Analysis of Impact of Electric Vehicles Penetration on Indian Distribution Network

Gajendra Malviya, Bharat Nandan, and Himanshu J. Bahirat

Abstract The recent advances in electric vehicles (EVs) technologies like batteries, increase in greenhouse gas emissions and increase in fossil fuel prices have caused the more interest in using EVs. But the charging of these EVs may put an additional requirement on the existing electricity grid. Therefore, the power grid must be ready for these challenges. In order to know the type of EVs charging infrastructure required for India, the distribution feeder ratings and different charging levels should be studied. The impact of number of EVs i.e. penetration impact on Indian distribution grid will be analysed. This will lead to identification of different issues due to charging. A typical Indian distribution network will be modelled in OpenDSS. The critical infrastructure issues like voltage profile at different nodes, transformer loading, peak load and power losses will be investigated for different penetration levels. Finally, the results will be analyzed to mitigate the impacts and to suggest various measures.

Keywords EVs charging infrastructures · Electric vehicle · Supply equipment · Loadshapes · OpenDSS

1 Introduction

THE transport sector currently relies on fossil fuels and therefore accounts for a significant part of greenhouse emissions. Issues associated with greenhouse gas emissions, reduction of fossil fuel resources, energy efficiency and security are among the factors that caused the increasing interest in using EVs. Therefore, one of the main future technologies to combat greenhouse gas emissions is the battery powered Electric Vehicle (EV) and Plug-in Hybrid Electric Vehicle (PHEV) [1]. A range of passenger electric vehicles are currently being developed by different manufacturers. Despite of the shortcomings associated with EVs like limited driving range, high cost

G. Malviya (✉) · B. Nandan · H. J. Bahirat
Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India

H. J. Bahirat
e-mail: hjbahirat@ee.iitb.ac.in

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of battery, short life cycle of battery, high charging time, EVs are still gaining popularity. As the penetration of EVs in the market is perpetually escalating, thus, there is an urgent need of analyzing the impact of charging station loads on the power grid network. The increase in load due to EV charging may have adverse impacts like voltage deviations [2], transformer overloading [3], system losses and power quality issues etc. [4].

A residential EV charger in America provides a 120 V (Level-1) or a 240 V (Level-2) voltage supply to the connected EV through either a normal wall outlet or a dedicated charging circuit. Commercial chargers are generally high-powered, fast AC/DC chargers and installed in heavy traffic corridors and at public charging stations. However, because commercial chargers are still in the primary stages of deployment, EV owners typically charge their EVs overnight at residential charging stations primarily using Level-2 chargers. Unfortunately, the increasing number of residential EV chargers may cause several challenges for the distribution system. Therefore, both a system level analysis of the impacts of EV integration on the residential distribution circuit and solutions to address their impacts are needed.

A. *Background*

The impacts of EVs charging on the distribution grid are addressed in terms of different parameters in the literature. An impact study of EVs charging on the Hungarian low voltage distribution system is conducted in [2]. For this purpose, a typical Hungarian low voltage grid was modeled in DIgSILENT software. Several distribution system parameters like the transformer loading, feeders loading, voltage deviation and total system losses were assessed on the uncoordinated and delayed charging at different penetration levels of EVs.

The potential impacts of EVs charging in different penetration scenarios for Singapore with particular regard to distribution transformer rating is analyzed in [3]. This paper address the problems on the distribution side and also analyze the capacity based on a projected EV penetration and calculate and predict the overloading on the distribution transformer requirements in particular under the different EV penetration scenarios mentioned in the Electro mobility roadmap study for Singapore.

Evaluation of supply/demand matching and potential violations of statutory voltage limits, power quality and imbalance due to EVs charging are presented in [4].

The review paper [5] makes an attempt to provide a qualitative as well as quantitative review of the literatures in this area published in the past few years.

Some of the batteries ratings of 2 wheelers, 3 wheelers, electric cars and electric buses are also reviewed to understand EVs scenario in India. It was found that 2 wheelers have battery of around 2 kWh (Ather e-scooter), 3 wheelers have battery of around 5 kWh (Mahindra e-rickshaw), electric cars have battery of around 15–20 kWh (Mahindra, Tata EVs) and electric buses have battery of around 50–100 kWh (Goldstone BYD). The study conducted by India Smart Grid Forum

(ISGF) on the implementation plan for electrification of public transportation in Kolkata also recommends potential models for electrification of public transportation in Kolkata (buses, 3 wheelers etc.) [8]. It suggests ratings of batteries for 3 wheelers, Buses (AC and Non-AC) use for public transportation.

2 EVs Charging Infrastructures

EV charging is either provided using a normal wall outlet or a dedicated charging circuit (e.g. wall box or charge pole). Usually EV charging is provided by a 120 V (Level-1) or a 240 V (Level-2) voltage supply (see Table 1) in North America and a 230 V single-phase or 400 V tri-phase in most other countries worldwide.

Although the couplers are specified for up to 690 V AC and up to 250 A at 50–60 Hz, Level-1 (up to 16 A) and Level 2 (up to 32 A) are most commonly implemented [6]. Fast charging circuits, for example, CHAdeMO and the Combined Charging System (CCS), usually deployed close to highways or on parking sites, are also becoming popular.

The Society of Automotive Engineers (SAE) is responsible for the standardization of EV charging stations, it is the American standard for EV electrical connectors. SAE identifies three charging levels (see Table 1) depending upon the energy transfer rate. Note that Level-1 and Level-2 chargers are deployed at residential facilities while Level-3 chargers are used at commercial charging stations.

The EU distribution system maintains its three-phase characteristic all the way to the house service connections. This system provides a three-phase power supply with a separate neutral and earth. The line-to-line voltage is 400 V, and the line-to-neutral voltage is 230 V. For single-phase EV charging, EV load is connected between one of the phases and the neutral wire. The maximum charging power for the singlephase charging is restricted to 4.6 kW, 20 A on 230 V [6]. As for the three-phase charging, the power limitation is 44 kW, which equals 63 A at 400 V. Table 2 shows the charging levels for Europe.

Some common EVs in US that are charged from AC Level 2 charging at residence are mentioned in Table 3 with their battery sizes.

Table 1 EVs charging levels (America standards) [6]

Charging level type	Voltage level	Power level
Level-1	120 V AC	Up to 1.8 kW
Level-2	240 V AC	Up to 19.2 kW
Level-3 or DC charging	480 V DC	50–150 kW

Table 2 EVs charging levels (Europe standards) [6]

Charging level type	Voltage level	Power level
Level-1	Single phase 230 V AC	Up to 4.6 kW
Level-2	Tri-phase 400 V AC	Up to 44 kW
Level-3 or DC charging	480 V DC	50–150 kW

Table 3 Battery size of some common EVs [11]

EVs model	Battery size (kWh)
BMW i3	33.2
Chevrolet bolt EV	60
Nissan leaf	40
Fiat 500e	24
Ford focus electric	33.5
Kia soul EV	30

3 Modeling of Distribution System in Simulation Software

In this section, the test circuit IIT Bombay 10 node feeder, simulation software OpenDSS and different loadshapes curve were discussed that are used to model distribution network.

A. *IIT Bombay 10 node feeder*

IIT Bombay 10 node feeder taken as a typical Indian distribution network to do analysis. It is of 2.5 km length having primary voltage of 4.16 kV and peak load of 3.6 MVA. This small and highly loaded test feeder includes most of the common features that are used in actual networks like voltage regulators, shunt capacitor banks, overhead and underground lines, and unbalanced loads. This feeder provides a starting point to test power-flow convergence problems for a highly unbalanced system [7]. The substation transformer is of 5 MVA rating and it is 4.16 kV distribution network, which is common in US (Fig. 1).

B. *Simulation Software OpenDSS*

OpenDSS software was used to simulate IEEE 13 node feeder and do steady state analysis by adding EVs load on distribution network.

The Open Distribution System Simulator (OpenDSS) is a comprehensive electrical system simulation tool for electric utility distribution systems [12]. It can support all kinds of steady state analysis commonly performed for utility distribution systems. In addition, the most important advantage of OpenDSS is that it supports analysis with distributed generation integration and time series power flow.

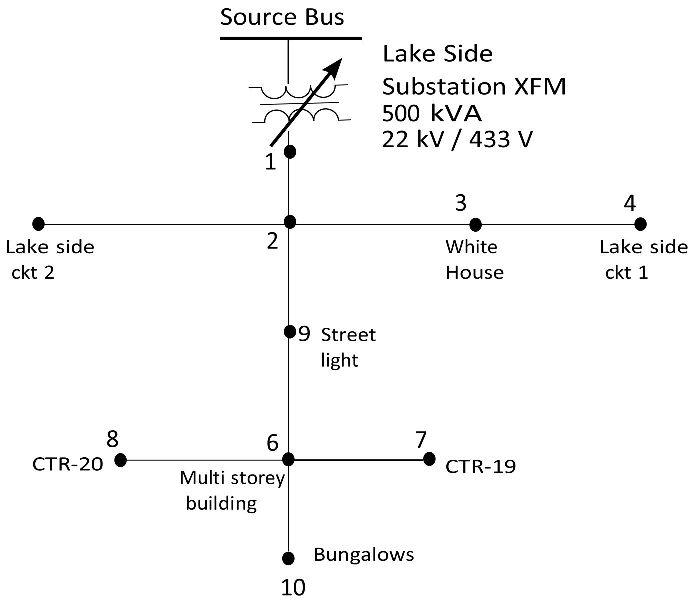

Fig. 1 IIT Bombay 10 node feeder

The iteration cycle is started by obtaining the current injections from all the power conversion elements and introducing them in the line vector. The sparse set of matrices is solved until the voltages converge to the specified tolerance. When performing daily or yearly simulations, the solution at the present time step is used as the starting point for the solution at the next time step. The solution typically converges in two iterations unless there is a large change in the load. After a converged solution, control iterations are performed to if control actions are needed.

C. *Different Loadshapes*

IIT Bombay residential loadshape is used to see AC Level 2 charging effect which was downloaded from Electric Power Research Institute (EPRI) website [10]. Residential loadshape of California is chosen as IEEE 13 node feeder network is a typical US distribution network, so the loadshape is also chosen of a state of US. Residential loads considered in loadshapes are lighting, central air conditioning (CAC), heating, refrigerator, TV & PC, clothes washer, clothes dryer, dishwasher and water heating. This residential loadshape is of an average weekday of peak season (summer) of California (Figs. 2 and 3).

EVs loadshape curve for AC Level 2 charging is chosen by taking some assumptions like there is facility for AC Level2 charging of EVs is available at all homes i.e. 240 V and 32 A (7.7 kW peak) charging facility is available at all homes. There are homes (as IEEE 13 node feeder is mainly residential) at each node of the feeder. The number of homes are counted by taking 4 kW as peak load of a home and it is

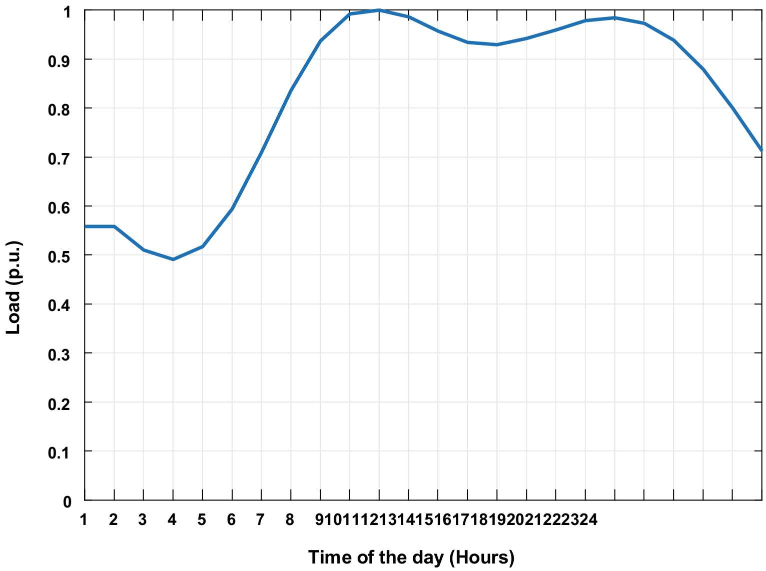

Fig. 2 IIT Bombay residential loadshape curve for Jan (winter)

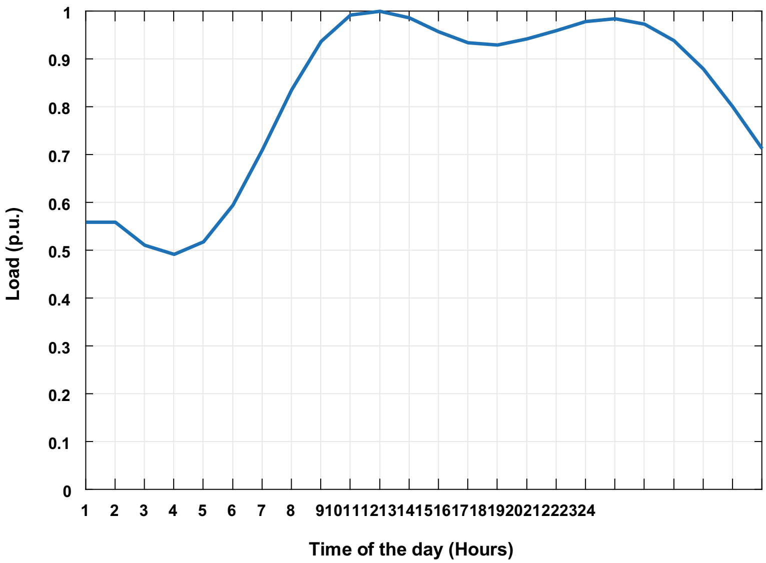

Fig. 3 IIT Bombay residential loadshape curve for May (summer)

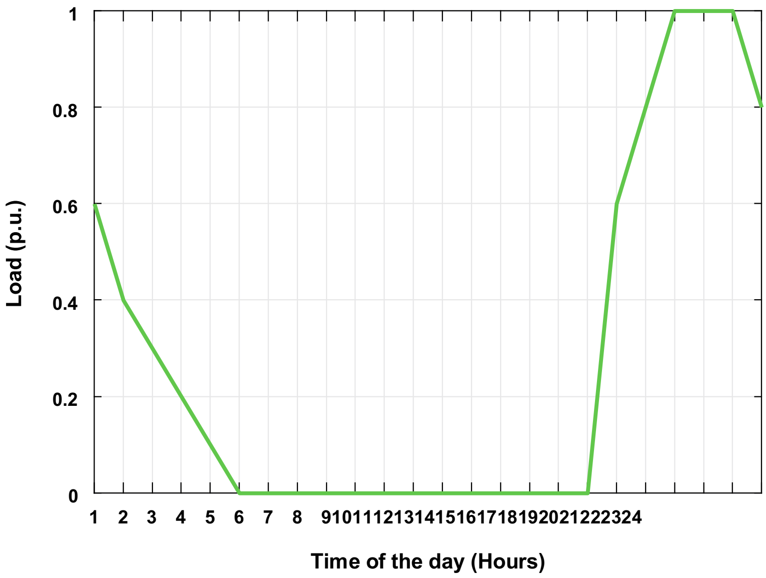

Fig. 4 EVs loadshape curve for AC level 2 charging

assumed that there are two vehicles in each home. Thus, accordingly EVs penetration level is given for study. In OpenDSS simulations, load of an electric vehicle is taken as 7 kW, thus EVs loadshape is generated considering 7–8 h of charging. Peak of loadshape is assumed at night (9–11 pm) considering large number of EVs are charging at that time (Fig. 4).

4 Impact of EVs Charging on Distribution Grid

In this, different impacts due to EVs charging on the distribution grid were studied using simulations.

A. *Voltage Drop*

As EVs charging load increases, it can draw more current through lines or cables that have impedances which results in voltage drop. There may be scenario where voltage may go below minimum required levels at certain homes in the network which are away from the transformer. Residence connected to highly loaded phase and most away from transformer is most vulnerable to the voltage drop. Due to this voltage drop electrical appliances may run inefficiently and there lifetimes can be reduced, thus it is important to have these voltages within limits (Fig. 5).

Node 671 is chosen for study of voltage drop as it is quite away from the substation and having load at all the phases. From the Fig. 1, Voltage profile of node 671 can be observed at different EVs penetration. V1, V2, V3 indicates the voltages of phases 1,

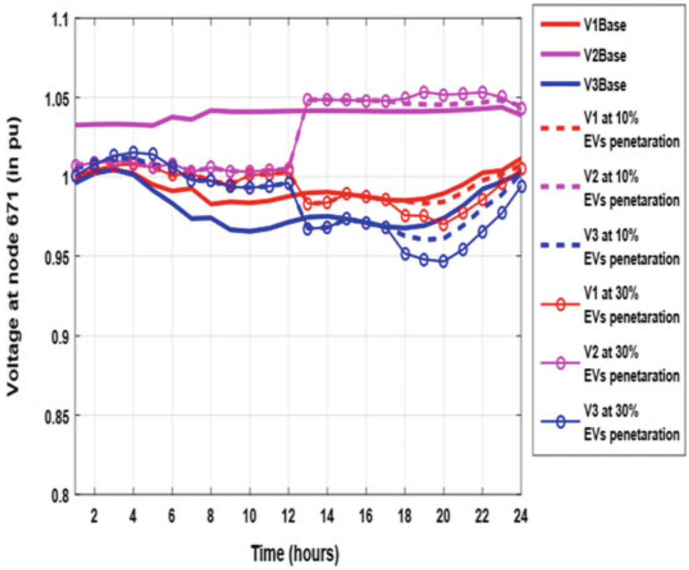

Fig. 5 Voltage profile of node 10 for different EVs penetration in Jan (winter)

2, 3 respectively. Minimum pu voltage at node at different EVs penetration can also be seen in Table 1. It can be observed that it is crossing the under voltage limits of American National Standards Institute (ANSI) at 30% penetration level as according to the American national standard the voltage deviation limit is ±5% of the nominal voltage [9].

Node 634 voltage profile was also plotted, it can be observed that its voltage remain within limits in different cases as it is not that farther from the substation. Node 634 is at 2500 ft. from substation transformer where as Node 671 is at 5000 ft. from substation transformer. Thus, it can observed from the Figs. 6 and 7, their is more voltage deviation at node which is farther from the substation and it may cross limits at higher penetration levels of EVs. These voltage profiles are found at unity power factor of an EV charger.

B. *Peak Load Demand*

Due to EVs charging, peak load demand will increase and there might be supply/demand mismatch. There should be sufficient power supply to cater EVs charging load. The increased load demand for EVs charging results in rise in the peak load demand of the grid which is accompanied by decrease in reserve margin. There can be scenario of increment in peak load demand as generally residential peak load demand is around 7–8 pm (lighting, AC) in US, when people come home from work and it may happen they just plug in their EVs as they reach home which can lead to huge increment in peak load demand.

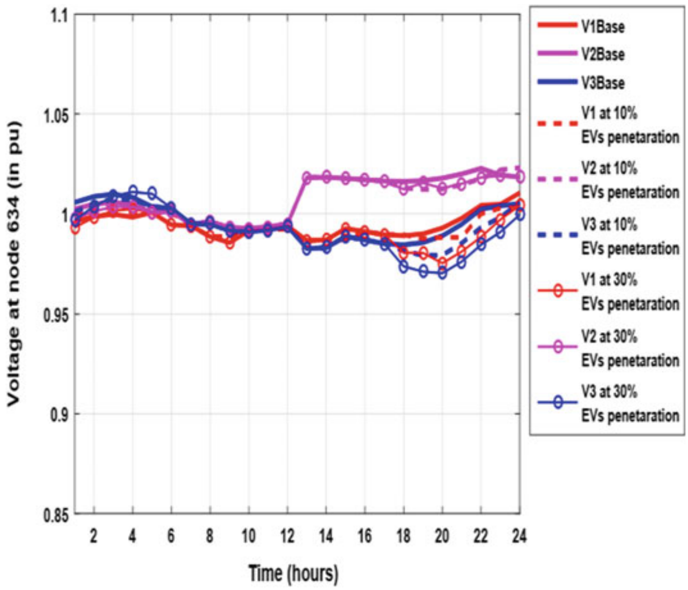

Fig. 6 Voltage profile of node 10 for different EVs penetration in May (summer)

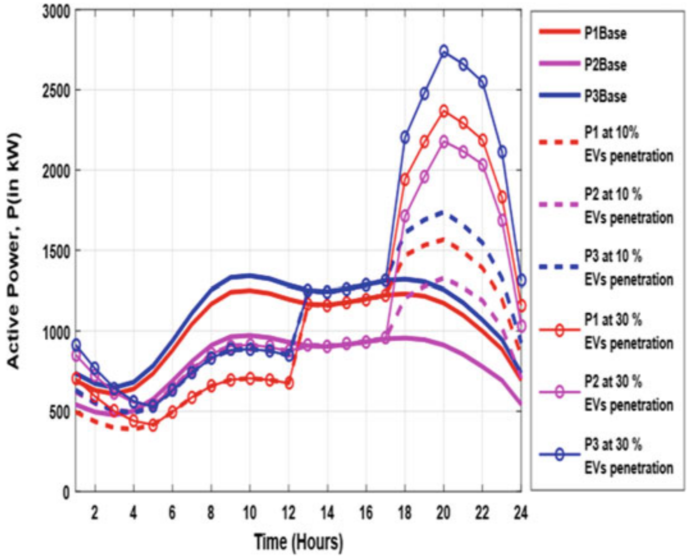

Fig. 7 Total active power demand of system at different EVs penetration in Jan (winter)

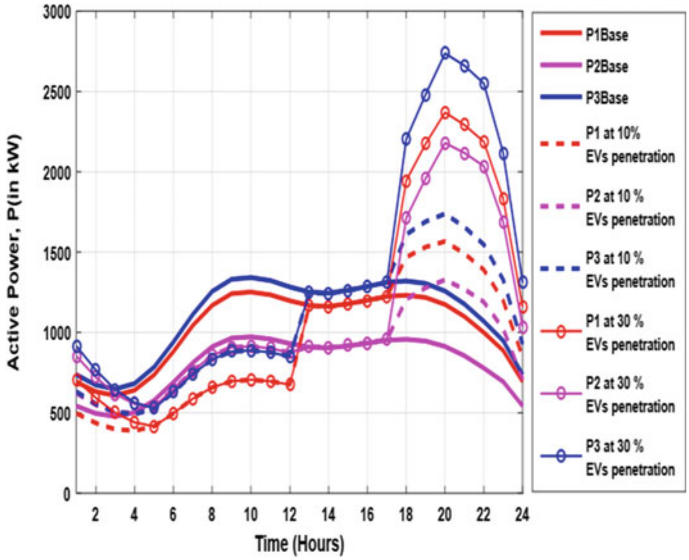

Fig. 8 Total active power demand of system at different EVs penetration in May (summer)

From the Fig. 8, the huge increment in peak load demand due to EVs penetration can be observed. The change in demand curve as well as shift in peak load can be observed from the figure. The curve shape is like residential loadshape in base case while it is a mix of residential as well as EVs loadshape in other two cases. P1, P2, P3 indicates the active power demand in phases 1, 2, 3 respectively. The power factor of an EV charger is assumed to be 1 while getting these simulations results.

C. *Transformers Overloading and Peak System Losses*

Large scale deployment of EVs produces additional stress on the distribution transformers which plays a prominent role in decreasing the life cycle of the transformer. Though exceeding normal ratings will not result in device failure [3], it effectively reduces the operation lifespan of the transformer thus transformer loading must be kept under permissible limits. The substation transformer is of 5 MVA rating and the maximum base loading of the transformer is 79% (3.96 MVA) and since PEVs charging coincides with the base load peak hours, at each penetration levels a new peak is formed and the transformer maximum loading reaching about 99% (4.95 MVA) at 10% EVs penetration level and about 152% (7.62 MVA) at 30% EVs penetration level which can be seen in Table 4. The power factor of an EV charger is assumed to be 1 while doing these simulations (Table 5).

EVs charging will result in increasing the load demand. With increasing the load demand, the current flowing in the feeders will increase which in turn will increase the system losses. In Table 4, it can be observed that by increasing EVs penetration, percentage peak active power losses increases.

Table 4 Simulation results at for EVs charging in winter

Case study [Jan (winter)]	Minimum node voltage (pu)	Peak active power demand (MW)	Peak MVA demand	Time of the day (Hour)	Peak active power losses (%)
Base case (No EVs)	0.961	3.57	3.96 MVA	10	3.15
10% EVs penetration	0.954	4.63	4.95 MVA	20	3.61
30% EVs penetration	0.937	7.23	7.62 MVA	20	5.18

Table 5 Simulation results at for EVs charging in summer

Case study [May (summer)]	Minimum node voltage (pu)	Peak active power demand (MW)	Peak MVA demand	Time of the day (Hour)	Peak active power losses (%)
Base case (No EVs)	0.961	3.57	3.96 MVA	10	3.15
10% EVs penetration	0.954	4.63	4.95 MVA	20	3.61
30% EVs penetration	0.937	7.23	7.62 MVA	20	5.18

5 Conclusion

From the case studies that were performed showed that large deployment of EVs may lead to potential problems for existing power distribution networks. It can be concluded that after a certain penetration levels of EVs, there is violation of statutory voltage limits. This increased EVs penetration may result in sustained secondary service under-voltage conditions, violation of under-voltage limits, and which would deteriorate the service voltage quality. The study also concludes that EV load charging may increase the system peak load demand. It can be speculated that if the charging infrastructure is not planned properly, the widespread adoption of EVs over the distribution network can significantly increase the substation load demand and could results in violation of supply/demand matching. Furthermore, the increased peak load demand due to EVs load charging may overload service transformers, resulting in transformer overheating, thus deteriorating the transformer's life.

The impacts like the transformer overloading and service voltage quality in the distribution network can be mitigated by some infrastructural upgrades like increasing the size of the service transformer and/or reconfiguring the distribution circuit using additional service transformers. Several methods like indirectly control EVs charging by utilities using Time of-Use (TOU) pricing and smart charging were proposed in literature to mitigate the impacts of EVs charging on the distribution grid. Integration of renewables (solar PVs) and storage devices in distribution network can also be studied to mitigate the impacts of EVs charging.

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