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Increasing Feeder PV Hosting Capacity by Regulating Secondary Circuit Voltages

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***Abstract*—Voltage rise is one of the major concerns that limits the photovoltaic (PV) hosting capacity or the maximum amount of PV generation that a distribution circuit can accommodate. This paper examines the effectiveness of low-voltage distribution static compensators (LV-DSTATCOMs) in increasing the PV hosting capacity of distribution circuits by mitigating voltage rise. Stochastic analysis framework is used to determine the PV hosting capacity while an iterative placement technique is used to identify effective device locations. To provide insights on the optimal device size, number, and control settings, sensitivity analysis is carried out. The results show that, with appropriate size and control settings, installation of few LV-DSTATCOMs in a distribution circuit can significantly increase its PV hosting capacity. For the circuit under consideration, a set of 23 devices has increased the PV hosting capacity from 15% to 100% of the median day time peak load.**

***Index Terms*—Distribution circuit, DSTATCOM, FACTS device, Overvoltage, Photovoltaics.**

I. INTRODUCTION

High amounts of residential PVs are being integrated in distribution grids. Some of the states in the US such as California, Hawaii and Arizona have experienced significantly high PV penetrations. Studies and observations in these areas have shown that quite often increased penetration of PV generation results in high voltage levels across distribution system, also known as overvoltage condition [1], [2]. Given that ANSI C84.1 standard recommends a maximum operating voltage of 1.05 p.u across the distribution circuit, it results that overvoltage condition is often the limiting factor in the maximum PV penetration levels.

Traditionally, distribution utilities rely on equipments such as load tap changers (LTC), line voltage regulators, and fixed or switched capacitor banks installed on the primary circuit to regulate the load voltages. However, these electromechanical devices are inadequate to regulate the service voltages on the secondary circuits within the ANSI limits, especially when high levels of PV generations are present [3]. To meet the voltage regulation challenges effectively, various advanced secondary-side voltage control devices have emerged [3]. These are essentially the low-voltage implementations of the flexible ac transmission system (FACTS) devices that are installed in high-voltage transmission systems.

The advanced voltage control devices or low-voltage FACTS devices are designed to be installed on the secondary distribution circuit, i.e., the secondary of the service transformer. They are available in sizes up to 50 kVA and are designed to operate at 240 V. One of these devices functions like a static var compensator (SVC) [4], [5] by supplying the required amount of capacitive reactive power to regulate the voltage at its terminals to a preset voltage setpoint. With an architecture similar to that of a unified power flow controller, another low-voltage FACTS device [6], [7] can perform both voltage regulation and power factor correction. The PV smart inverter can also help regulate the secondary circuit voltages in the distribution grid through reactive power control. But the reactive power support from the inverter requires the overrating of the inverter or the PV real power output curtailment. Additionally, it is not practical to expect all customer PV installations have smart inverter functionality.

Motivated by the applications of the low-voltage FACTS devices, this study investigates the application of low-voltage distribution static compensators (LV-DSTATCOMs) in increasing the PV hosting capacity of distribution circuits. The LV-DSTATCOM is a shunt-connected device that can inject or absorb reactive power as needed to regulate the voltage at its terminals. The controlled reactive power absorption can help in reducing the overvoltages on the secondary-wire due to high levels of PV generation. Although several studies reported the benefits of voltage regulation by secondary-side voltage control [6], [7], they have not focused on increasing the PV hosting capacity. In this paper, the effectiveness of LV-DSTATCOMs in increasing the PV hosting capacity of distribution circuits is addressed. One of the test distribution circuits developed by EPRI, namely Circuit 24, is used for this study [8]. The circuit's PV hosting capacity is determined using a stochastic analysis framework. The LV-DSTATCOMs are deployed at strategic locations using an iterative placement technique. The results show that the LV-DSTATCOMs are very effective in increasing the PV hosting capacity of distribution circuits. In particular, installation of 23 devices removed overvoltage violations from 1517 loads to increase the PV hosting capacity of the studied circuit from 15% to 100% of the median day time peak load of 16.88 MW. Furthermore, the sensitivity analysis shows that a reduced number of LV-DSTATCOMs are needed to achieve the desired PV hosting capacity level when the devices of higher rating are operated with a lower voltage setpoint.

II. PV HOSTING ANALYSIS FRAMEWORK

A stochastic analysis framework is used to evaluate the impacts of PV systems on the distribution circuits. The framework developed in [9], [10] simulates and examines a large variation of PV deployment scenarios. The analysis estimates the PV penetration level (in kW) likely to cause overvoltage in the distribution circuit. The steps used to implement the framework are described in the next sections.

A. Create PV Deployment Scenarios

In order to reasonably represent the effects of customer-owned small-scale PV systems, multiple PV deployment scenarios are simulated by associating random variations to both locations and sizes of the PVs connected to the customer loads. The location of customers with PV systems are randomly selected from the pool of customers in the distribution circuit. The size of the PV system at each customer location is chosen from a probability density function obtained from installed PV capacities in California [11].

For a PV deployment scenario, 50 customer penetration levels are simulated by increasing customer penetration from 0% to 100% with 2% steps. The customer penetration defines the percentage of customers equipped with PV systems. A 100% customer penetration indicates that all customers have PV installed and the size of the PV is based on the random allocation from the probability density function. In this paper, 100 such PV deployment scenarios are simulated, resulting in a total of 5000 deployment scenarios. The methodology to systematically simulate PV deployment scenarios is depicted in Fig. 1. Note that each scenario is unique in the order that PVs are deployed.

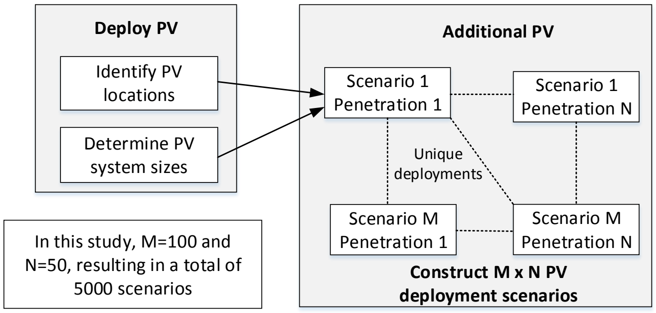

Fig. 1. The stochastic analysis framework.

B. Quantify Feeder Impacts

First, a base case model of the selected distribution feeder is developed. The existing PV systems, if any, are incorporated in the distribution circuit. Loads are modified such that total load demand at the substation is 10 percentile of minimum load measured between 10 am to 2 pm throughout a year. The load value is chosen in order to perform a conservative study in which PV generation is at its peak (10 am to 2 pm) while load is at its minimum. A three-phase load flow analysis is then conducted, and the voltage variations are evaluated for the base case model. The status of the LTC transformers and existing capacitors are fixed, and the corresponding state of the distribution circuit is referred to as the base case in this study.

The load flow analysis is then carried out for each PV deployment scenario for a representative minimum load value. From the load flow results for each scenario, steady state voltage at all load terminals are analyzed. If any load terminal voltage exceeds 1.05 p.u., this is recorded as a violation.

The PV hosting capacity of a distribution feeder is defined as the maximum amount of PV generation that can be integrated without violating overvoltage criteria. From the load flow analysis of all scenarios, the hosting capacity corresponding to the first violation scenario is calculated.

III. PV HOSTING CAPACITY OF CIRCUIT 24

Circuit 24, selected for this study, is an actual 34.5 kV distribution circuit where the longest feeder is 8 miles long [8]. The total primary circuit length is 74 miles to serve 3885 customers (87% residential load). The absolute peak and minimum load demands are 28.67 MW and 6.11 MW, respectively. The representative minimum load value of the circuit is 10.93 MW, which is 10 percentile of the load demand of the circuit between 10 am to 2 pm throughout a year. The median daylight time peak load of the circuit is evaluated to be 16.88 MW.

The PV hosting capacity of the selected feeder is calculated using the stochastic analysis framework described in Section II. The results are presented in Fig. 2. In this analysis, the maximum PV capacity corresponding to 100% customer penetration is 17.43 MW. The overall hosting capacity of the feeder is 2.6 MW, corresponding to 15.5% of the median day time peak load. Even though the voltage class of the feeder is high, the overall hosting capacity of the feeder is low. The reason for the low hosting capacity may be due to the length of the feeders. The presence of single voltage regulation equipment (LTC transformer) at the feeder head is not sufficient to maintain the voltage level across the circuit within acceptable limits.

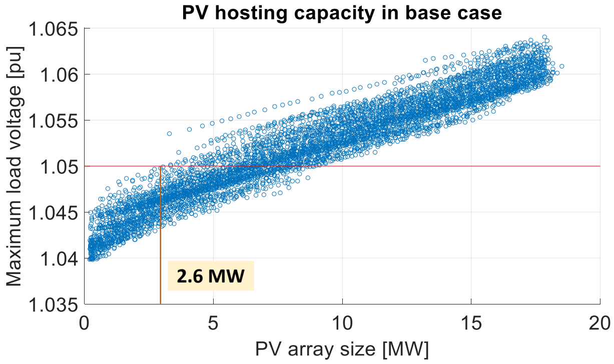

Fig. 2. Maximum voltage recorded on Circuit 24 for 5000 scenarios with varying levels of PV penetration

The geographical distribution of the loads experiencing overvoltages (OV) is shown in Fig. 3. In this figure, the color of the primary buses represents the number of scenarios in which the load connected on the associated secondary node has experienced an overvoltage violation. The loads associated with the primary buses in blue color do not experience overvoltage violations. On the other hand, the loads experiencing overvoltage violations with PV integration are highlighted with different colors. There are 1517 loads experiencing overvoltage violations, and 266 primary buses are associated to these loads. These primary buses are grouped in five clusters as shown in Fig. 3. This paper will demonstrate that installing low-voltage DSTATCOMs in those clusters will help increasing PV hosting capacity by reducing the number of voltage violations.

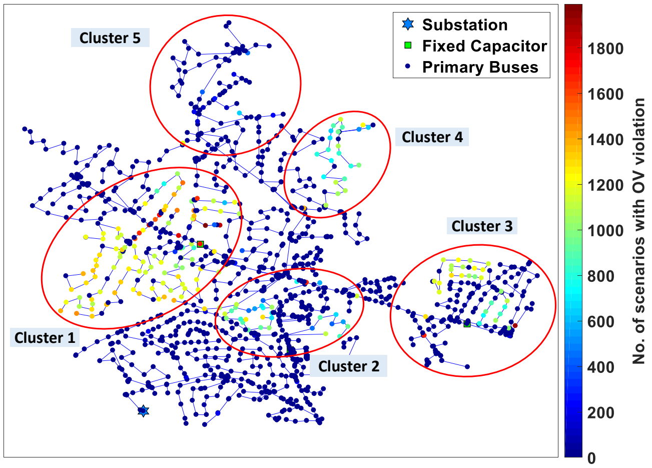

Fig. 3. Distribution of overvoltage violations in Circuit 24.

IV. Low-Voltage DSTATCOM Characteristics

The LV-DSTATCOM is emulated using the voltage controlled generator model available in OpenDSS. The device voltage regulation characteristics can be plotted by connecting a generator object (LV-DSTATCOM) to the service transformer secondary node in a small test circuit as done in [4], [7]. The device, rated for 10 kvar, is set to regulate the service transformer secondary node voltage in the test circuit at 1 pu (240 V) while varying the node voltage. This is to study the ability of the device to regulate the voltage at its terminals. The node voltage without and with the LV-DSTATCOM is plotted as shown in the first graph of Fig. 4. The reactive power injection/absorption by the device is shown in the second graph of Fig. 4. It can be observed that, as the node voltage deviates from the voltage setpoint of 1 pu, the device injects or absorbs the required amount of reactive power up to the maximum power rating to regulate the node voltage at 1 pu. If the node voltage rises above 1 pu, reactive power is absorbed (device behaves like an inductor) to reduce the voltage, and if the node voltage becomes lower than 1 pu, reactive power is injected (like a capacitor) to boost up the voltage.

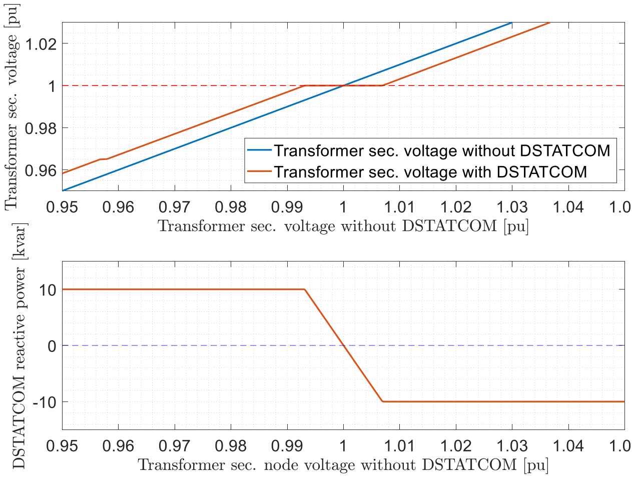

Fig. 4. Low-voltage DSTATCOM voltage regulation characteristics.

V. Device Placement and Increase of PV Hosting Capacity

In this section, the iterative placement technique used for determining the locations of LV-DSTATCOMs is described and the resulting increase in PV hosting capacity is discussed.

A. *Iterative Device Placement Method*

As the LV-DSTATCOMs regulate the node voltage by reactive power control, their reactive power injection/absorption helps regulate the voltages at other secondary nodes in the proximity. Therefore, the selection of the most appropriate locations for the device placement helps achieving the desired PV hosting improvements with a low number of devices. In this work, an iterative placement method, similar to the technique proposed in [7], [12] is used. The steps involved in the iterative device placement method are shown in Fig. 5. PV hosting analysis of the selected distribution circuit is performed for the base case in the first iteration and the load node experiencing overvoltage in the highest number of scenarios is determined. Then an LV-DSTATCOM is placed at the transformer secondary corresponding to that load. In the next iteration, the PV hosting analysis is performed again with the LV-DSTATCOM in service. This process is repeated by placing one device in each iteration while keeping the devices placed in the preceding iterations in service, until there are no overvoltages in the circuit up to the desired PV penetration level.

B. *PV Hosting Capacity Results after Deploying LV-DSTATCOMs*

The effective locations for the LV-DSTATCOMs in Circuit 24 are shown in Fig. 6. Forty devices are placed to increase the PV penetration level to 100% of the median day time peak load without any overvoltage violations at the load terminals. The devices are rated for 10 kvar each, and are configured to regulate the voltage at 240 V (1 pu) at their connection point. Numerous devices are installed in cluster 1 as many loads

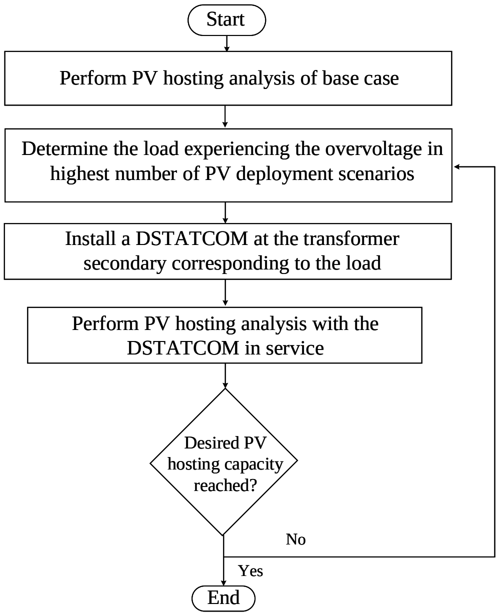

Fig. 5. Iterative device placement method.

in this region are experiencing overvoltages in a very high number of PV deployment scenarios. Few devices are placed in clusters 2, 3, and 5. No device is required in cluster 4 as the reactive power support provided by the LV-DSTATCOMs already deployed can regulate the load voltages in this cluster.

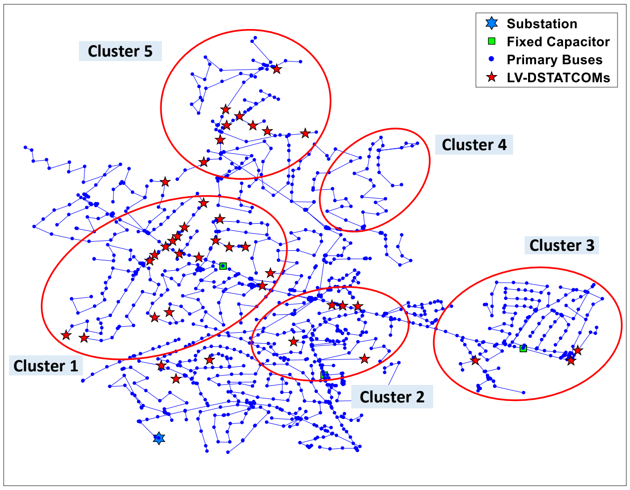

Fig. 6. LV-DSTATCOM locations in Circuit 24.

The PV hosting analysis is performed with 40 LV-DSTATCOMs in the circuit and the results are shown in Fig. 7. It can be observed that none of the PV deployment scenarios have overvoltage violations. The total reactive power output from all devices in all scenarios is shown in Fig. 8. In most of the scenarios having low PV penetration levels, the total reactive power absorbed is less than the total rating of the devices which is -400 kvar (the negative sign represents reactive power absorption). In these scenarios, the devices are absorbing only the required amount of reactive power so as to regulate the voltage at their terminal at the voltage setpoint. As the PV penetration level increases, more reactive power is absorbed by the devices to regulate the node voltages to the given setpoint (1 pu). In almost all scenarios above 10 MW PV penetration level, full capacity of all LV-DSTATCOMs is utilized for voltage regulation.

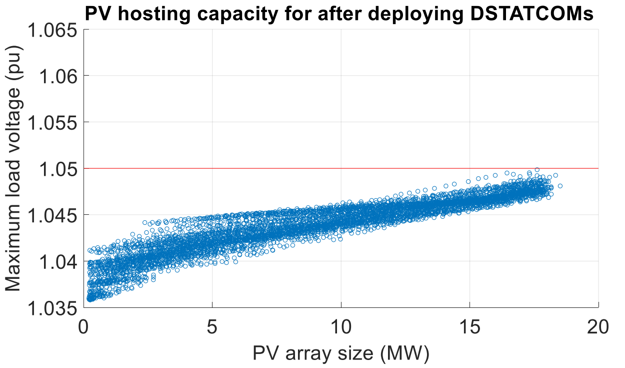

Fig. 7. Maximum load voltage for varying levels of PV penetration, with 40 LV-DSTATCOMs in service.

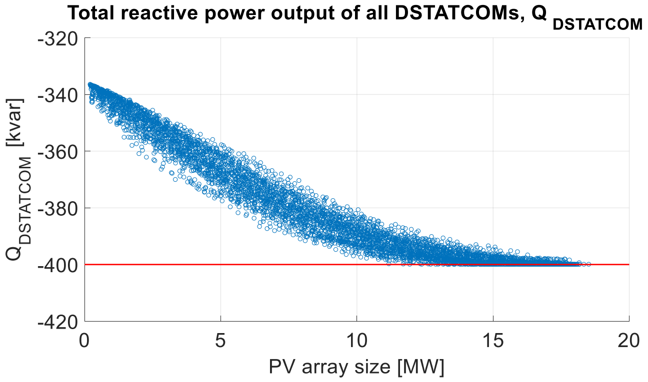

Fig. 8. Total reactive power output of all LV-DSTATCOMs for varying levels of PV penetration.

C. *Sensitivity Analysis*

In this section, results of sensitivity analysis performed with respect to device sizes, voltage setting, and increase in PV hosting capacity are discussed. In Section V-B, a device rating of 10 kvar with a voltage setting of 1 pu is considered. In this section, first the device size is increased in steps of 5 kvar while keeping the same voltage setpoint, the resulting number of devices required to increase PV hosting capacity up to 100% of the median day time peak load is shown in Fig. 9. As the device rating increases, the number of devices that are required to achieve 100% customer penetration decreases, but the number of devices remains constant when the rating reaches 25 kvar. This is because as the rating increases, each device is able to provide more reactive power to regulate the node voltages, thus less devices are required to provide the same level of reactive power support. Upon providing the sufficient number of devices with appropriate sizes at the effective locations, increasing the rating does not impact the number of devices, as increased available reactive power will not be fully utilized.

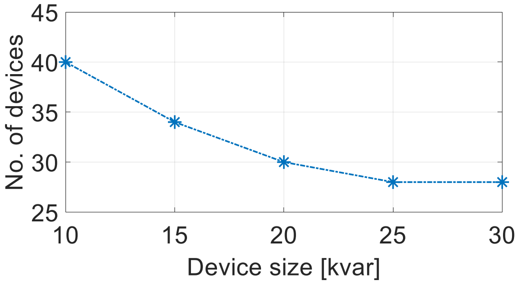

Fig. 9. Number of devices needed as the device rating increases.

The improvement in the PV hosting capacity of the circuit for different LV-DSTATCOM ratings is also analyzed in this work. The PV hosting capacity results when 10 kvar and 25 kvar devices are installed, with 1 pu voltage setpoint, are shown in Fig. 10. It is observed that, when the devices of higher rating (25 kvar) are installed, the PV hosting capacity improves more rapidly compared to the case when the devices of lower rating (10 kvar) are employed. Thus, the desired PV hosting capacity is reached with a low number of devices.

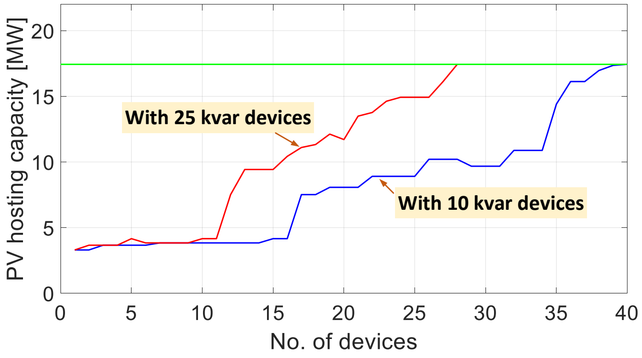

Fig. 10. Comparison of increase in PV hosting capacities.

The next step consists in the following: the device rating is selected as 25 kvar (observed to be the optimal rating for this circuit from Fig. 9) and the devices are installed using the iterative placement method for varying device voltage regulation setpoints. The results are shown in Fig. 11. It is observed that, for lower device voltage regulation setpoints, a lower number of devices is needed to achieve 100% of median day time peak load. This is because as the voltage regulation setpoint is lowered, more inductive reactive power is obtained from the existing LV-DSTATCOMs, and therefore less devices are needed.

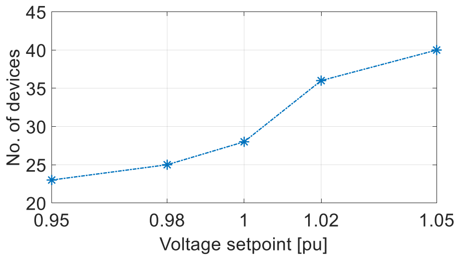

Fig. 11. Number of LV-DSTATCOMs required as the device voltage setpoint varies.

VI. CONCLUSION AND FUTURE WORK

In this paper, application of low-voltage DSTATCOMs to improve the PV hosting capacity of large distribution circuits is proposed. Iterative placement method is used to select the effective locations of these devices. Sensitivity analysis is performed with respect to the device numbers, sizes, and voltage setpoints. The results show that, low-voltage DSTATCOMs are effective in increasing the PV hosting capacity. Furthermore, less devices with higher rating and low voltage setpoints can be used to achieve a desired PV hosting capacity. Future work on this topic will focus on the determination of optimal device size, location and voltage settings.

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