Grid-Edge Dynamic Volt-VAr Control Solution to Mitigate System Impacts Caused by Vast EV Charging Infrastructure Integrations

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Abstract

Electric vehicle (EV) sales are booming everywhere. Extensive EV charging infrastructure integration into the legacy distribution networks may cause several system vulnerabilities, including system voltage drop. In this paper, Dynamic VAr Controllers (DVC) are proposed as a cost-effective, non-wires alternative (NWA) and distributed control solution to mitigate the impacts on system voltage. In this approach, the singlephase DVCs are deployed at the secondary of the service transformers at locations with lowest voltages to provide voltage support through dynamic VAr injection. To verify the mitigating effect of DVCs, several scenario-based time-series simulations are performed in OpenDSS on actual distribution networks, using historical load and EV profiles, while the DVC controller is modeled in Python. Simulation results confirm the significant performance of DVCs in resolving the under-voltage issue, as well as system voltage unbalance. The proposed solution is a promising alternative to costly distribution infrastructure expansion and electro-mechanical voltage control devices.

Index Terms—charging infrastructure, dynamic VAr Control, electric vehicle, grid-edge, non-wires alternative, voltage support, secondary circuit

I. INTRODUCTION

According to the United States Department of Energy (DOE), the electric grid may experience a 38% increase in demand by 2050 largely due to electric vehicle (EV) load [1]. The fast development of the EV market in transportation provides both opportunities and challenges to electric utilities [2]. With the increased demand, the quality of the power delivered to customers will be a major concern; system voltage will drop during the peak charging hours due to the increased loading, especially when coinciding with the network non-EV peak demand [3]. Moreover, network active power losses rise, and the infrastructure may age earlier due to continuous overloading conditions [2]. Thus, unmanaged deployment of EV charging infrastructure may cause adverse impacts to nearby customers. Therefore, cost-effective technologies and solutions to manage power flow and power quality will be critical in avoiding such impacts.

Traditional solutions for voltage support, such as on-load tap changers and primary capacitor banks, have discrete action domain and slow responses, making them ineffective in addressing fast voltage variations caused by EV charging infrastructure [4]. The reactive power compensation through Static VAr Compensators (SVC) has long been a popular approach for system voltage support [5]. However, EV charging load is randomly distributed over time and space, making the conventional VAr compensation equipment a bit less effective.

IEEE 1547-2018 standard has recommended every DER to have the capability of VAr support [6]. Therefore, recent studies have focused on the reactive power compensation through the smart inverters associated with the EV chargers; [7] showed that the EV chargers can participate in reactive power compensation. In [8] a reactive power support method was proposed using off-board. A distributed model predictive control strategy was proposed in [9] to incorporate the EV charger reactive power capability for real-time voltage support. Nonetheless, this approach has practical limitations as the voltage violation is more likely during the peak charging period customers hence restraining the charging rate of the charger in order to provide VAr support would cause driver's charging opportunity loss [10]. Moreover, the charging facilities are mostly owned by individual customers who need a proper incentive to participate in VAr control.

Dynamic VAr Controller (DVC) is a new power electronicbased grid-edge technology that is classified as the nonwires alternative (NWA) to conventional electro-mechanical medium-voltage Volt-VAr control assets. This device performs automatic real-time Volt-Var optimization (VVO) through subcycle VAr injection, boosting the voltage at low-voltage locations [11].

In this paper, DVCs are proposed as a solution to adverse impacts of unmanaged EV charging infrastructure integration on customer voltages. To this end, DVCs are deployed at secondary of the service transformers with the lowest node voltages, providing voltage support through dynamic VAr injection. As single-phase VAr devices, DVCs reduce the voltage unbalance of the system.

This paper is organized as follows: Section II introduces the grid-edge DVCs and their operation logic, while section III presents a variety of scenarios and case studies, as well as the results and discussion. Section IV concludes the paper.

II. DYNAMIC VAR CONTROLLERS

Grid-edge DVCs are new technologies [12], in a reasonable price range, with promising functionality, which are currently being adopted by the utilities for various use cases such as improving conservation voltage reduction (CVR) [13], resulting in peak demand reduction and an increased energy saving. Other applications involve increased PV hosting capacity and voltage flicker reduction [14]. These utility-owned singlephase shunt-connected devices are rated around 10 kVAr, which reside at secondary side of the service transformers (208, 240, and 277V) at the locations that require voltage support. An adequate number of DVCs can mitigate the undervoltage issue on the primary side and alleviate the need for primary capacitors by providing reactive power support. DVCs can regulate voltage tightly at a configurable setpoint within a configurable bandwidth (±0.5V), by injecting VAr when the measured voltage falls below the setpoint, and reducing VAr injection when the voltage rises above the setpoint. These fastresponse devices can inject reactive power in the steps of 1 kVAr, on a sub-cycle basis, providing a solution for several short-term voltage issues such as voltage flicker, and voltage fluctuations caused by intermittent renewable resources [12].

Grid-edge DVCs operate autonomously with the slightest intervention from the system operator who only sets the voltage setpoint. Thus, they are classified as the distributed control mechanism. Furthermore, DVCs are capable of monitoring power flow and quality, which could extend the observability over the edges of the distribution network, along with the control. This will allow distribution system operators to manage the grid at a granularity required for EVs, mitigating adverse impacts on customer reliability and power quality. The increased observability will improve the real-time situational awareness to support the growing charging infrastructure integration [15].

A. Concept of Volt-VAr Control via Grid-Edge DVC

In this section, the mechanism of voltage improvement through the grid-edge DVCs is presented. Fig. 1 shows a single-line diagram of a service transformer connection; the load and the DVC are connected to the secondary (load) side of a service transformer. In this figure, the voltage drop across the service transformer ΔV_T can be expressed as follows:

$$\Delta V_T = |V_S| - |V_L| \tag{1}$$

where $|V_S|$ and $|V_L|$ are voltage magnitudes at primary (source) side and secondary (load) side of the transformer, respectively.

The phasor diagram of the voltages and currents corresponding to Fig. 1 is illustrated in Fig. 2.a, considering a lagging power factor (PF) load and no VAr injection by DVC, in which $I_T = I_L$. On the other hand, Fig. 2.b shows the impact of VAr injection by DVC on the transformer current (I_T), consequently the voltages, and the voltage drop. The ΔV_T in Fig. 2.b is lower than the one of Fig. 2.a, indicating the voltage improvement made by the DVC.

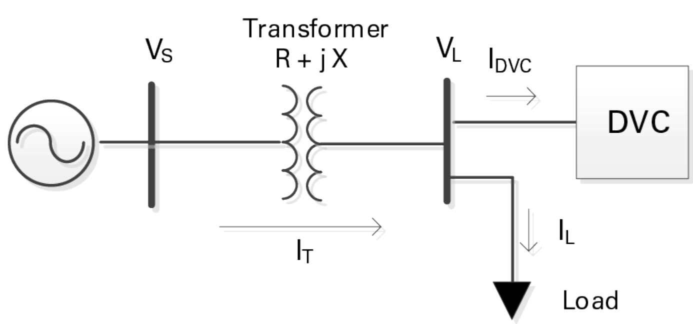

Fig. 1: Single-line diagram of a service transformer connection

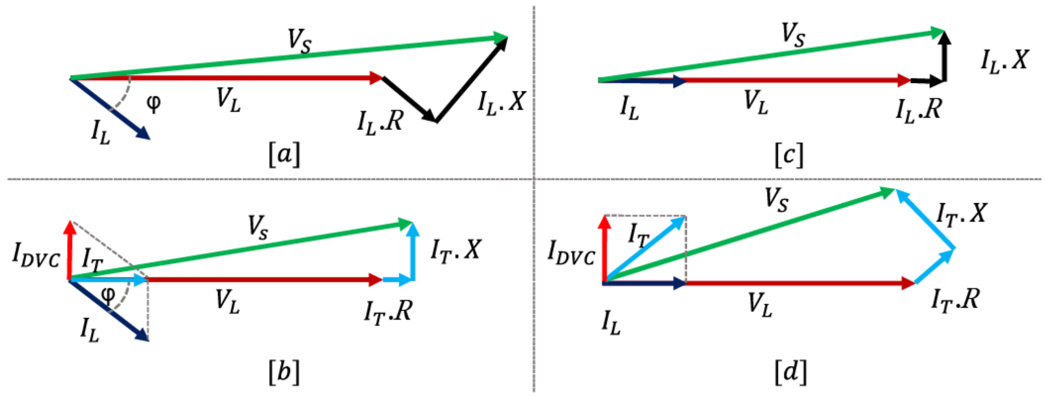

Fig. 2: Phasor diagram at transformer connection and a lagging PF [a,b], and a unity PF load [c,d]: [a,c] without VAr, [b,d] with VAr injection by DVC

The DVC provides voltage improvement even when a unity PF load, such as a single-phase level 2 charger, is connected to the secondary of the service transformer. As illustrated in Fig. 2.c and 2.d, ΔV_T from (1) is lower in Fig. 2.d.

III. CASE STUDY

In this paper various EV charging infrastructure types are taken into account, including residential, commercial, and commercial fleet facilities. To this end, actual distribution networks, including a rural and an urban feeder are modeled in OpenDSS. Quasi-steady-state simulations are performed using time-series load flow in OpenDSS. To enhance the fidelity of the study historical load and EV profiles were acquired. A highly accurate model of the grid-edge DVCs and their corresponding controllers is developed in Python. Multiple scenarios are considered to demonstrate the DVC performance in a network with high EV penetration. In each scenario, three cases are investigated;

1. Network with no EV infrastructure
2. The network with high penetration of EV charging infrastructure
3. The network with high EV penetration along with DVCs deployed as voltage support solution.

A. Scenario 1: Unmanaged Residential EV Chargers on a Rural Distribution Feeder

In this scenario, an actual rural feeder, featured in Fig. 3, is used as the test network. The rural feeders tend to be long and hence higher in impedance. The majority of the customers on this feeder are residential. This feeder is characterized by 12.47 kV nominal voltage, a length of 9.84 miles, and 538 service transformers. The peak load of the feeder is 2.72 MW with a power factor of 0.9. A 600 kVAr cap bank is also located in the middle of the feeder, and the LTC setpoint at the feeder-head is 125 V. The peak demand takes place around 8:30 PM. As a residential feeder, most service transformers are single-phase and sized between 15 to 50 kVA.

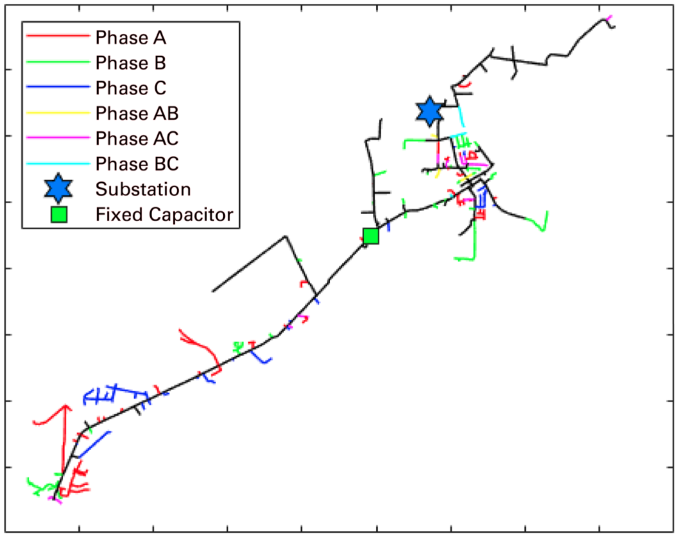

Fig. 3: Topology of the rural distribution network

120 residential level 2 EV chargers are distributed across the feeder, summing up to 830 kW EV load, equivalent to 30% EV penetration. 30 EV charging profiles are created to account for uncertainty in the charging process of different EV chargers. To create a variety of charging profiles, a random start time; between 6 PM to 8 PM, a random charging duration of 3 to 8 hours, and a random charging rate of 3.8, 7.7, and 9.6 kW are applied. Some examples of these random profiles are displayed in Fig. 4. These 30 charging profiles are randomly assigned to 120 EV loads on the feeder.

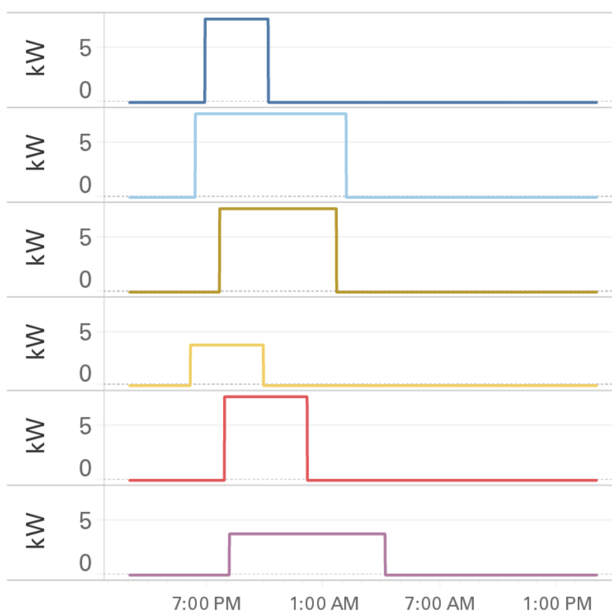

Fig. 4: Some examples of the random charging profiles assigned to the residential EV loads

The EV loads are modeled as constant power loads with a unity power factor. Fig. 5 illustrates the voltage profiles at the secondary side of all service transformers across the network for the baseline loading and after applying EV loads and their corresponding demand profile. As shown in the figure, the accumulated peak load of the EV chargers causes the minimum secondary voltage to drop from 114.4 to 108.5V, violating ANSI minimum voltage limit.

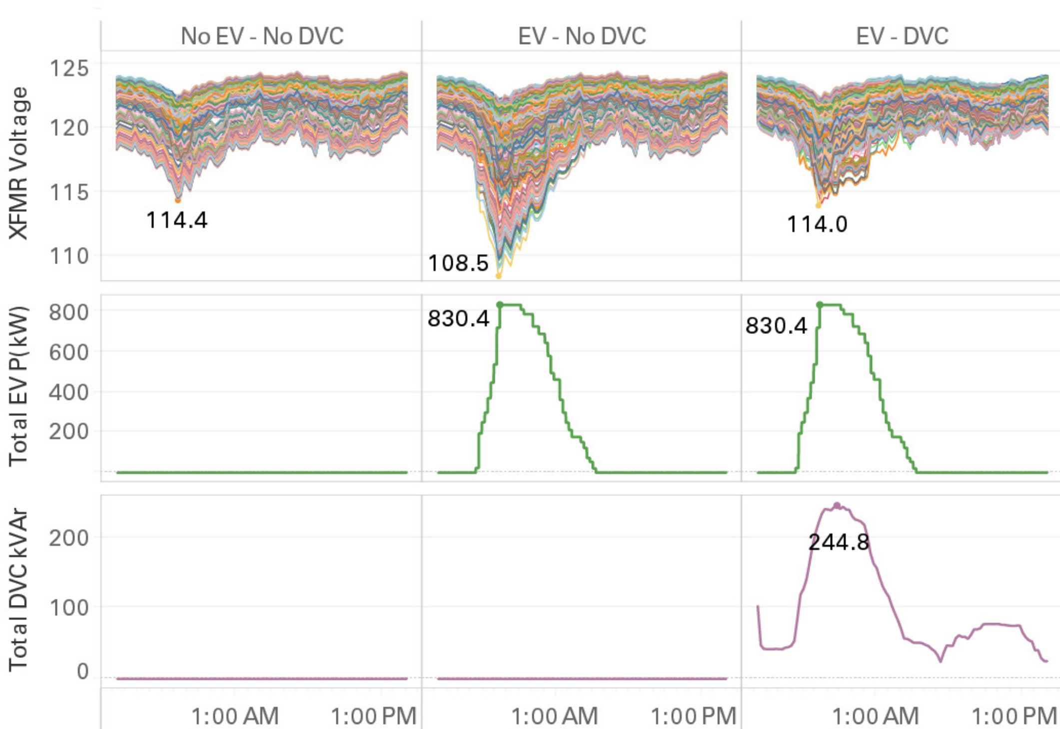

Fig. 5: Adverse impact of unmanaged residential EV chargers integration on load voltages, and mitigating effect of DVCs

To resolve the under-voltage issue, 25 DVCs are deployed at 25 EV locations with the lowest voltages. The voltage setpoints of all DVCs are set to 120V. As demonstrated in Fig. 5 (EV- DVC), these DVCs inject dynamic kVAr to support the voltage locally throughout the day. Hence, the DVCs effectively boost the voltages to meet the ANSI limit (114V).

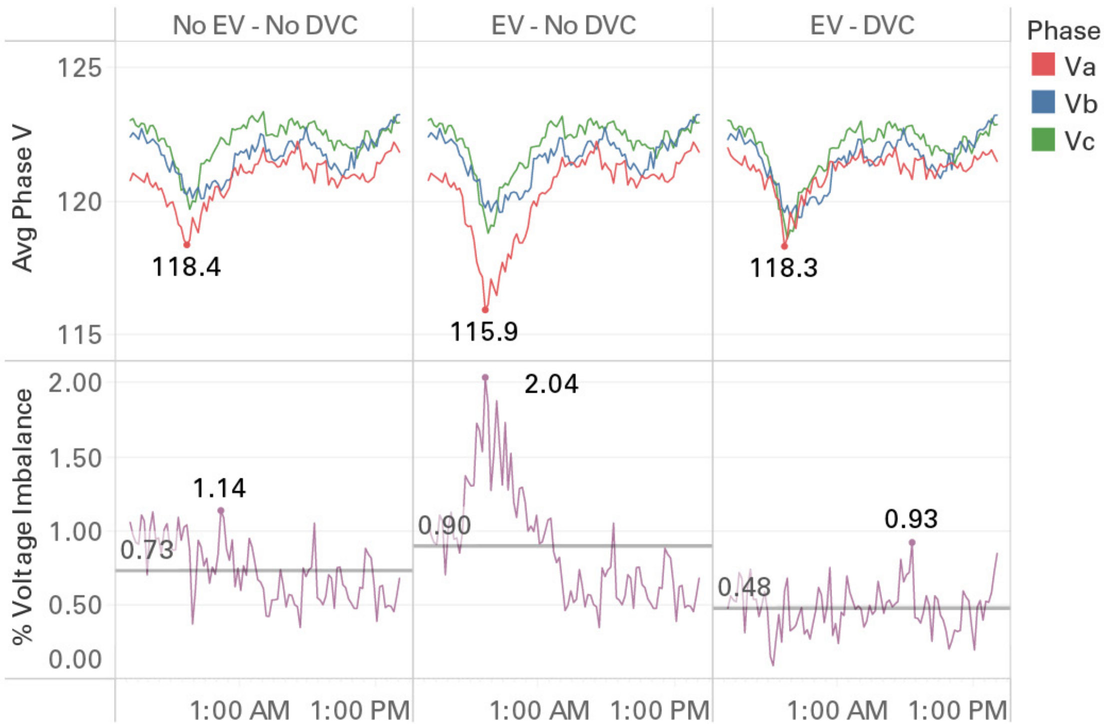

Fig. 6: Adverse impact of EVs, and mitigating effect of DVC on system voltage unbalance

As single-phase devices, DVCs can be deployed unequally on different phases, hence reducing the voltage unbalance as a side benefit. Fig. 6. highlights this improvement; DVCs reduce both the maximum and average voltage unbalance over the day, while the high EV penetration in the absence of DVCs causes the maximum voltage unbalance to exceed the 2% compatibility level suggested by IEC 61000-4-15:2010 [16]. Note that the phase voltages shown in Fig. 6 are the average of all load voltages on the corresponding phases.

B. Scenario 2: Commercial Highway EV Charging Station on a Rural Distribution Feeder

In this scenario, instead of distributed residential EV chargers, a big-size commercial highway EV charging facility is located downstream of the feeder described in previous scenario. The EV charging profile (Fig. 7) corresponding to this facility was created based on a gas station traffic data. The charging station is modeled as a balanced 3-phase constant power load with a peak of 1.35 MW, equivalent to 50% EV penetration, emulating about 9 DC fast chargers rated at 150kW.

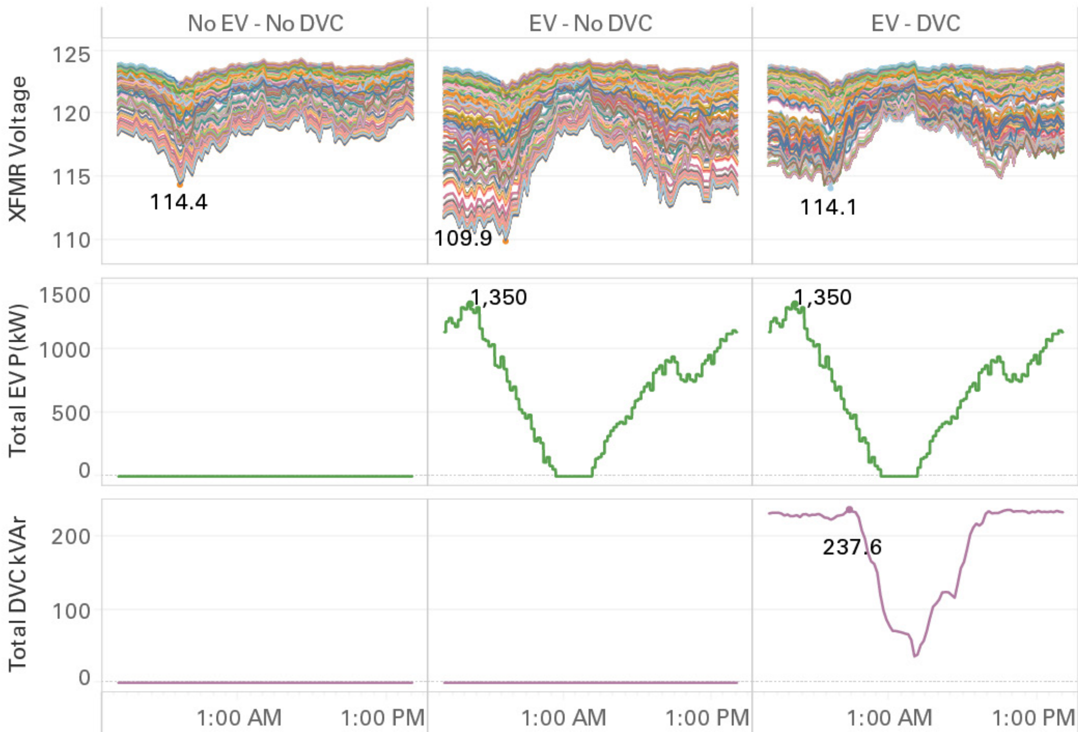

Fig. 7: Service transformers secondary voltages, EV charging profile, and DVCs kVAr injection, in the commercial EV charger setup

As displayed in Fig. 7, the peak of the charging profile takes place at 7:00 PM and takes down the lowest node voltage from 114.4 (see Fig. 5) to 109.9 V, causing ANSI voltage violation. This adversity can be resolved with the deployment of 24 DVCs that boost the minimum voltage up to 114.1 V, as featured in Fig. 7.

It is worth mentioning that EV infrastructure integration solely improves the power factor at the feeder-head by increasing the amount of the unity power factor load. In this scenario, the average PF rises from 0.94 to 0.95. On top of that, dynamic Volt-VAr control via DVCs improves the average PF to 0.97.

C. Scenario 3: Fleet EV Charging Station on a Rural Distribution Feeder

Fleet charging stations are facilities designated for fleet and heavy duty EVs and the charging process is often scheduled to start and end at specified times (10 PM and 6 AM, in this scenario) to avoid coincidence with the non-EV demand. The location and configuration of the charging station is same as the previous scenario with a different charging profile demonstrated in Fig. 8. This figure displays the impact of the fleet charging facility on the system voltage.

Since the charging station is a balanced 3-phase unity-PF load, part of the under-voltage can be compensated through a 600 kVAr primary capacitor bank installed close to the charging facilities. The rest of the under-voltage issues can be addressed by deploying 14 DVCs at low voltage nodes. The system voltage improvement via combination of these two solutions is illustrated in Fig. 8.

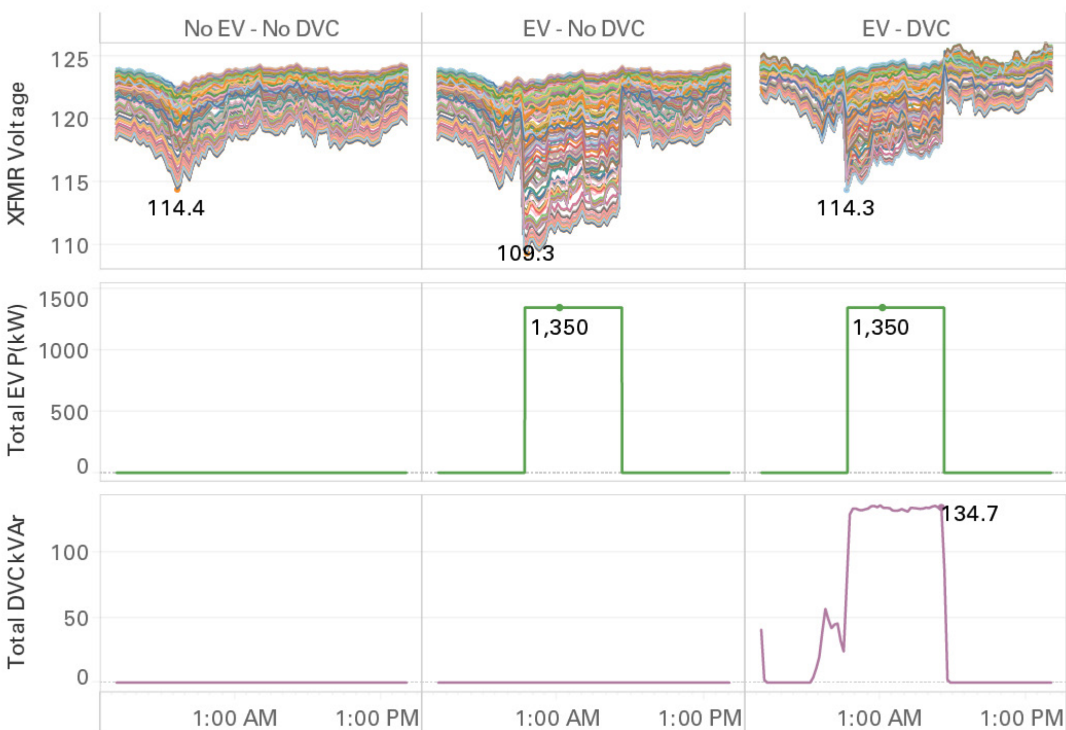

Fig. 8: Service transformers secondary voltages, EV charging profile, and DVCs kVAr injection, in the fleet EV charging station setup

D. Scenario 4: Commercial EV Charging Station and Residential EVs on an Urban Distribution Feeder

In this scenario, an actual urban feeder, demonstrated in Fig. 9, is used as the test network. Unlike the rural feeders, urban feeders are rather short and hence lower in impedance. This feeder is characterized by 13.2 kV nominal voltage, a length of 3.58 miles, and 191 service transformers. The peak load of the feeder is 8.68 MW with a power factor of 0.97. The LTC setpoint at the feeder-head is set at 122.5 V.

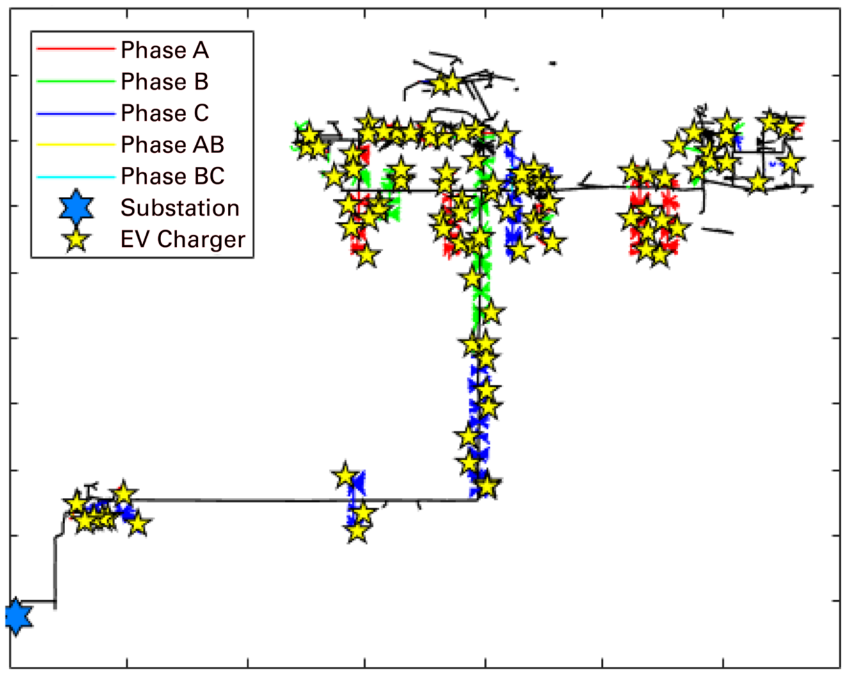

Fig. 9: Topology of the urban distribution feeder, showing the location of the EV chargers

It is assumed that 100 residential EV chargers, with the characteristics and charging profiles described in section III.A, are distributed across this network as shown in Fig. 9. along with a 2.7 MW commercial EV charging station, located in the middle of the feeder with the charging profile used in III.B. The accumulated peak demands of the EV chargers sum up to 2911 kW, equivalent to 34% of EV load penetration. The voltage profiles at the secondary of the service transformers are shown in Fig. 10.

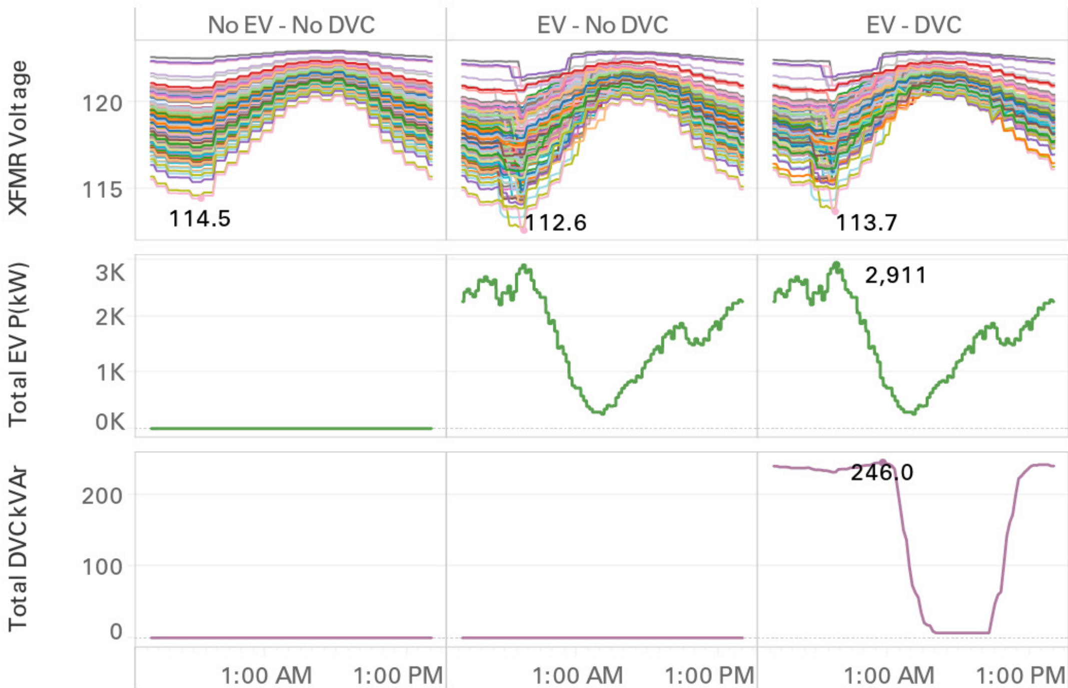

Fig. 10: Service transformers secondary voltages, EV charging profile, and DVCs kVAr injection, for urban feeder

As shown in the figure, 34% additional peak demand from EV chargers decrease the minimum voltage to 112.6V. 25 DVCs are placed at EV locations with the lowest voltages to boosts the minimum voltage up to 113.7V. This example enlightens the effect of network impedance on the voltage improvement made by the DVCs. As mentioned earlier, although the short network and large-sized transformers prevent an severe voltage drop, they require more grid-edge DVCs to achieve the same performance. A summary of all the above scenarios and the results are highlighted in table I.

Scenario #	1	2	3	4
Feeder Type	Rural	Rural	Rural	Urban
Original Peak Load (kW)	2720	2720	2720	8680
Feeder Max. Distance (Miles)	9.84	9.84	9.84	3.58
EV Charger Type	Residential	Commercial	Fleet	Res. & Com.
# of EVs	120	1	1	100 + 1
EV Location	Distributed	Downstream	Downstream	Distributed/Middle
EV Peak Demand	830	1350	1350	2911
# of DVCs	25	24	14	25
# of 600 kVAr Cap Bank	1	1	2	0
Min. Voltage				
No EV - No DVC	114.4	114.4	114.4	114.5
EV - No DVC	108.5	109.9	109.3	112.6
EV - DVC	114.0	114.1	114.3	113.7
Max. V Unbalance				
No EV - No DVC	1.14%	1.14%	1 14%	1.19%
EV - No DVC	2.04%	1.78%	1 71%	1.43%
EV - DVC	0.93%	0.78%	1.18%	1.26%

TABLE I: Summary of Results of All Scenarios

IV. CONCLUSION

Growing integration of EV charging infrastructure across the legacy distribution networks may cause several adverse impacts, including under-voltage issues at the customers' locations. In this paper, the under-voltage issue at the secondary side of the service transformer has been investigated in various scenarios, including residential and commercial EVs as well as rural and urban distribution networks. To mitigate the the system impacts caused by vast EV charging infrastructure integration, DVC are proposed as a cost-effective, non-wires alternative and distributed control mechanism.

The simulation results have shown a significant improvement in minimum voltage of the system in every scenario. Dynamic Volt-VAr control at the edge of the gird, using singlephase DVCs also contributes to reducing system voltage unbalance condition. The DVC can operate autonomously or fully integrated with a ADMS SCADA system. This approach is a cost-effective alternative to costly power system infrastructure investments and other voltage control devices.

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