Research on Impacts of Distributed versus Centralized Solar Resource on Distribution Network Using Power System Simulation and Solar Now-casting with Sky Imager

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***Abstract* — As solar energy penetration in the power grid increases, utilities face great challenges coping with the variable output of solar power, especially from photovoltaics (PV) panels. In this research, we investigate the impact of distributed versus centralized solar resource on distribution network using power system simulation and solar now-casting with sky imager. The distribution network studied is a large and realistic distribution system in San Diego area modelled by our research team at UCSD and validated against power flow and short circuit data given from a local utility. The network has 1733 customer loads, summing up to 11.1 MW demand, and 2.3 MW PV in peak power production. Special scenarios are set up to simulate the difference between distributed and centralized solar resource with PV penetration levels (defined as max PV power output divided by max load demand) from 0 to 100%. OpenDSS is used for quasi steady-state simulations of the network on a partly cloudy day (December 12th, 2012). Solar now-casting using UCSD Sky Imaging (USI) system is utilized to provide unique PV production curves for all PV systems on the network. The impacts of solar resource including voltage level, line losses, power consumption and number of tap operations are reported for each investigated case and. It is shown that centralized configuration is much more severely impacted by high PV penetration than distributed set up in terms of high voltage level, increasing number of tap operations, and reverse power flow.**

***Index Terms* —distribution network, simulation, solar forecasting, sky imager, PV impact.**

I. Introduction

A common concern with renewable resources is the effect of weather on power production. For systems with natural resource storage, such as large hydroelectric plants, this concern is for time scales of weeks and months. For PV, the concerns and effects are for much shorter timeframes due to intermittent disturbances. While it is possible to forecast weather with reasonable accuracy and predict average power production across a region quite accurately, clouds can cause sudden disturbances in wind and PV production. For solar PV interconnected at the distribution feeder level, this can have a sudden and significant effect on power supply and power quality on the feeder. Although there is significant interest in the potential issues of high PV penetration [1, 2], there is a lack of a method to do in-depth investigation of the impacts of high variable solar resource on distribution network depending on the distribution (distributed versus centralized setup) of the resource. In this paper, we proposed a unique approach to provide such an in-depth investigation using (1) high temporal and spatial resolution of PV generation profiles using solar resource assessment with a sky imager, (2) distribution power simulation using OpenDSS and (3) realistic and topology-diverse distribution models created from data provided by a host utility in the U.S. The simulations results are presented and conclusions are made based on them.

II. Solar forecasting using sky imager

The basic steps of solar forecasting using sky imager include cloud detection, cloud height determination, cloud velocity calculation, cloud advection, projection of clouds to the ground, global irradiance calculation, and power output determination. At the end of the process, we obtain individual power output profiles with high temporal and spatial resolution for all PV systems on site. More detail on solar forecasting using sky imagers can be found in our previous works [3, 4]. A partly cloudy day, the worse situation with high variability in solar resource, on Dec 12th, 2012 is used in this research.

III. Distribution system modelling using OpenDSS

System information for the investigated distribution feeder in SynerGEE software was provided by the host utility, including: (1) network topology: information on buses, equipment settings, and the equipment connected to the buses, (2) equipment characteristics: specifications of capacitors, voltage regulators, and other utility equipment, and (3) the locations and characteristics of the loads. This information was used to generate an equivalent distribution model in OpenDSS. The topology of the feeder along with its existing solar resource is shown in Fig. 2. The substation is at the bottom right corner of the network. Short circuit currents and power flow results from SynerGEE simulations were provided and used as a benchmark to validate our OpenDSS model. Distribution system simulation with this model is done by solving the power flow equations using OpenDSS.

Fig. 1 shows the voltage level of all buses along the feeder at max load demand when solar resource is not present. Due to the long feeder and large load, there is large drop in voltage along the feeder. There are also differences in voltage levels between the 3 phases due to the load imbalance.

TABLE I

SIMULATION RESULTS FOR THE TWO INVESTIGATED CONFIGURATIONS: CENTRALIZED VS. DISTRIBUTED SOLAR RESOURCE

Section	Centralized Solar Configuration (S1) PV penetration levels					Distributed Solar Configuration (S2) PV penetration levels				
	0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
# Tap operations [-]	376	916	1318	1530	1618	376	478	666	828	1052
Max voltage [p.u.]	1.0311	1.0368	1.0671	1.1095	1.1462	1.0311	1.0311	1.0311	1.0357	1.0420
Min voltage [p.u.]	0.9103	0.9103	0.9103	0.9103	0.9103	0.9103	0.9103	0.9103	0.9103	0.9103
Line losses [MVA]	1.7421	1.5812	1.5494	1.6465	1.8335	1.7421	1.6519	1.5815	1.5297	1.4846
Power cons. [MWh]	16.013	15.078	14.255	13.559	12.951	16.013	15.285	14.571	13.870	13.174

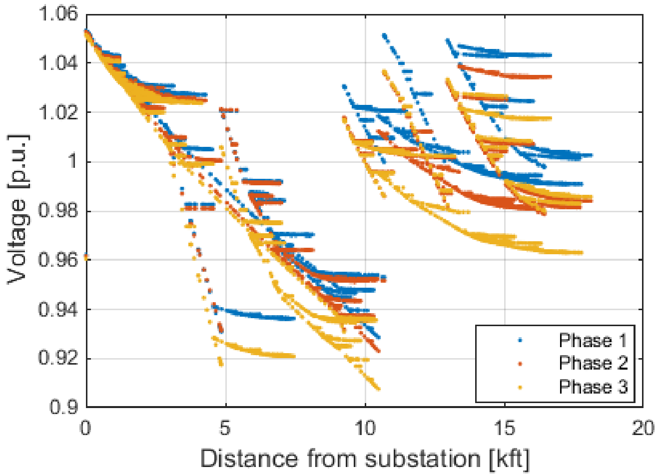

Fig. 1. Voltage profile from OpenDSS simulation along the investigated feeder at max load demand when solar resource is not present.

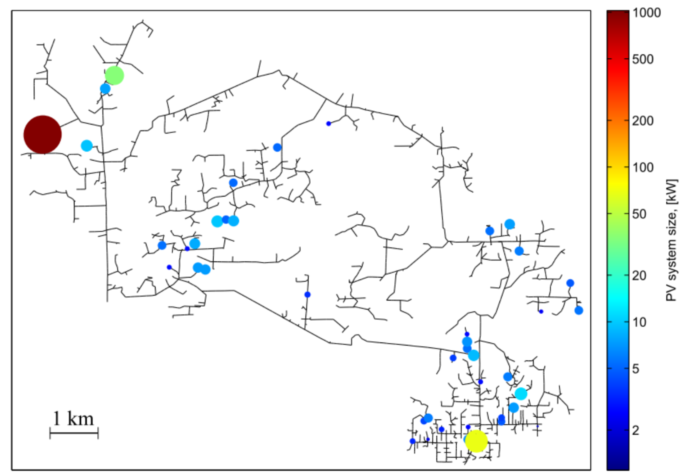

Fig. 2. Topology of the investigated feeder with 11MW load and 2.3MW PV. This is used as centralized configuration.

IV. SUMMARY OF SIMULATED SCENARIOS

To investigate the impact of large, centralized PV versus many small, distributed PV systems at the same PV penetration level, two configurations were set up Feeder A at 20.6% PV penetration level: (1) the centralized setup S1 (Fig. 2) mimicking the existing configuration consists of the 2-MW PV site, amounting to 87% of total PV generation, and 43 small distributed PV systems, amounting to 296 kW; and (2) a distributed setup S2 with 430 small PV systems (Fig. 3) totaling 2.3 MW PV. To achieve other PV penetration levels (0, 25, 50, 75 and 100%), the PV systems' power output on both configurations are scaled appropriately. As a result 10 different scenarios were simulated.

IV. RESULTS AND ANALYSIS

Table I shows the results of these simulations. The investigated impacts are number of tap operations of transformers and voltage regulators, maximum and minimum voltage during the day, line and total losses, and power consumption. Some interesting conclusions can be made from Table I as follow:

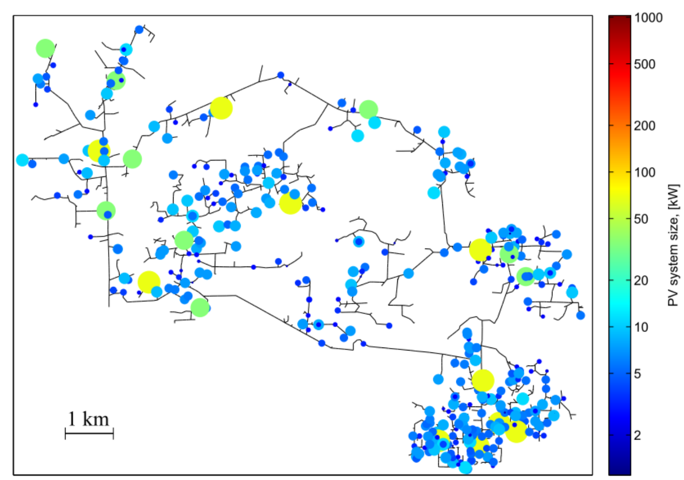

Fig. 3. The distributed configuration of the investigated feeder with 430 small PV systems.

- **Voltage range:** It can be seen from Table I and Fig. 4 that the centralized configuration was affected heavily (V_{max} going from 1.0311 to 1.1462 p.u., which is out of regular desired voltage range) as increasing PV penetration while the same impact is insignificant in the distributed configuration.

- **Number of tap operations:** In both configurations, the number of tap operations increases significantly as increasing PV penetration but the level of increase is much larger in the centralized case (Fig. 5). This increases the wear and tear and shortens the lifetime of the equipments.
- **Total daily line loss reduction:** In S2, as increasing PV penetration providing power to local loads, the daily line losses decreases (or the line loss reduction increases) as a monotonic function (Fig. 6). However, in S1, at first, the losses decrease then increases again as PV level becomes higher than 50%. This is due to the reverse power flow on the branch that the big 2MW PV is located. The reverse power flow is neglegible or non-existent in S1 as solar resource is more evenly distributed in all branches of the feeder.

V. Conclusion

In this paper, we presented a quantitative and rigorous method to investigate the impacts of solar resource on distribution network based on their distribution using solar now-casting with sky imager, a realistic distribution model and power system simulation using OpenDSS. It was shown in Section IV that the distribution of solar resource (distributed vs. centralized) has significant impacts on the ability to host high PV penetration of the distribution network. Configuration with centralized solar resource is significantly affected by high PV penetration. This is demonstrated in significant increase in number of tap operations (400% in comparison with 250% as in centralized case), high max voltage observed during the day, and reverse power flow. Our future work will focus on designing control schemes to mitigate these issues using the PV inverters and/ or energy storage systems.

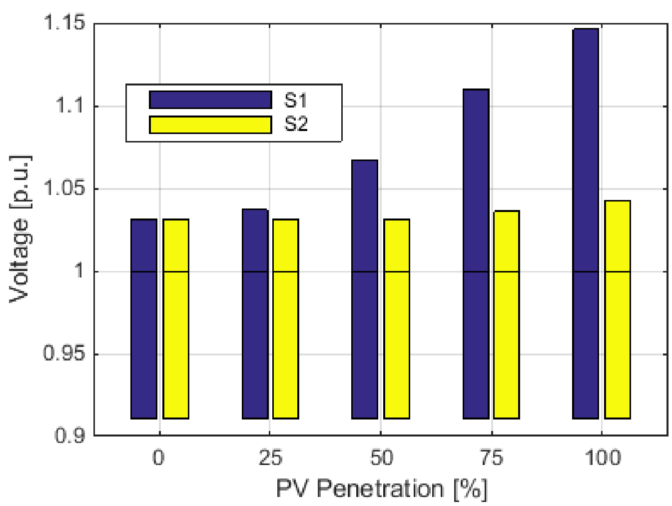

Fig. 4. Voltage range at different PV penetration levels of the centralized (S1) and distributed (S2) configurations.

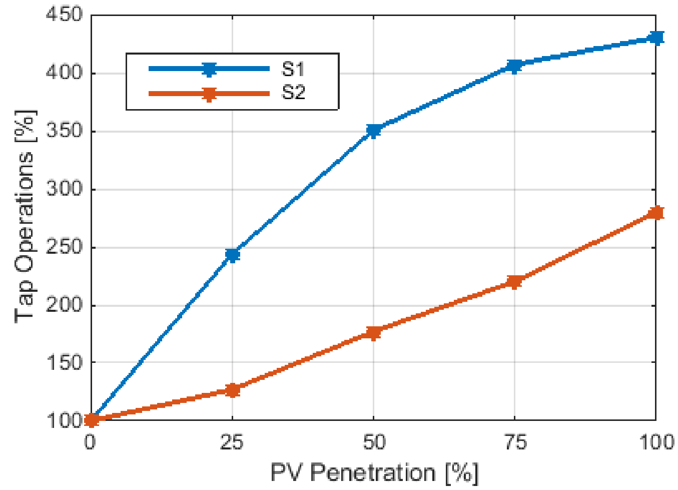

Fig. 5. The percentage change in number of tap operations of the two investigated configurations at different PV penetration levels in comparison to the base case of 0% PV penetration.

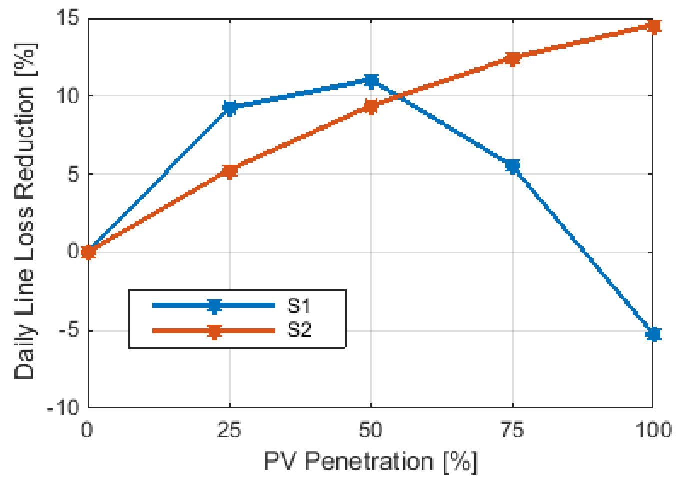

Fig. 6. Daily line loss reduction of the two investigated configurations at different PV penetration levels in comparison to the base case of 0% PV penetration.

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