electrical lines typically have a higher resistive impedance compared to inductive impedance. This results in voltage fluctuations being more affected by active power rather than reactive power. Consequently, the main emphasis is placed on regulating active power to improve voltage, contingent on the battery SoC allowing for charging and discharging.

2.2.1 Voltage rise condition

The voltage rise occurs when the PV power generated exceeds the demanded power. To address this voltage rise, the battery inverter operates in APC, acting as a rectifier to absorb active power for battery charging. Depending on whether the grid voltage (Vg) is moderate or high, the reference for active power (Pref) can be estimated. In cases where the measured grid voltage (Vg) undergoes a moderate increase, ranging from 1 p.u to 1.05 p.u, P_{ref} can be calculated using the droop curve depicted in Figure 2 and specified in equation (1).

$$P_{ref} = \frac{-P_{\max}}{0.05 \times V_{nom}} \times \left(V_g - V_n\right) \tag{1}$$

where P_{ref} is the active power reference absorbed (–ve). $P_{\max}$ is the maximum power that can be absorbed by the battery, V_g is the measured grid voltage, and V_n is the nominal grid voltage.

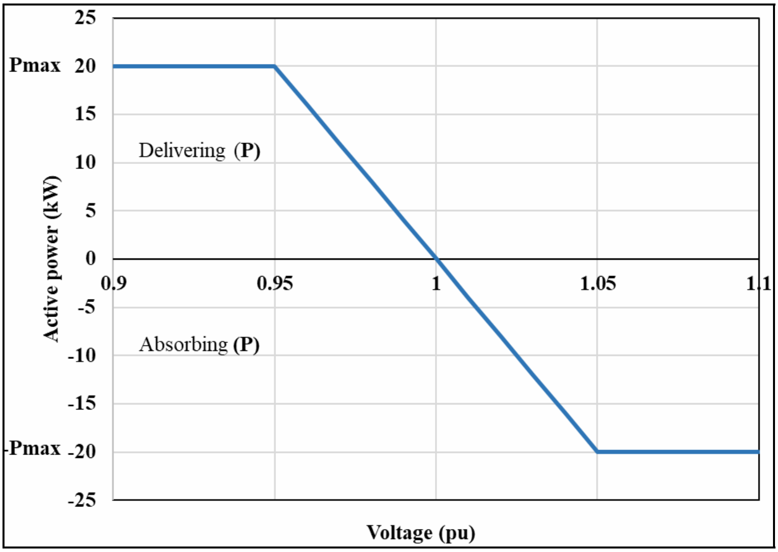
According to Figure 2, if the voltage exceeds the standard limit of 5% (meaning Vg is higher than 1.05 p.u), the battery inverter will charge the battery at maximum power to reduce the voltage rise as much as possible. Then, P_{ref} is defined in (2). In cases illustrated in equations 1 and 2, the battery is charged with P_{ref} and the battery SoC can be calculated as depicted in (3).

$$P_{ref} = -P_{\max} \tag{2}$$

$$SOC(t) = SOC(t-1) + \frac{\left|P_{ref}(t)\right|}{C_{batt}} \times 100\% \tag{3}$$

where C_{batt} is the battery capacity in Wh.

Figure 2 P/V droop curve (see online version for colours)



2.2.2 Voltage drop condition

The primary purpose of the battery inverter is to enhance PV penetration, which leads to a voltage rise. This implies that the battery charges. Conversely, a voltage drop occurs when the demanded power exceeds the generated PV power, which may reach its maximum at night when no PV power is being generated. Discharging the battery serves not only to reduce voltage but also to deplete it, enabling it to be recharged for the primary purpose of mitigating voltage rise from high PV power generation next day. The extent of voltage drop depends on the disparity between demanded power and PV-generated power. In cases where the drop is moderate Vg falls within the range of 0.95 p.u and 1 p.u, the battery inverter will deliver real power into the grid by discharging the battery with a P_{ref} value as defined in (4).

$$P_{ref} = \frac{-P\max}{0.05 \times Vnom} \times \left(V_g - V_n\right) \tag{4}$$

When Vg drops to a value below 0.95 pu, the battery inverter will discharge $P_{\max}$ from the battery, as outlined in equation (5). The SoC can then be calculated using equation (6).

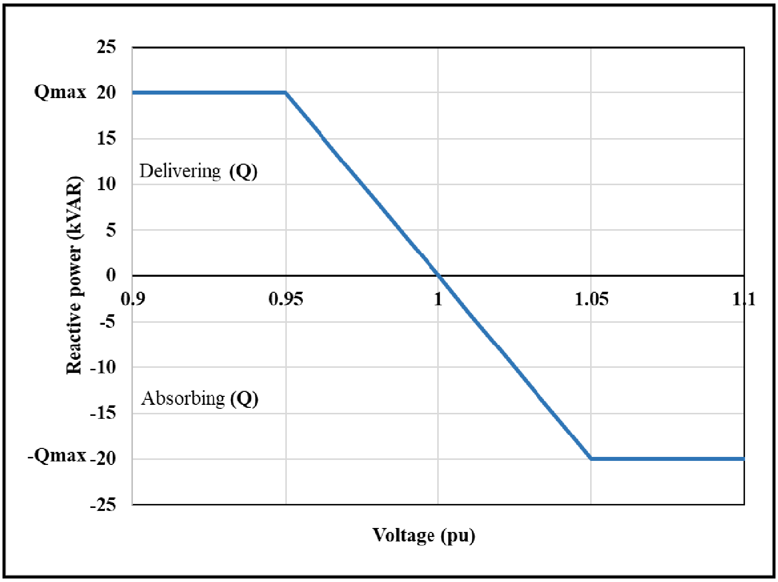
$$P_{ref} = P_{\max} \tag{5}$$

$$SOC(t) = SOC(t-1) - \frac{P_{ref}(t)}{C_{batt}} \times 100\% \text{ SO} \tag{6}$$

2.3 Reactive power control

As mentioned previously, in a low voltage network, the voltage is primarily influenced by the flow of active power, rather than reactive power, due to a high R/X ratio. Consequently, APC can mitigate voltage fluctuations by absorbing and delivering active power, if the battery is capable of charging and discharging. However, when the battery is fully charged or discharged, APC may not be operational. Therefore, to fully utilise the inverter, RPC can be employed to manage voltage rise and drop by absorbing or delivering reactive power, respectively.

Figure 3 Q/V droop curve (see online version for colours)



2.3.1 Voltage rise condition

RPC can be employed to absorb reactive power to reduce the voltage rise. The amount of reactive power to be absorbed depends on the extent of voltage drop. If the grid voltage V_g is not very high; between 1 and 0.95 pu, the amount of reactive power can be calculated using equation (7), which is derived from the droop curve shown in Figure 3. However, if the voltage drop exceeds the standard limit; V_g is less than 0.95 pu, the amount of reactive power to be absorbed is set to its maximum as in (8). In the case of

RPC, the battery SoC remains unchanged, as it is solely affected by APC, as demonstrated in equation (9).

$$Q_{ref} = \frac{-Q_{\max}}{0.05 \times V_n} \times \left(V_g - V_n\right) \tag{7}$$

$$Q_{ref} = -Q_{\max} \tag{8}$$

$$SOC(t) = SOC(t-1) \tag{9}$$

2.3.2 Voltage drop condition

The RPC improves voltage drop by delivering reactive power to the grid. The amount of reactive power delivered is contingent on the measured voltage *Vg*. In the event of a moderate voltage drop, the reactive power to be supplied can be estimated using the droop curve, as described in (10) derived from Figure 3.

$$Q_{ref} = \frac{-Q_{\max}}{0.05 \times V_n} \times \left(V_g - V_n\right) \tag{10}$$

If the voltage Vg drops to a value below 0.95 pu, the inverter supplies the maximum reactive power, as indicated in (11). The SoC remains unchanged, as shown in equation (12), which has been previously explained.

$$Q_{ref} = Q_{\max} \tag{11}$$

$$SOC(t) = SOC(t-1) \tag{12}$$

3 Case study

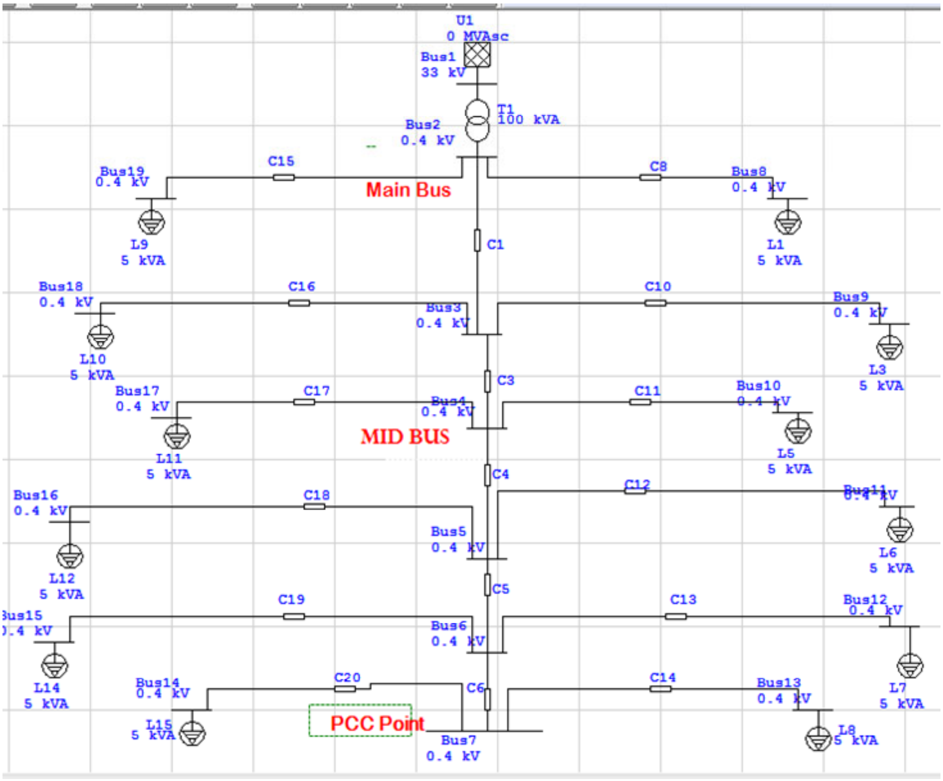
3.1 Description

The proposed control strategy described in the previous section is applicable to use for battery inverter to improve voltage profile and increase PV penetration level in any low voltage network to approve that we chose to test its effectiveness by using electrical transient analyser program (ETAP). The tested low voltage network comprising a three-phase transformer rated at 100 kVA, 33 kV/0.4 kV. The low voltage feeder serves 12 houses, as depicted in Figure 4. The distance between the main bus and the farthest is 800 m. The cables are used to connect the houses to the main feeder. The feeder has a cross-sectional area of 50cm^2, while the cable has a cross-sectional area of 35m^2. The resistance and inductance values for the feeder and cable are presented in Table 1. Load flow analysis was carried out in various scenarios, both with and without a PV system of varying penetration levels. The impact of using a battery inverter to increase the PV penetration level was also examined. Additionally, critical scenarios were simulated, including when the battery was fully charged or discharged to minimum SoC.

Table 1 Lines and cable rating data

Data line type	*Cross section (mm^2)*	*Resistance (Ω/km)*	*Reactance (Ω/km)*	*R/X*
ICEA S-68-516	50	0.71225	0.0811	8.782
BS5467 XLPE	35	0.669	0.08	8.363

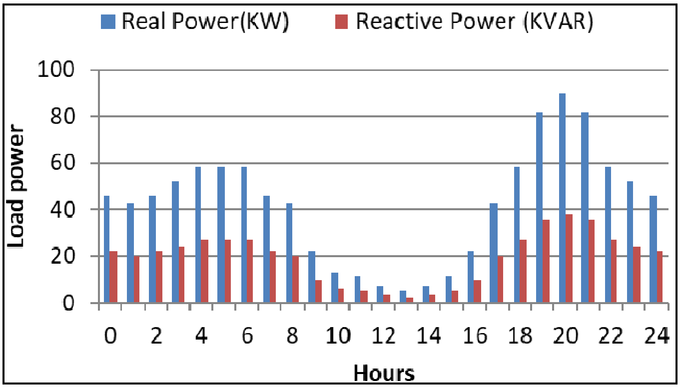
Figure 4 One-line diagram of tested network (see online version for colours)



3.2 Load profile

To account for potential worst-case scenarios during the integration of a PV system with the grid, the load profile has been designed to include instances of high PV generation and low loading conditions at 1 PM, as well as low PV generation and high loading conditions at 8 PM. The daily load profile of a complete feeder with identical load demand is depicted in Figure 5.

Figure 5 Daily load profile at main bus (see online version for colours)



3.3 *PV system description*

A PV system was installed at the furthest bus to create significant voltage drops and rises. The PV generator has a rated power of 50 kWp and 20 kWp, which were used to analyse the voltage profile at two different penetration levels: 50% and 20%. The definition of the PV penetration in a distribution network is the PV-rated peak power generated from the PV system divided by the apparent power of the peak load as (13) (Kordkheili et al., 2014).

$$PV\ \ Penteration\ level(\%) = \frac{PV\ \ Peak\ \ Power}{Peak\ load(apparent\ \ power)} \times 100\% \tag{13}$$

Figure 6 illustrates the hourly solar radiation for a clear day, with a maximum value of 996 W/m². The maximum power generated by PV systems is 18 kW and 46 kW for systems with a rated capacity of 20 kWp and 50 kWp, respectively, as shown in Figure 7. Its worth noting that the peak power produced less than the rated power due to losses in the system and losses due to high temperature (Omar and Mahmoud, 2019a, 2019b).

Figure 6 Solar radiation of a clear day (see online version for colours)

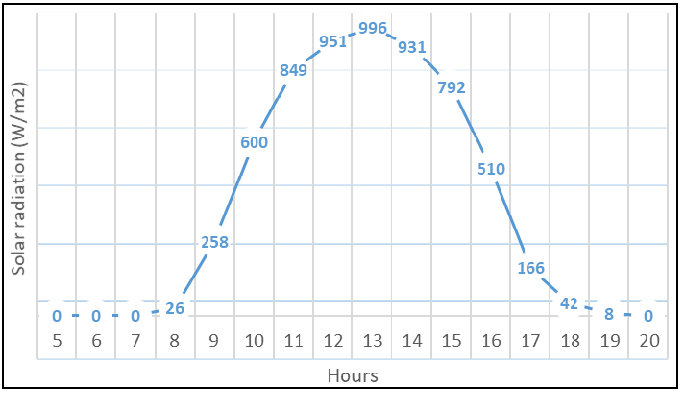
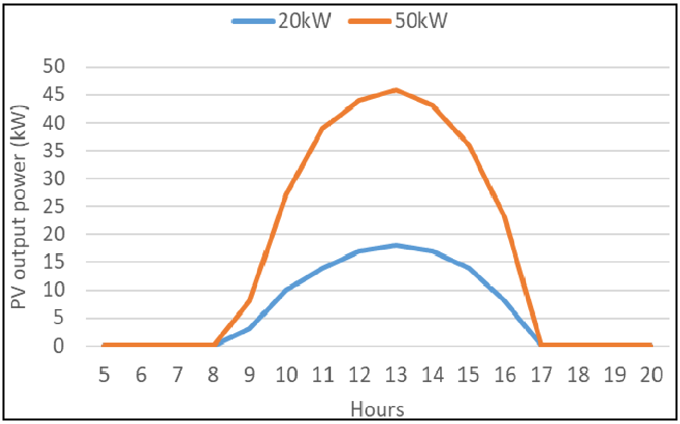


Figure 7 Generated power from PV system (see online version for colours)



3.4 *Description of battery system*

The case study involves the selection of a 100 kWh battery with a discharging rate of C-rate 5 hours, enabling a maximum power of 20 kW for charging or discharging. This battery size is chosen to match the energy generation capacity of the PV system located in an area with 5 hours of daily sunshine. The PV system consists of a 50 kWp system, generating a total of 250 kWh per day. When the PV system with a peak wattage of 50 kWp generates approximately 45 kW of power, the battery can absorb up to 20 kW, while the remaining 25 kW is injected into the grid with a peak demand of 100 kVA. This results in a penetration level of less than 30%, which is an acceptable level according to the literature.

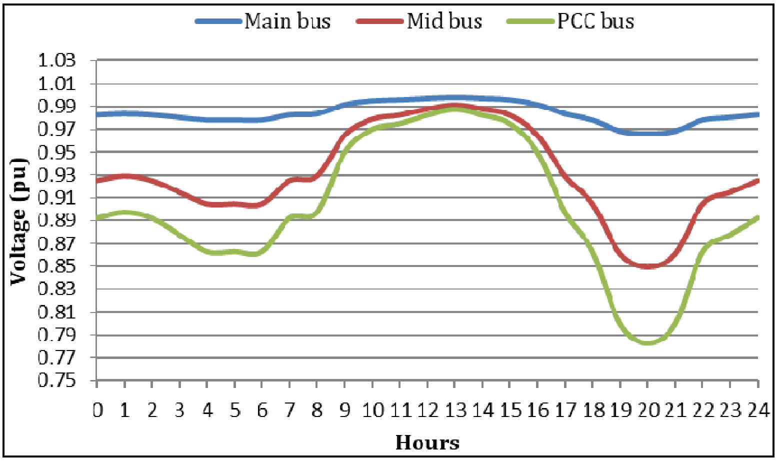
4 Results and discussion

In this study, different scenarios are analysed to compare and determine the benefits of utilising a battery to enhance voltage profile and increase PV penetration levels in a low voltage network. The aim is to reach a conclusion regarding the advantages of employing the battery in the network.

4.1 *Scenario-1: grid only*

In this scenario, we consider that no PV system is installed, and we examine the grid voltage both before and after the PV system installation. It is worth noting in Figure 8 the voltage variation becomes more pronounced in buses that are far from the transformer due to the flow of currents in the line impedances. The impedance values increase as the distance between the buses and the transformer increases. For instance, the voltage of the main bus slightly changed even with the load variation. In contrast, the voltage variation is more significant in the PCC bus, which is the furthest bus from the transformer. Here, the voltage varies between 0.8 pu under heavy load conditions, while it is 0.99 pu in light load conditions.

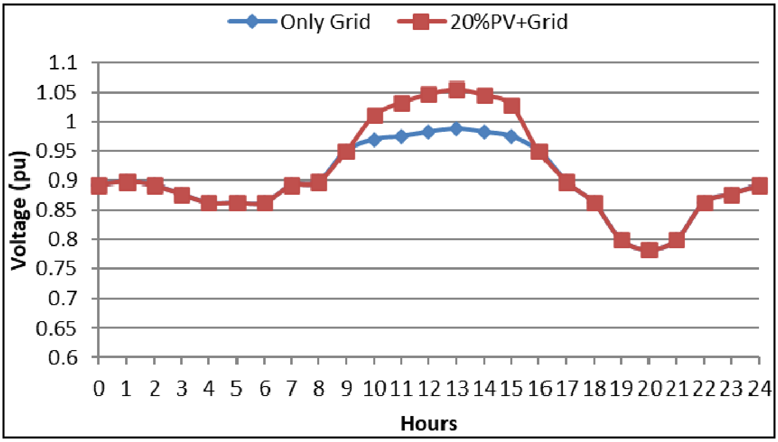
Figure 8 Hourly simulated voltage of scenario 1 (see online version for colours)



4.2 Scenario-2 of low PV penetration level

Compared to the previous scenario, in this scenario we have added a 20 kWp PV system to the PCC bus, which is the most sensitive bus and experiences more voltage variation than other buses. As shown in Figure 9, the voltage increases and becomes higher than in scenario-1 after 10:00 AM due to the active power injected into the grid by the PV system.

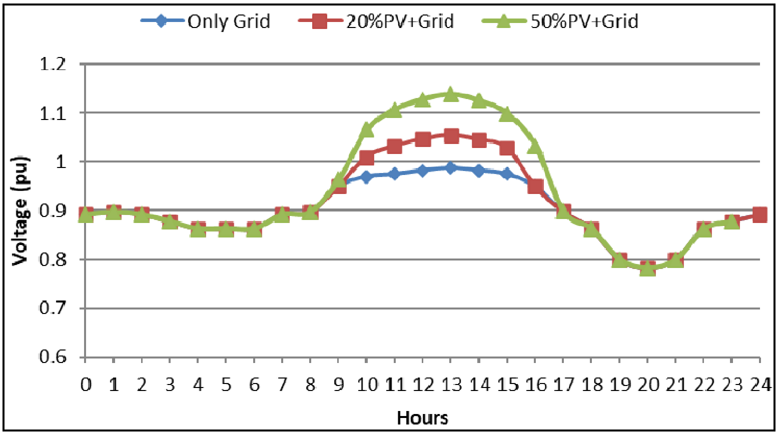
Figure 9 Hourly simulated voltage of scenarios 1 and 2 (see online version for colours)



4.3 Seanario-3 of high PV penetration level

In this scenario, a 50 kWp PV system is added, which has a higher rated power than in scenario-2. The PV system injects high active power into the grid at 13:00, causing the voltage to rise to 1.14 pu compared to 1.05 pu in the case of a 20 kWp system, as shown in Figure 10.

Figure 10 Hourly simulated voltage of scenarios 1, 2, and 3 (see online version for colours)



4.4 *Seanario-4 of high PV penetration level with battery*

It is clear that in the scenario-3, the voltage rise exceeded the standard specified by IEEE 1547, which allows for ± 6 voltage variation at the PCC when connecting a RDG to an electrical network (NERSA, 2014). Therefore, a battery system has been added to improve the voltage profile even with a high penetration level. However, it is crucial to control the battery inverter while considering the specifications of the battery. For example, it should not exceed the maximum charge/discharge power, and the battery should be protected from overcharging or over discharging. Figure 11 shows the voltage improvement achieved by the battery inverter. It is noteworthy that the battery reduces the maximum voltage rise from 1.13 pu to 1.05 pu and also decreases the voltage drop after 17:00 when the PV system production is reduced. In this case, the battery discharge active power to improve the voltage, which is crucial because it ensures that the battery is not fully charged the next day and has the ability to consume excess active power in case of a voltage rise. Figure 12 show the battery charged/discharged by power not exceeds Pmax (20kW). Moreover, the SoC of charge varies between 20% to 100%.

Figure 11 Hourly simulated voltage of scenarios 3 and 4 (see online version for colours)

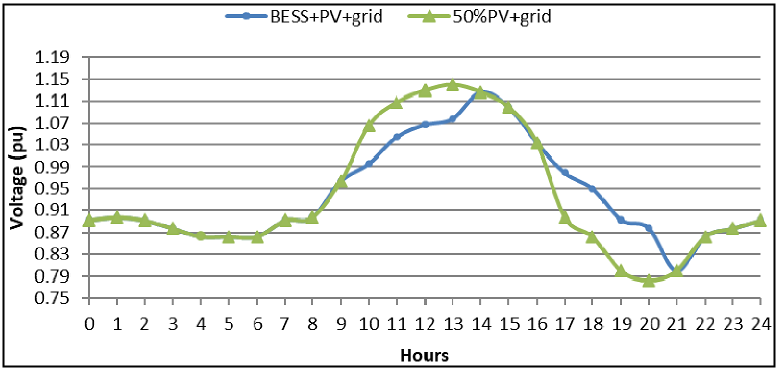
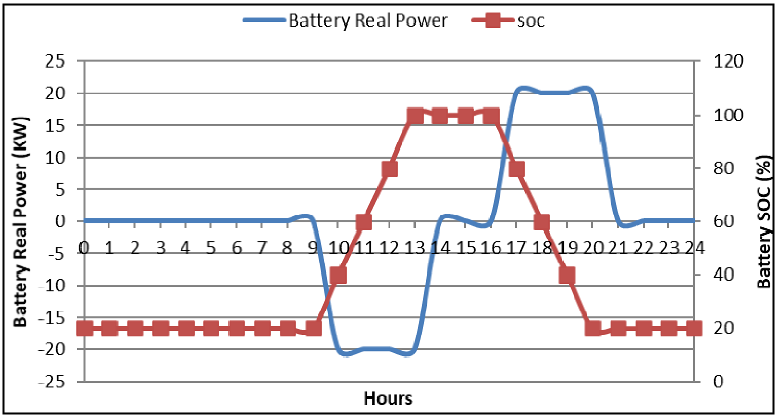


Figure 12 Hourly battery SoC with APC (see online version for colours)



As mentioned earlier, active power has a significant effect on voltage in low voltage networks, so controlling active power is given priority. If APC is not possible, RPC of the battery inverter can be activated to fully utilise the battery inverter. This is done when the battery is fully charged to the maximum SoC or when it is discharged to the minimum SoC. In the case of a voltage rise, the battery inverter absorbs active power. If the battery SoC reaches the maximum, the battery inverter can absorb reactive power to reduce the voltage rise. Similarly, in the case of a voltage drop and the battery is unable to deliver active power, the battery inverter can deliver reactive power to improve the voltage drop condition. RPC should be specified during periods when the battery cannot be charged or discharged for active power. This is because active power effectively changes the voltage in low voltage networks, making it important to utilise the battery inverter to deliver or absorb active power as much as possible. As shown in Figure 13, reactive power is only delivered when the SoC is at its maximum or minimum. In Figure 14, RPC improve the voltage by injecting reactive power and reduces voltage by absorbing reactive power. However, it’s worth noting that the impact of RPC does not affect voltage as much as APC due to the high R/X ratio.

Figure 13 Hourly battery SoC with RPC (see online version for colours)

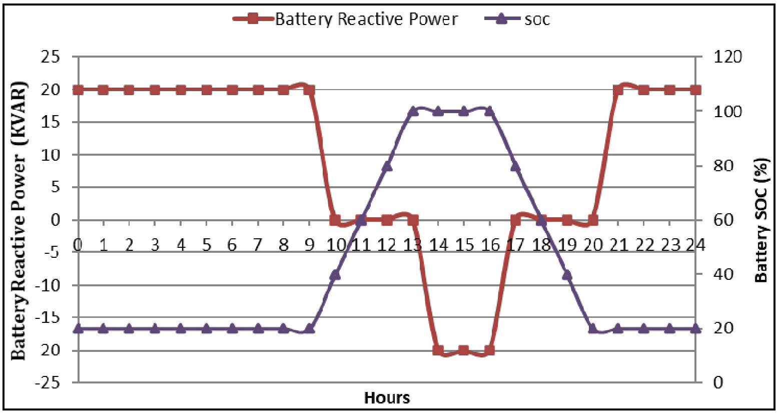


Figure 14 Hourly voltage with and without RPC (see online version for colours)

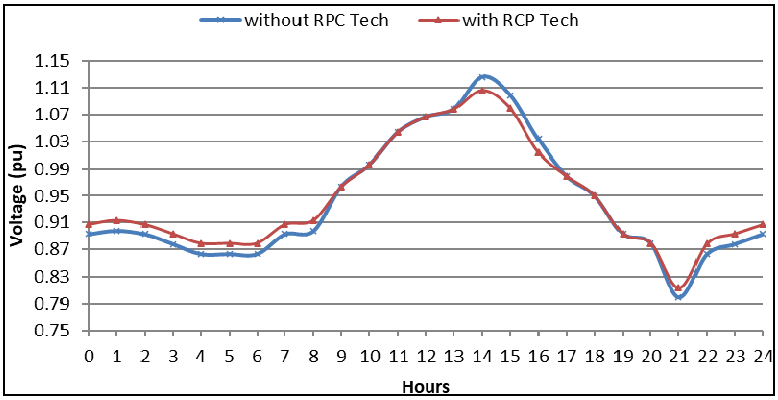
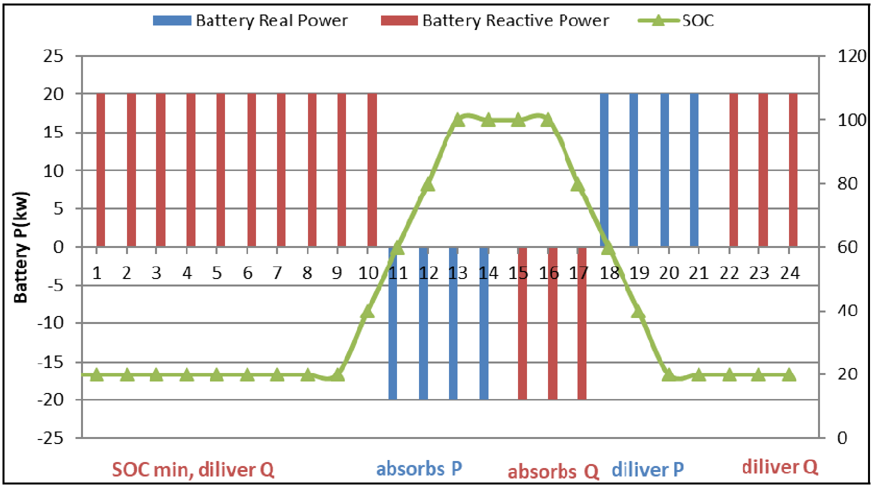


Figure 15 depicts the active and reactive power flow into and out of the battery inverter, as well as the SoC of the battery. Before 9:00, the battery SoC was at a minimum and no power was being generated by the PV system. This resulted in a voltage drop, so the battery injected reactive power to improve the voltage.

From 9:00 to 11:00, the PV system started to generate active power and feed it into the grid, but this power was not greater than the load, so there was no voltage rise. The battery continued to deliver reactive power because the voltage was still dropping. As solar radiation increased at 11:00, the PV power output exceeded the power of the load. This caused the voltage to rise and the battery to start charging until it reached maximum SoC. At 15:00, the voltage continued to rise, and the SoC was at a maximum. Therefore, the battery started to absorb reactive power to reduce the voltage. At 18:00, the voltage dropped because no power was being delivered from the PV system. The battery in this case started to deliver active power until it reached a minimum SoC. At 20:00, the RPC began delivering reactive power to improve the voltage.

Figure 15 Battery SoC with APC and RPC (see online version for colours)



5 Conclusions and future works

The LV network has a high R/X ratio, which means that real power has a greater impact on the network voltage profile than reactive power. Integrating a PV system with the grid can increase the generation of real power, causing the voltage to rise beyond permissible limits when the power produced exceeds the load demand. This surplus power can be absorbed by a BSS to improve the voltage profile, but it requires an appropriate controlled strategy. The overvoltage issue at LV network is a major drawback of PV system integration at high penetration levels. However, using a BSS with a grid-tied PV system can minimise the voltage rise problem, thereby increasing the PV penetration level. This paper presents a detailed control strategy for the battery inverter to deliver required active and reactive power depending on the conditions of battery storage constraints and the value of the grid voltage. The proposed control strategy maximises the PV penetration level up to 50%. The maximum voltage rise without BSS is 1.13 pu, but after applying the BSS control strategy, the voltage reduced to 1.05 pu. The RPC technique involves using the BSS inverter to absorb or deliver reactive power to improve the voltage profile and for fully utilising the battery inverter at the time battery can't be delivered or absorbed active power due to its SoC. The impact of RPC is not as significant as APC; however, it can improve the voltage and also reduce the losses in the network. The PV inverter is controlled and works in four quadrants, able to absorb or deliver real or reactive power, which improves the voltage under different conditions and keeps the battery storage within its SoC limits and P_{max} constraints. In future work, intelligent algorithms like recurrent neural networks discussed in Kumar et al. (2017) and Kumar (2022) can be introduced for optimising inverter set points based on forecasted data of PV-generated power and demand power. Moreover, an extended investigation could focus on the real-world deployment and validation of the proposed control strategy.

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