Integration of PEVs and PV-DG in Power Distribution Systems using Distributed Energy Storage – Dynamic Analyses

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Abstract— **growing numbers of utilities are experiencing proliferation of Plug-in Electric Vehicles (PEV) and Photovoltaic Distributed Generation (PV-DG) in their distribution systems. Charging patterns of PEVs tend to increase the original day-time and evening peak demands of distribution feeders, while PV-DG units are highly intermittent energy sources. Therefore, the integration of large amount of PEVs and PV-DGs represents a significant challenge for distribution planning and operations. As an emerging technology, Distributed Energy Storage (DES) is a promising alternative to improve the reliability and efficiency of distribution systems. DES serves as an energy buffer to manage demand and supply fluctuations. Through proper control algorithms, DES has the potential to facilitate the integration of both, PEVs and PV-DG units. Previous works have studied the mitigation of steady state impacts of PEVs and PV-DG units by using DES systems. However, this topic has not been fully investigated from a dynamic analysis perspective. This paper discusses the utilization of DES to alleviate dynamic impacts of PEVs and PV-DG units on power distribution systems. This alternative is analyzed by using models of PV-DGs, PEV and DES developed in PSCAD. Results of dynamic simulations, including voltage profiles at critical points on a test distribution feeder and operations of Load Tap Changer (LTC) are presented and discussed. Simulation results show the potential of DES for improving dynamic performance of distribution feeders with PEVs and PV-DGs proliferation.**

Index Terms— **Plug-in Electric Vehicle (PEV), Photovoltaic Distributed Generation (PV-DG), Distributed Energy Storage (DG), distribution systems, dynamic analyses**

I. INTRODUCTION

The utility industry is experiencing proliferation of Photovoltaic Distributed Generation (PV-DG) largely interconnected to medium and low voltage distribution lines. Similarly, incipient proliferation of Plug-in Electric Vehicles (PEVs) is starting to occur in large metropolitan areas. Most distribution systems were not originally designed to manage this type of Distributed Energy Resources (DER), hence there are growing concerns regarding impacts of these technologies in distribution operations and planning aspects, including voltage regulation and control, equipment loading, power quality, efficiency, etc. These concerns have prompted interest in quantifying impacts and identifying solutions to alleviate these issues and ensure seamless integration.

In the specific case of PV-DG integration, the subject was discussed sporadically in the early 80s [1]-[3], and it was not until the last decade that it received widespread attention [4]-[14]. In the case of PEV, early studies conducted in the 90s identified a series of expected impacts [15], [16], which have been discussed in more detail in recent publications [17]-[23]. Furthermore, a variety of mitigation measures have been discussed in the literature, including alleviating impacts using feeder components (e.g., voltage regulators), settings of PV-DG plants (e.g., reactive power absorption), and more recently utilizing Distributed Energy Storage (DES) [24]-[27]. In most cases the proposed approaches have considered proliferation of PV-DG or propagation of PEVs separately, and only a few studies have considered the interaction of both technologies. Similarly, the large majority of studies have focused on quantifying and alleviating impacts from a steady state perspective. More recently the scope has broadened to include impacts and solutions from a dynamic/transient standpoint. However, there is still a need to investigate impacts due to interaction of both technologies and potential solutions to these problems from a dynamic viewpoint.

This paper proposes to perform dynamic analysis to study the integration of PV-DG and PEV units in distribution systems by using a DES system. First, PV-DG intermittency and PEV random in-and-out are simulated for a test distribution feeder. Then, feeder demand and voltage fluctuations as well as substation transformer LTC operations are examined under two scenarios, 1) base case (without DES), and 2) mitigation case (with DES). Finally, results for both scenarios are compared to assess how DES alleviates dynamic impacts of PV-DG and PEVs, improves system performance, and facilitates integration. The rest of the paper is organized as follows: Section II describes the dynamic modeling of PV-DG, PEV and DES; Section III describes the case study and DES control strategy; Section IV presents the simulation results and analysis; and Section V summarizes the main findings and conclusions of the paper.

II. MODELING OF PV-DG, PEV AND DES

This section discusses the modeling aspects of PV-DG, PEV fleet and DES systems.

A. Model Development for PV-DG

Several PV-DG models with different levels of complexity have been proposed in the specialized literature for a variety of studies [28]-[32]. For instance, Gow and Manning [28] presented a circuit-based simulation model for a PV cell in

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order to allow the interaction between a proposed converter and a PV array. This specific model was designed to be of used by power electronics specialists. Park and Yu [29] proposed a real-time simulation method for PV generation systems under real weather conditions using a real-time digital simulator (RTDS). Tan et.al [30] proposed a PV generation model built on the basis of experimental results, the model is suitable for studying interactions with power systems. Campbell [31] proposed a piecewise linear PV model for dynamic and transient power system studies. Simões et.al [32] presented results of electric model development and validation for PV cells.

In the dynamic study conducted in this paper, one of the key aspects for investigation is the impact due to fast intermittency of PV-DG output. Therefore, a time-series irradiance profile based on actual one-second solar radiation measurements was adopted (Figure 1). Here, intermediate data points were determined through linear interpolation. The selected profile represents different ranges of power fluctuations due to variable cloud alternation and shading effect.

An "acceleration" method was used to capture PV generation impacts on the test feeder over a 60 minute actual time frame (60 second simulation period). The data points were entered to the model every 1/60 seconds, hence, a simulation time of 1 second represents an actual time of 1 minute. This way, an "accelerated" 60 second simulation time frame replicates the effect of solar variations over a 60 minute period. Moreover, delay times of distribution equipment (LTC, capacitor banks, and voltage regulators) were adjusted accordingly to study the effect of voltage fluctuations on tap positions and status of voltage-controlled capacitor banks. Since the maximum outputs of PV-DG units (and the most significant impacts on the distribution system) are expected to occur around noon, the intermittent profile of Figure 1 is used to represent PV-DG output between 1 PM and 2 PM. In this study, solar radiation is considered to be zero for the first 5 seconds of the simulation to create initial conditions for analysis, and then the PV profile is used for 60 seconds (65 seconds in total) for simulation and analysis.

B. *Model Development for PEV Fleet*

There are numerous proposals for PEV charging modeling published in the specialized literature. For instance, Zoroofi [33] presents methods to model Lead-acid and Lithium-ion batteries in electric (PEV) and hybrid (PHEV) vehicles, including tests to find internal battery parameters. Kroeze and Krein [34] present a PEV battery model specifically for utilization in dynamic studies. In long term steady state studies PEV fleet charging is usually modeled as an aggregation of random charging behavior. For instance, ORNL [35], NREL [36] and EPRI [37] have all developed different PEV charging profiles based on the driving distance and plug-in time.

In this paper, the opportunity charging profile used in [36] was selected for the simulations (Figure 2). Moreover, the PEV charging profile between 1 PM and 2 PM was assumed to fluctuate randomly between the lowest and highest level with a 10-minute resolution. The profile was normalized to be scalable by the PEV units in the fleet. The basic individual PEV charging profile is shown in Figure 3.

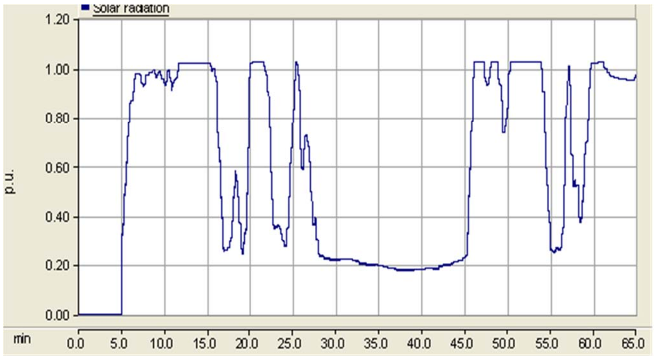

Fig. 1. Solar irradiance profile used in the simulation model

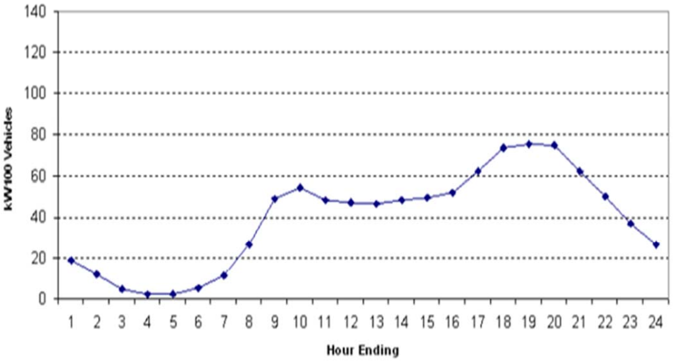

Fig.2 PEV fleet opportunity charging profile [36]

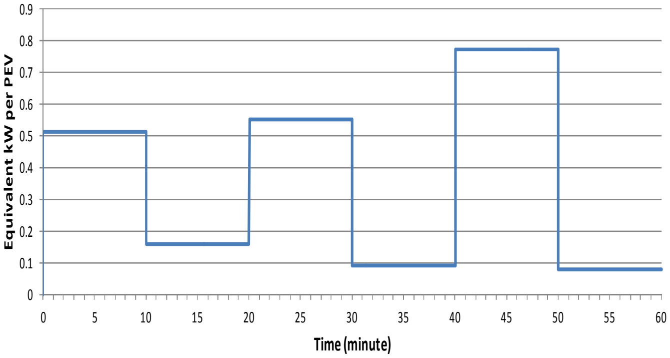

Fig. 3. Basic PEV fleet charging profile (scalable)

C. *Model Development for DES*

Battery model selection is a key aspect for DES modeling and simulation. Divya and Østergaard [38] review battery energy system storage models for economic and power system stability studies. Chung et.al. [39] present a sodium sulfur (NAS) battery model that can be used in simulation studies of Battery Energy Storage Systems (BESS). Since different types of DER are often utilized together to maximize benefits (e.g., PV-DG and BESS), many researchers have studied the modeling of more than one type of DER. For instance, Kim et.al. [40] modeled a hybrid generation system that includes BESS, wind and PV generation. Similarly, Ma [41] modeled a PV and DES system, and Kim et.al. [42] presented results of dynamic modeling and control of hybrid generation systems consisting of wind, PV and battery units.

In this paper, the DES unit is modeled as a controlled active power source with power electronics interface, connected to the distribution system via a dedicated interconnection transformer. The proposed DES control strategy is as follows: 1) the DES unit starts charging when PV-DG output exceeds 62% of rated capacity; 2) the DES starts discharging (injecting active AC power) when PV-DG output is below 30% of rated capacity. In the latter case DES active power injection is equal to 30% of rated capacity. The state of charge (SOC) of the DES is limited within 10% and 90% and the DES started at 90% SOC.

III. CASE STUDY DESCRIPTION

Figure 4 shows the simplified one line diagram of the test 12.47 kV feeder used in this study. This feeder has a peak demand of 5.8 MW and six main branches that for simplicity were modeled as lumped loads. Moreover, the feeders connected to the same substation bus were modeled as a lumped load (adjacent feeders). The substation transformer LTC has a typical regulation range of ±10% (32 steps).

The authors decided to limit the scope of this initial study to using DES for integration of clustered PV-DG and PEV. Hence, potential interaction effects between DERs spread along the feeder are not included in this initial investigation. The cluster under analysis is located in the feeder branch shown in Figure 4. This branch has about 1,000 customers and peak demand of about 2.5 MW (0.9 lagging power factor). The penetration levels of PV-DG and PEV are assumed to be 50% and 20%, respectively. Since the average number of cars in a household is roughly 2 [43], the 1,000 customers in this feeder branch will have about 2,000 cars, 400 of which are assumed to be PEVs. The individual PV-DG output and PEV demands are scaled according to the profiles and descriptions presented in Section II.

Two scenarios were studied: 1) base scenario, it only includes PV-DGs and PEVs units in the branch, no DES is used; 2) mitigation scenario, a DES system (1.0MWh/1.0MW peak power) was added to the branch point of interconnection (POI) and operated according to the control strategy described in Section II to alleviate impacts due to PV-DG and PEV proliferation.

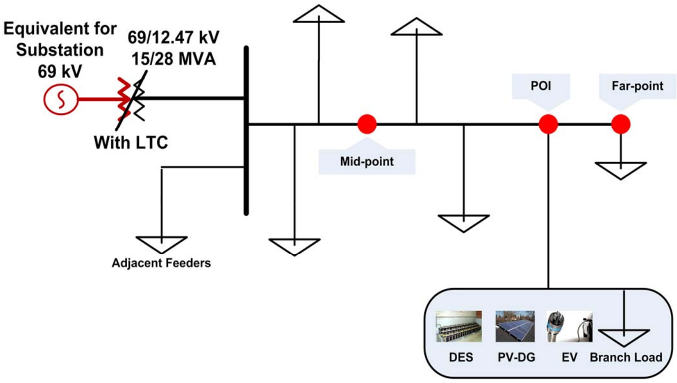

Fig. 4. Simplified one-line diagram of the study feeder and observation points

Figure 5 shows the detailed feeder model built in PSCAD. During the simulations voltage and power flow values were monitored at the following observation points: feeder breaker, feeder mid-point, POI, and feeder end (far point). Simulation results are presented in Section IV.

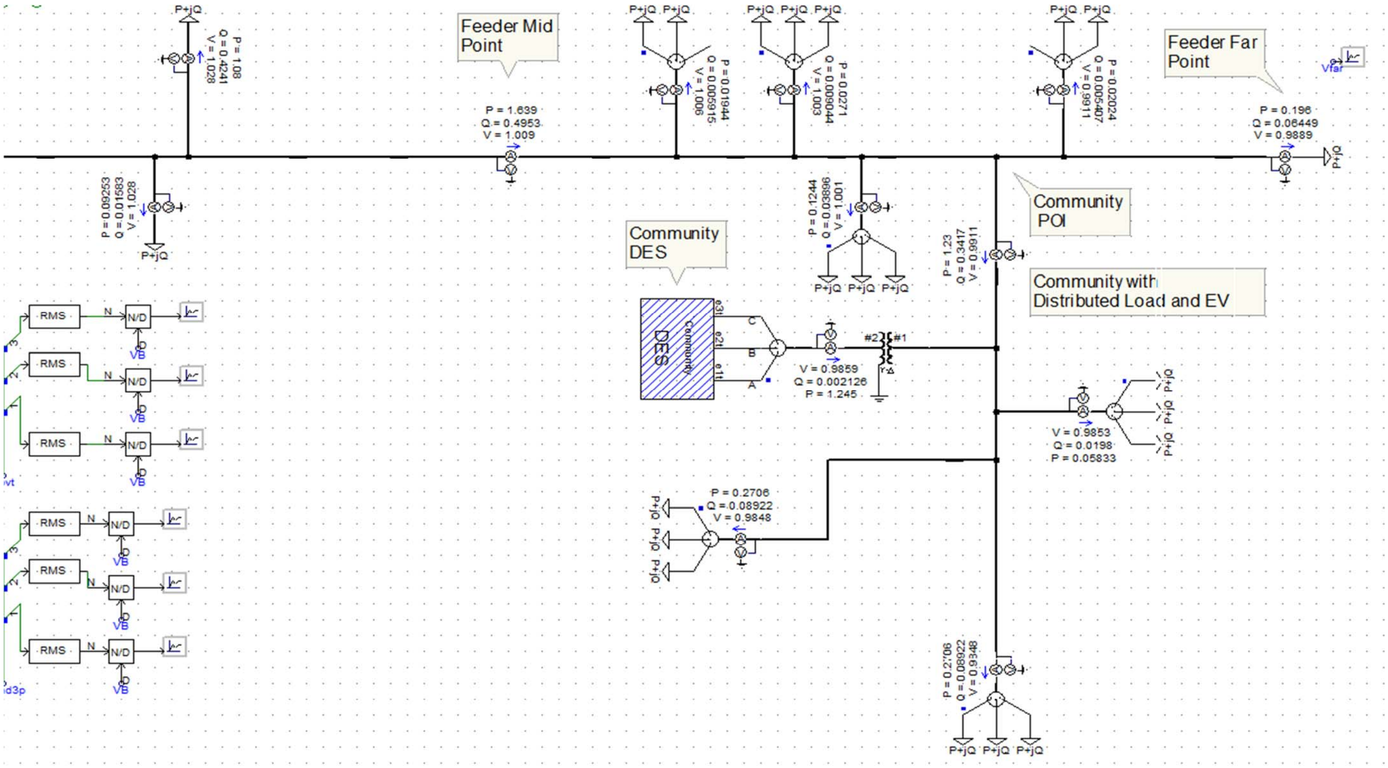

Fig.5 Detailed model of distribution system under analysis

IV. CASE STUDY SIMULATION RESULTS

This section compares simulation results for base and mitigation scenarios, and discusses the benefits of using DES for PV-DG and PEV integration.

Figure 6 shows power flow, voltage, and LTC operation results for the base scenario (without DES). Figure 7 shows the same results (power flow, voltage and LTC operation) for the mitigation scenario (with DES).

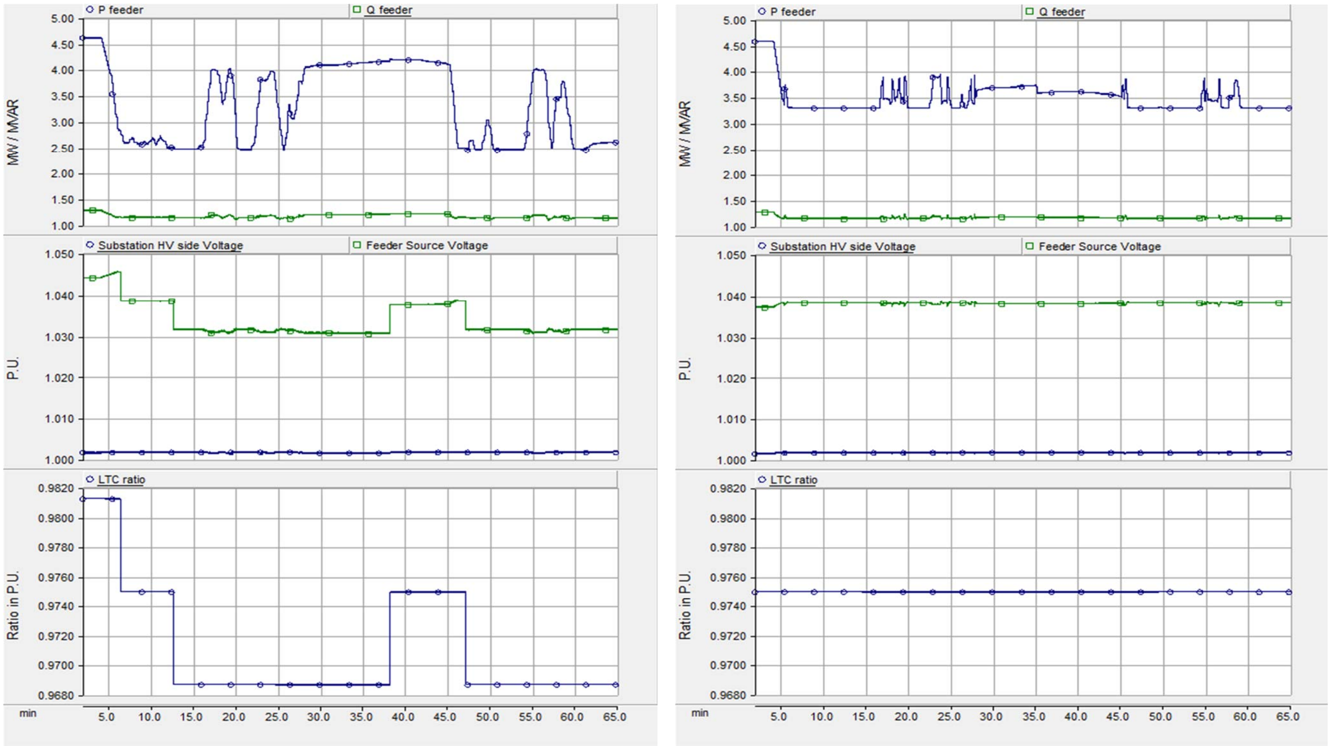

Fig.6. Results for base (left) and mitigation (right) scenarios: (a) feeder power flows (P & Q); (b) substation high and low side voltages; (c) LTC tap position

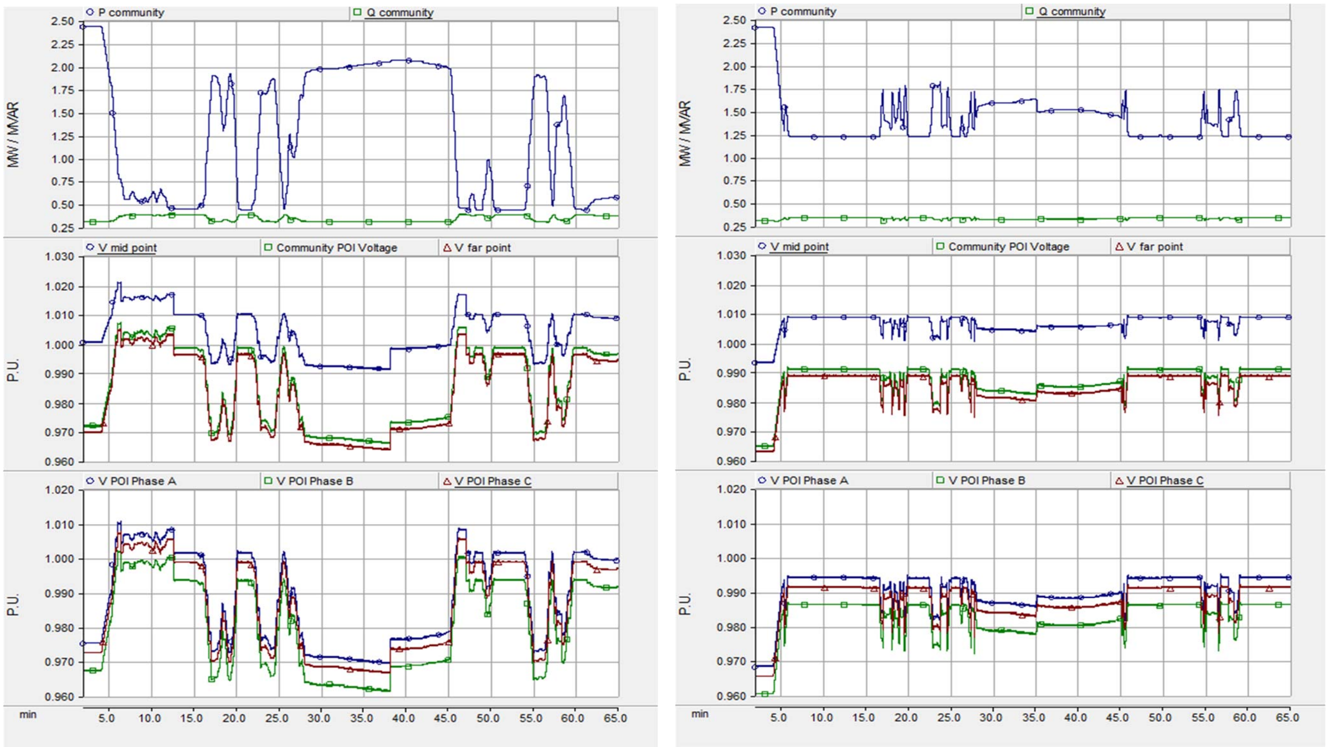

Fig.7 Results for base (left) and mitigation (right) scenarios: (a) power flows (P & Q) at POI; (b) voltages at midpoint, POI, and feeder end; (c) three-phase voltages at POI

Expectedly, base scenario results of Figure 6 show that the feeder power flow fluctuates due to both PV-DG output intermittency (Fig. 1) and PEV charging profile randomness (Fig. 3). This also leads to LTC tap operations, since the LTC tries to keep feeder voltage within the limits defined by its reference voltage and bandwidth (the LTC operates 4 times in 60 minutes). Moreover, voltage fluctuations increase in magnitude for points located farther from the substation (feeder mid-point, POI and feeder end). The results show that voltage is expected to rise when PV-DG output is high and drop when PV-DG output is low. Additionally, LTC tap changes will cause sudden voltage rise or drop on top of that.

Figure 7 shows the simulation results for the mitigation scenario with DES installed at the branch POI. The results show obvious improvements, feeder and branch demands are smoothed. At the same time, there is no LTC operation needed during the 60 minute simulation period, since PV-DG output and PEV in-and-out fluctuations are compensated locally by the DES unit. Hence, voltage fluctuations are confined to a smaller range than that observed in the base scenario.

Table I shows a summary of the simulation results. Moreover, Figure 8 shows a statistical comparison of feeder voltages for both scenarios using a box-and-whisker plot. The plot shows minimum, median, maximum, and first and third quartiles for the voltages shown in Figure 6b and Figure 7b. The summary and the comparison show clearly that DES can reduce the voltage fluctuation range and LTC operations due to PV-DG output intermittency and PEV random in-and-out.

Table I - Summary of simulation results

Scenario	**Max/min voltage (PU) at observation points**				**# of LTC operations**
	Feeder	**Midpoint**	**POI**	**Feeder end**	
without DES	1.046 1.030	1.020 0.990	1.008 0.965	1.005 0.963	4
with DES	1.038 1.036	1.010 1.002	0.993 0.980	0.990 0.977	0

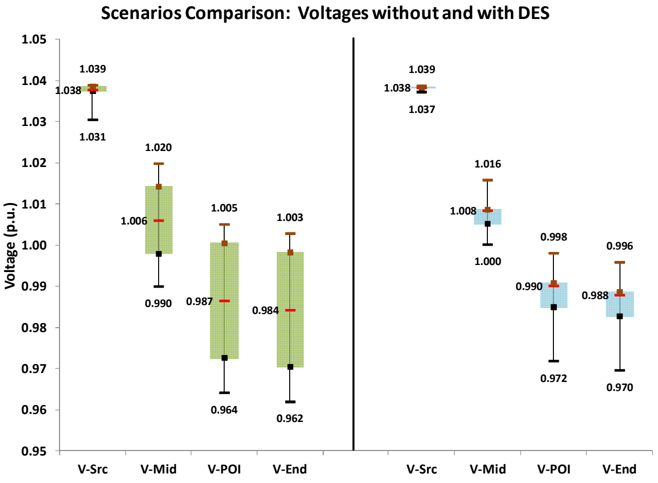

Fig. 8 Statistical analysis of feeder voltages for base and mitigation scenarios (minimum, median and maximum voltages of Figures 6b and 7b)

V. CONCLUSIONS

This paper discussed the utilization of DES for alleviating impacts due to PV-DG and PEV proliferation and facilitating integration in a power distribution system. Dynamic analyses were conducted in PSCAD for a real distribution feeder; moreover, PV-DGs, PEVs and DES were modeled for a 60-minute time frame and 1-minute resolution using an acceleration method. In order to understand the pros and cons of using DES, two scenarios were studied: 1) base scenario with PV-DG and PEV proliferation and no DES, and 2) mitigation scenario with DES. Simulation results for the base scenario showed that voltage fluctuation due to PV-DG output intermittency and PEV in-and-out cause frequent voltage fluctuations and LTC operations during a short time period. Simulation results for the mitigation scenario showed that installing a DES system at the POI shown in Figure 3 can smooth demand fluctuations and mitigate feeder voltage fluctuation, and LTC operations.

The analysis shows that the intrinsic fluctuating characteristics of PV-DG outputs and PEV demands can cause frequent feeder power flow and voltage changes in a short time, particularly for large penetration levels of these technologies. This may result not only on power quality issues and customer complaints but also in much more frequent operations of voltage regulating devices. Simulation results also show the potential of DES to mitigate these impacts by acting as an energy buffer.

This study analyzed clustered proliferation of PV-DG and PEV in a feeder branch. Further analyses are required to study interaction effects between numerous PV-DG, PEV, and DES units spread along a feeder, substation or region. Moreover, additional studies are required to investigate the combined utilization of different mitigation strategies, for instance, using a combination of DES, PV-DG inverters operating at non-unity power factor, and demand response. Finally, more analyses are required to study the behavior of these technologies under transient conditions such as those caused by accidental islanding.

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VII. BIOGRAPHIES

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