Congestion Management in High Solar PV Penetrated Distribution System using Smart Charging of Electric Vehicles

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Abstract

Electric-powered vehicles are introduced as a sustainable transportation solution in an evolving road transportation sector. The uncontrolled charging of electric vehicles (EVs) results in negative impacts, such as system overloading, congestion, increased power losses, and voltage stability issues in the distribution system. On the other hand, high penetration of solar PV generation leads to network congestion, overloading, voltage instability, and power quality, in addition to its intermittent power generation. However, smart charging of EVs offers high controllability, so the negative impacts on the distribution system in the presence of high penetration of solar PV can be mitigated by controlled EV charging. In this work, the smart charging of electric vehicles is developed to mitigate the congestion issue in high solar PV penetrated distribution systems. The charging control of EVs in grid-to-vehicle (G2V) charging mode is considered with the objective of network power loss minimization to manage network congestion. The objective function is formulated as a mixed integer non-linear programming (MINLP) optimization problem. Modified IEEE 33 bus system is considered for simulation with different percentage penetration of solar PV and EVs. The result shows that the smart charging of EVs minimizes network power loss while managing network congestion.

Keywords: Congestion management, electric vehicle, network power loss, smart charging, solar PV

1. Introduction

The alarming concern of global warming is motivating sustainable development in fossil fuel-dominated sectors, i.e., the energy and transportation sectors. The developing energy sector promotes sustainable energy solutions like solar PV, wind energy, biofuels, etc., to reduce and decelerate the impact of global warming. Solar PV technology has evolved as a cost-effective renewable energy generation technology. Hence, the integration of solar PV is increasing in the electrical system. The high penetration of solar PV generation in the distribution system can lead to increased power loss, reverse power flow, voltage rise, network congestion, voltage imbalance, reactive power fluctuation, deteriorated power quality, and protection issues (Uzum et al., 2021). Further, network limit violations in the distribution system result in network congestion that prevents additional power flow through the lines (Lo and Ansari, 2012; Zhao et al., 2019). The issue of network congestion and increased network losses in the presence of high solar PV penetration is addressed in this work using controllable electric vehicle loads. However, the increased penetration of EVs through uncontrolled charging leads to technical impacts such as system overloading, congestion, increased power loss, voltage instability, etc. Apart from the above-mentioned disadvantages, electric vehicle charging through power electronics converters offers higher charging controllability. Smart charging of electric vehicles in high solar PV penetrated distribution systems is implemented in this work to address the issue of network congestion and power loss. In solar PV integrated distribution systems, smart charging of EVs can reduce the charging cost and leverage the positive impact in terms of reduced emissions from vehicle and power generation plants.

Centralized and hierarchical methods are prominently used for network congestion management in the presence of renewable generations. A rolling horizon-based look-ahead stochastic dynamic programming algorithm is implemented in (Caramanis and Foster, 2009) to reduce the charging cost of EV charging and the cost associated with regulatory services in the presence of network congestion. The objective function such as

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charging cost minimization with line constraints, is formulated as convex optimization to manage the network congestion. The line loading constraint in the optimization problem ensures the power flow below the rated value and schedules the EV charging accordingly (Hu et al., 2014). EV fleet operators can better manage network congestion with a high capacity for charging and discharging power (Hu et al., 2015). A game theory-based congestion management considering charging and discharging prices is developed using the Greedy game approach (Haq et al., 2022). The objective of minimizing the change in the charging power is adopted to reduce network congestion. The robust optimization for minimizing consumer charging cost and peak-to-average is developed considering the flexible loads to mitigate the network congestion due to increased network loading (Khan et al., 2023). Reactive power support, battery energy management system, and curtailment of peak load are studied in (Shabbir et al., 2022) for congestion management in the distribution system. The objective functions of social welfare maximization and load-shedding minimization are used for congestion management in distribution networks (Reddy, 2017; Schermeyer et. al, 2018).

Solar PV integrated into the distribution system deteriorates the voltage profile and causes voltage rise exceeding the tolerance band of $\pm 5\%$. This voltage rise issue can be more adverse in the case of a weakly loaded distribution network, where the restricted power flow in the network due to the voltage limit violation leads to network congestion. Therefore, this paper addresses the issue arising from solar PV, i.e., network congestion, to reduce the impacts of solar PV integration in the distribution network. This work utilizes electric vehicles as the controllable load for managing network congestion.

The contributions of this paper are summarized as below:

1. The optimization framework using mixed integer non-linear programming (MINLP) for congestion management with network power loss reduction as an objective is developed using smart charging of EVs in distribution system with high solar PV penetration. This framework considers the bus voltage limit for minimizing network congestion. EV charging constraints such as maximum charger capacity limit and charging/discharging SoC limits are considered to maintain the charging requirements of EV users.
2. This work establishes the relation between the solar PV hosting capacity and the EV integration capacity of the distribution system. This study shows that in the presence of smart charging of EVs, the solar PV hosting capacity of the distribution system will increase. Whereas, with increased solar PV penetration, more EVs can be integrated into the distribution system.

The paper is structured as Section II discusses the proposed problem formulation for congestion management in distribution networks, and the result & discussion in Section III, followed by the conclusion.

2. Problem Formulation

This paper focuses on network congestion issues arising due to the integration of solar PVs in the distribution system. To mitigate this, a network loss minimization problem with bus voltage limits is formulated. The proposed congestion management and network power loss reduction problem in a distribution system is formulated as a MINLP problem. The objective function of network loss minimization is defined as the summation of the network power loss in the distribution system. The mathematical formulation of the objective function for power loss minimization is defined as a function of line resistance and branch current as given in (eq. 1). Here, t is the time slot, and T denotes the total number of time slots in a day considering 15-minute interval. The constraints in the distribution system are bus voltage limits, which are considered for congestion management. In this formulation, EV charging power is considered as a decision variable in the congestion management framework. The necessary information of arrival and departure time of the EV, maximum charging power, departure SoC level, and charging/discharging limits are considered as constraints for optimization problem. The proposed optimization framework for congestion management is developed for a day-ahead scenario.

$$min \sum_{t=1}^{T} \sum_{(i,j)\in M} R_{ij} \times I_{ij,t}^{2} \qquad \text{(eq. 1)}$$

The branch power flow model in the distribution system is shown in Fig. 1. Here, $(i,j) \in M$, which represents the line between bus i and j, where M represents a set of lines in the distribution system. The line resistance is R_{ij}, and $I_{ij,t}$ is the current flowing through bus i and j at time slot t. The active and reactive power balance equations are mentioned in (eq. 2) and (eq. 3). It establishes the relation between incoming power at the bus ($P_{ij,t}$ and $Q_{ij,t}$), load power ($P_{L,t}$ and $Q_{L,t}$), losses in the line, and the outgoing power from the bus at each time slot t. $P_{ij,t}$ and $Q_{ij,t}$ are active and reactive power flow; $P_{L,t}$ and $Q_{L,t}$ denoted active and reactive load power. The nodal voltage $(v_{j,t})$ and branch current $(I_{ij,t})$ at time slot t are given in equation (eq. 4) and (eq. 5). The voltage constraint with $\pm$ 5% tolerance is considered as an inequality constraint, mentioned in (eq. 6).

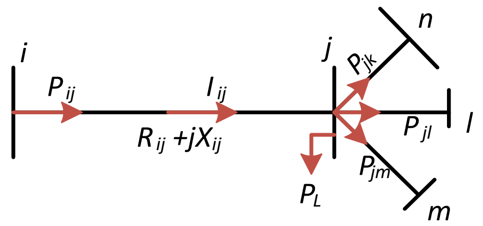

Fig. 1: Branch power flow model in a distribution system

$$P_{L,t} = P_{ij,t} - R_{ij} \times I_{ij,t}^2 - \sum_{k\in C:\{n,l,m\}} P_{jk,t} \quad \text{(eq. 2)}$$

$$Q_{L,t} = Q_{ij,t} - X_{ij} \times I_{ij,t}^2 - \sum_{k\in C:\{n,l,m\}} Q_{jk,t} \quad \text{(eq. 3)}$$

$$v_{j,t} = v_{i,t} - 2\left(R_{ij}P_{ij,t} + X_{ij}Q_{ij,t}\right) + \left(R_{ij}^2 - X_{ij}^2\right) \times I_{ij,t}^2 \quad \text{(eq. 4)}$$

$$I_{ij,t} = \frac{P_{ij,t}^2 + Q_{ij,t}^2}{v_{j,t}} \quad \text{(eq. 5)}$$

$$0.95 \leq v_{j,t} \leq 1.05 \quad \text{(eq. 6)}$$

The constraints for maintaining EV charging requirements are modeled as equality to ensure the desired SoC at the time of departure. It is given in (eq. 7), where the SoC update formula is mentioned in (eq. 8) as a function of arrival SOC, battery rating, charging power, and charging time.

$$SoC_{nm}^{T_d} = SoC_{nm}^F \quad \text{(eq. 7)}$$

$$SoC^t = SoC^{t-1} + \frac{P_{nm}^t \,\Delta t}{B^c} \quad \text{(eq. 8)}$$

$$P_{min} \leq P_{nm}^t \leq P_{max} \quad \text{(eq. 9)}$$

SoC_{nm}^F is the final SoC of n^{th} vehicle at bus m where $SoC_{nm}^{T_d}$ is desired SoC departure of EV. t denotes the time slot, B^c is battery capacity and P_{nm}^t is the charging power at t instant for n^{th} EV. P_{max} and P_{min} are the maximum and minimum limits of charging power. The charging power constraint is given in (eq. 9).

3. Results and Discussion

In the presence of solar PV scenarios and lightly loaded distribution network conditions, overvoltage at the distribution system can lead to network congestion. Therefore, to address the overvoltage-driven network congestion/PV generation curtailment, electric vehicles are utilized under a controllable charging scenario, where the power withdrawal by the EVs is controlled such that the voltages can be kept within the tolerance limit of $\pm 5\%$. Hence, as discussed in Section II, the MINLP optimization method is proposed to analyze the use of controlled EV charging to address PV penetration impact on the distribution system. The modified IEEE 33 bus distribution system with solar PV penetration (shown in Fig. 2) is considered in this work for implementation of the proposed MINLP optimization framework for congestion management.

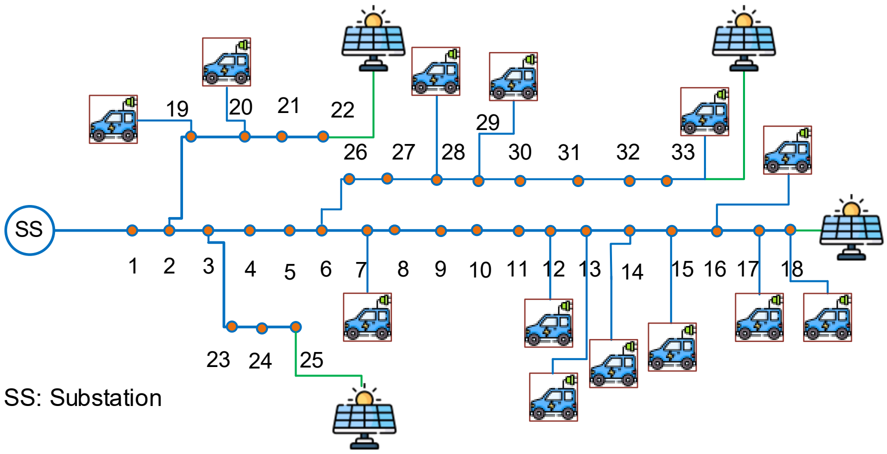

Fig. 2: Modified IEEE 33 distribution network with EV and solar PV integration

The test network considers 130 EVs with 40 kWh battery capacity and a 6.6 kW charger rating (Dahiwale and Rather, 2023). The arrival and departure times of EVs follow the normal probability distribution (Cao Chong et al., 2016). To understand the congestion in the distribution network, the load profile for IEEE 33 bus system is taken from (Dolatabadi et al., 2021) with a peak load of 3.9 MW. As shown in Fig. 2, the solar PV generators are placed at bus 18, bus 22, bus 25, and bus 33 (Dolatabadi et al., 2021). To realize overvoltage scenario due to solar PV integration in a lightly loaded condition, the system is simulated with 50% of peak load condition, and this scenario is considered as a base case. Various PV penetration levels of 100%, 150%, and 200% are considered in this study to simulate the network congestion in the distribution system. Under high solar PV penetration levels and lightly loaded distribution system, congestion is observed in the system due to voltage limit violation as shown in Fig. 3. The acceptable voltage range considered in this study are 0.95 pu and 1.05 pu. From Fig. 3, it can be observed that the voltage values are not maintained within the limit under different PV penetration levels of 100% (i.e., 4 MW) and above.

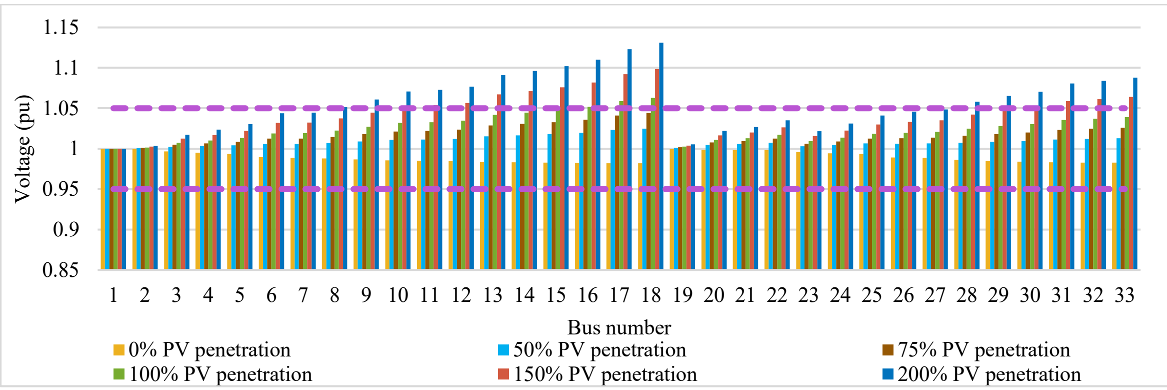

Fig. 3: Voltage profile of IEEE 33 bus distribution system with different solar PV penetration

Fig. 4 shows the power loss profile of the network under different PV penetration levels, and it can be observed that the network losses increased with increasing PV penetration. The system losses are increased because of the surplus PV generation in the system. It is noticeable from the results that the system losses follow the solar PV generation profile.

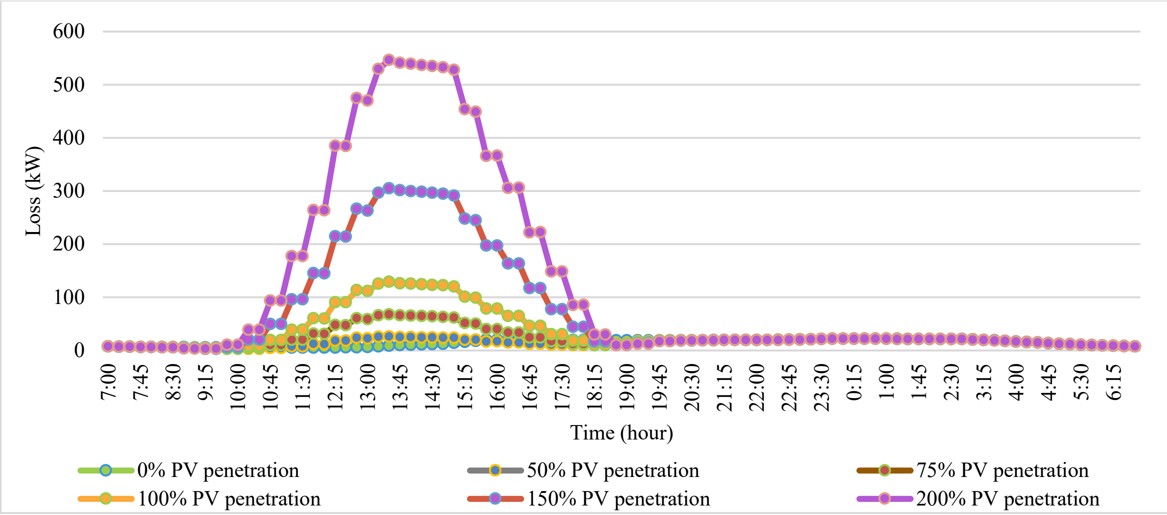

Fig. 4: System loss profile of IEEE 33 bus distribution system with different solar PV penetration

The relationship between grid power, solar PV generation, and system losses is shown in Fig. 5. The grid power is inversely proportional to solar PV generation. In contrast, the system losses are exponentially proportional to the PV generation. Fig. 5 shows that at 200% PV penetration, the grid power and losses have high values compared to the 150% PV penetration scenario followed by 100% PV penetration. The negative value of grid power indicates the reverse power flow from the distribution system to the grid due to surplus solar PV power.

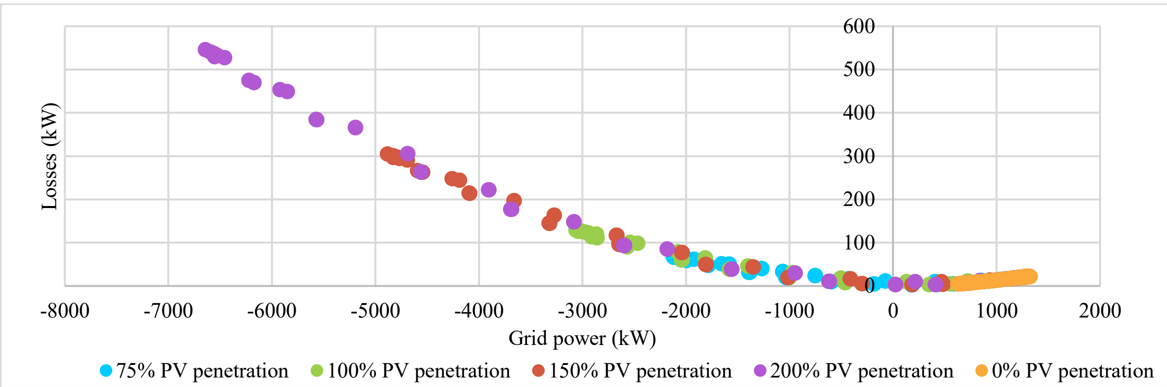

Fig. 5: Relation between Grid power and system losses at different solar PV penetration levels

Electric vehicles as controllable loads are adopted in this study to mitigate the voltage rise issue in the presence of solar PV penetration. In this work, EV charging methods such as dumb charging and controlled charging of EVs are considered for congestion management in the distribution system. The results of dumb charging and controlled charging of EVs are presented in Fig. 6. It is observed that the dumb charging of EVs cannot mitigate the voltage rise issue. Therefore, a controlled EV charging is adopted in this study by considering charging power as a decision variable, as mentioned in the optimization problem in Section II. Fig. 6 shows that the voltage in the presence of dumb charging is slightly reduced compared to the base case scenario with 150% PV penetration. Dumb charging cannot maintain the network voltages within the limits. In contrast, the proposed optimization-based controlled charging maintains the voltage within the bound of ±5%, as depicted in Fig. 6.

The losses in the different charging cases are given in Fig. 7, which indicates the significant reduction in the network losses with the proposed EV charging strategy. Fig. 7 shows that in the case of PV penetration in the system without EVs, the network losses are highest, whereas, in the case of dumb charging, the network losses reduce significantly for a charging duration only and do not guarantee the reduced losses through the day. The proposed optimized charging reduces the overall network losses in a day, as shown in Fig. 7

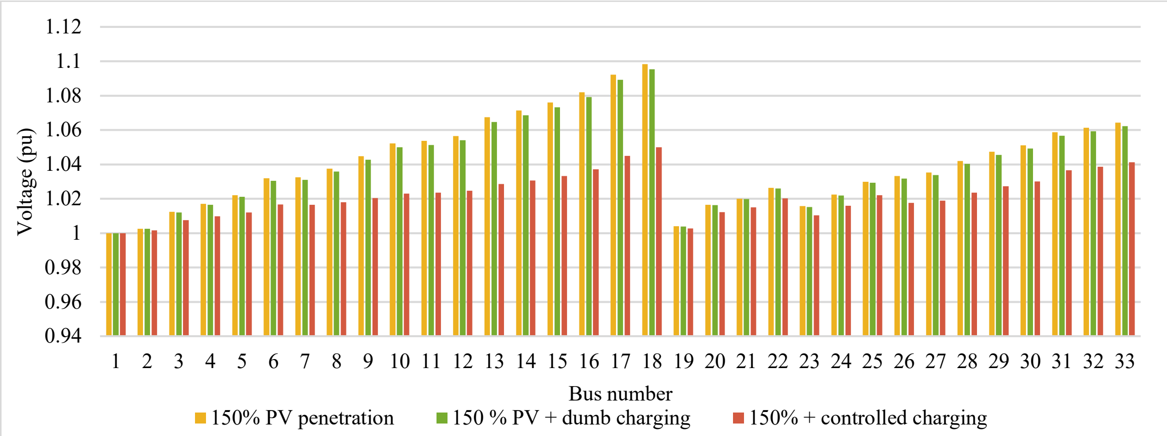

Fig. 6: Voltage profile of IEEE 33 bus distribution system with 150% PV penetration with dumb and proposed controlled charging

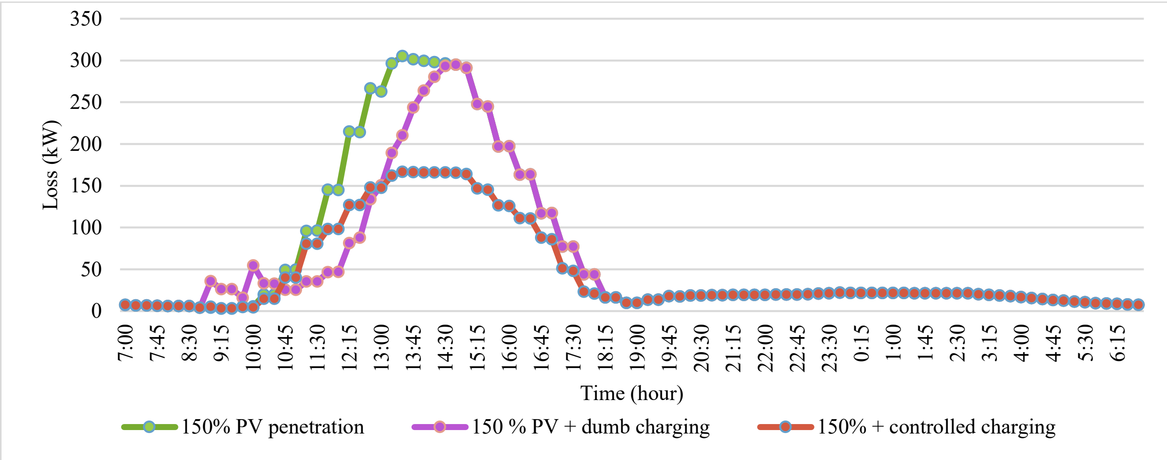

Fig. 7: System loss profile of IEEE 33 bus distribution system with 150% PV penetration with dumb and proposed controlled charging

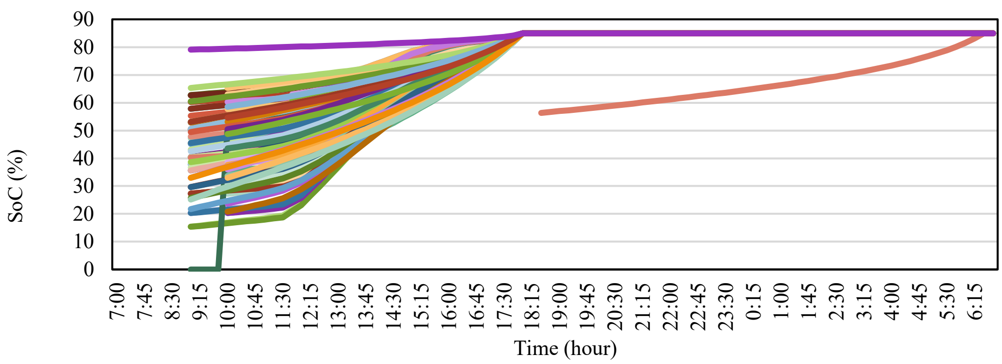

Fig. 8: SoC profile of EVs integrated in the distribution system under proposed controlled charging and 150% solar PV penetration

The SoC profiles of the EVs in the case of 150% PV penetration with controlled EV charging are given in Fig. 8. It shows that each EV has different charging curves, and with distinct charging profile's slope, each EV has a different charging trajectory to reach the desired SoC. The voltage and loss profiles for different PV penetration levels are given in Fig. 9 to Fig. 12. Fig. 9 and Fig. 11 show that at 100% and 150% PV penetration levels, the system voltage is maintained within the voltage limits under the proposed EV charging optimization.

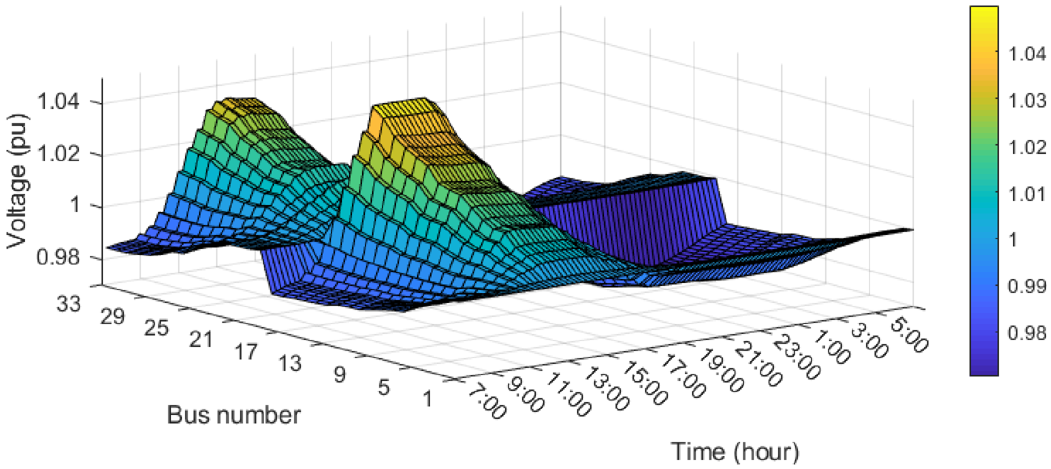

Fig. 9: Voltage profile of IEEE 33 bus distribution system under proposed controlled charging and 100% solar PV penetration

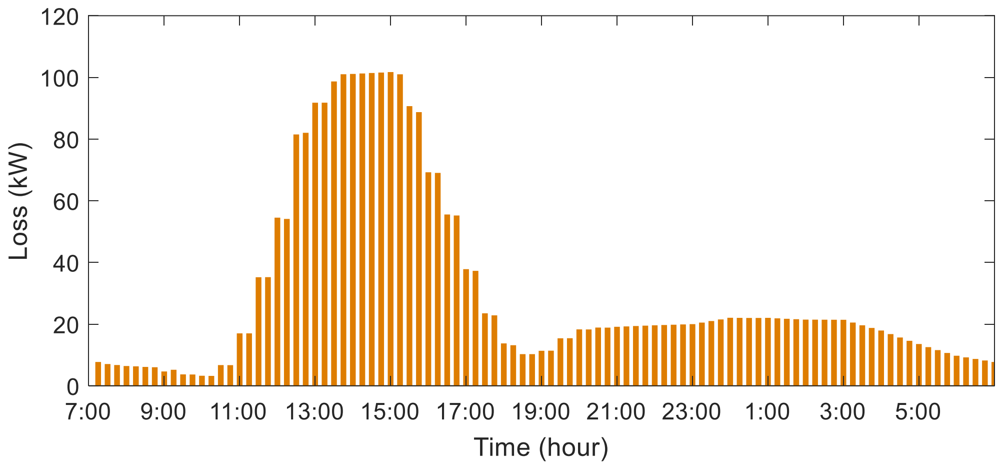

Fig. 10: Loss profile of IEEE 33 bus distribution system under proposed controlled charging and 100% solar PV penetration

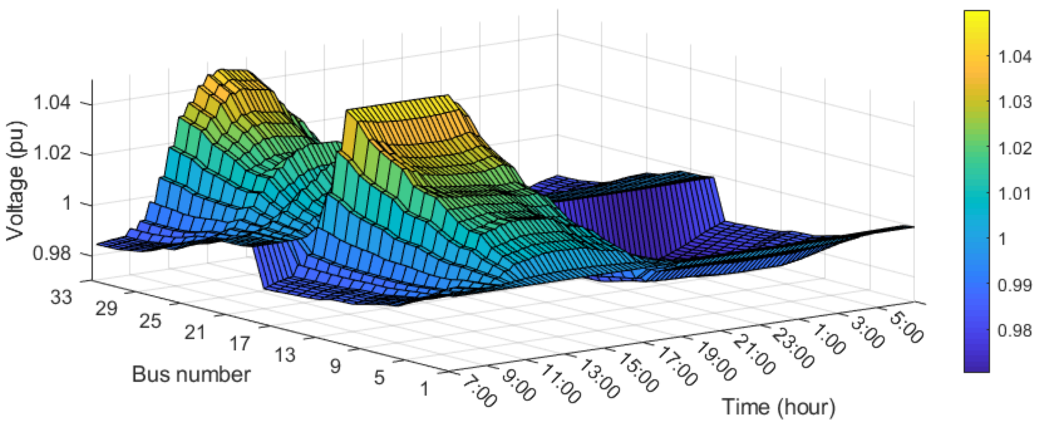

Fig. 11: Voltage profile of IEEE 33 bus distribution system under proposed controlled charging and 150% solar PV penetration

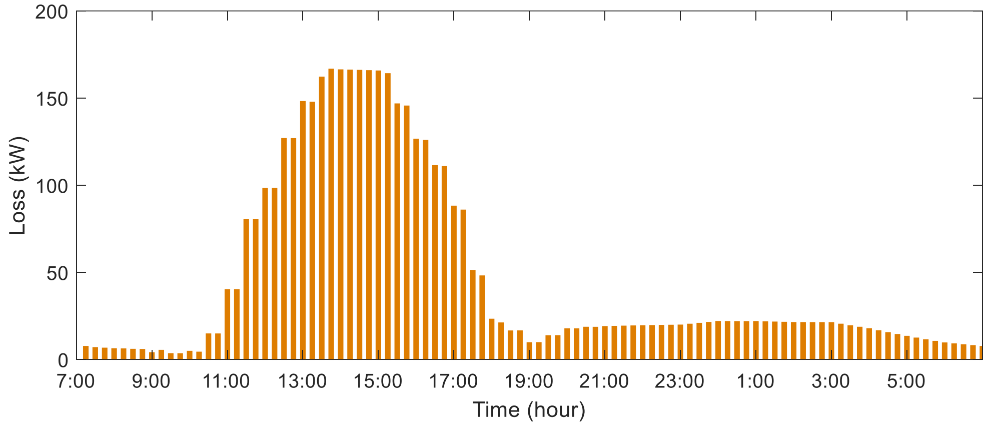

Fig. 12: Loss profile of IEEE 33 bus distribution system under proposed controlled charging and 150% solar PV penetration

Fig. 13 shows the comparative energy loss of the 33 bus system under different PV penetration levels. Energy loss (in MWh) in a day for 100%, 150%, and 200% PV penetration is provided in Fig. 13. The comparative energy losses without EVs, EVs with dumb charging, and EVs with control charging are shown in Fig. 13. It is inferred from the results that the energy losses are highest in the case of PV penetration without EVs. The energy losses are reduced with EV integration through dumb charging but cannot reach the optimal value. The controlled EV charging with the proposed optimization reduces the network losses and achieves the lowest energy losses compared to other cases.

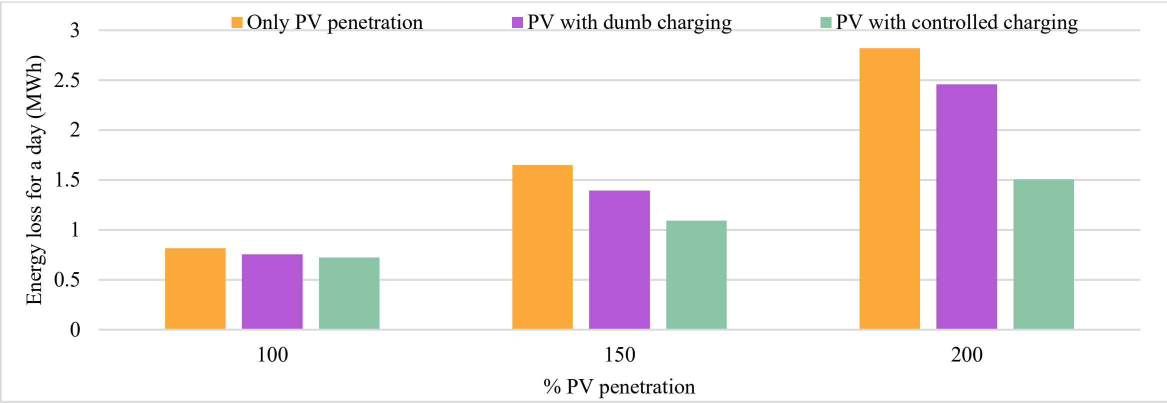

Fig. 13: Comparative energy loss of the test network under different solar PV loading and charging scenarios

The results show that controllable EVs can be used to incorporate PV penetration in the system without causing network congestion. Whereas, with increasing PV penetration, the percentage of controllable EVs should also need to be increased. The increased PV percentage in the network requires additional EV loads to cater the surplus PV generation. In this study, the 0.7MW of EV load, i.e., 17.5% EV load, can offer a PV hosting capacity of 100%, whereas the same EV percentage cannot host 200 % PV penetration in the system. To manage the higher percentage of feasible PV penetration, a higher percentage of EV loads are required. The increased EV penetration, i.e., 2.8MW EV load, offers a PV hosting capacity of 150%. Similarly, to host a 200% PV in the system, an aggregated EV load of 5.6MW is required. It depicts that the increase in the percentage of EVs as a controllable load increases the solar PV hosting capacity of the network.

4. Conclusion

The solar PV integration with a lightly loaded distribution system can cause network voltage rise, line overloading, and increased losses. The PV penetration in the distribution system causes network congestion due to network constraint violations such as line thermal constraint and voltage constraint. In this study, network losses and voltage are considered to reduce network congestion in the presence of solar PV penetration. To address it, a mixed integer non-linear programming (MINLP) optimization is formulated for network loss minimization. The proposed formulation considers network constraints such as active and reactive power balance, voltage constraints, and EV-related constraints such as SoC constraints and charging power constraints. The proposed method is implemented on a modified IEEE 33 bus network. Results show that EV integration through dumb charging in the distribution system reduces network losses but cannot provide an optimal solution to network congestion. The proposed optimization-based EV charging approach provides an optimal solution for network loss reduction and also maintains the voltage profile within limits. Thus, the proposed formulation manages the network congestion. It also indicates that the EVs are effectively utilized as controllable loads while achieving the desired SoC level at the end of the charging session. The analysis shows that the percentage of controlled EV charging load in the system and solar PV hosting capacity holds a direct relationship.

5. Acknowledgments

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