Increasing Renewable Energy Hosting Capacity using a Distribution STATCOM

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***Abstract*—Seasonal and daily mismatches in variable renewable energy (VRE) and loads have led to a wider range of operating voltages on feeders. This has introduced new voltage management challenges for distribution operators. Conventional voltage support devices, such as regulators and capacitors, lack the dynamic capability required to address these challenges. Reconductoring large sections of circuits improves voltage stability but requires substantial resources and may be cost prohibitive.**

A new distribution class STATCOM is evaluated in this paper as a non-wires, cost-effective solution for feeder voltage management challenges. The paper addresses practical challenges to integrating high levels of VRE on distribution circuits, including siting concerns and the unfeasible time or cost required for typical system upgrades. The STATCOM's speed-of-response and maintenance characteristics are compared with conventional regulators and shunt capacitor banks to explain its relative advantage for addressing VRE induced voltage fluctuations. Finally, case studies of observed voltage regulation problems due to VRE are presented to demonstrate the level of mitigation that is possible by adding a distribution STATCOM.

I. INTRODUCTION

Across the globe there is a heightened push toward electrification and the retirement of non-renewable power sources. Economies of scale and aggressive timelines for meeting energy goals naturally incentivize utility scale variable renewable energy (VRE). As of November 2018, the U.S. Energy Information Administration estimates that more than 70% of the utility-scale (1MW or larger) PV sites in the U.S. are rated between 1 MW and 5 MW [1]. Such sites are often proposed to interconnect on rural 15 kV and 25 kV radial distribution circuits since those circuits are prevalent, adjacent to inexpensive land, and offer lower connection costs compared to transmission. As applications for interconnection accumulate, distribution planners are tasked with identifying hosting capacity limits that do not require costly or long lead time upgrades.

The challenges of VRE hosting capacity of distribution feeders have been studied by technical organizations such as the National Renewable Energy Laboratory (NREL) [2] and IEEE [3]. As identified in NREL and IEEE publications, one of the most limiting factors of hosting VRE in distribution is voltage management. Some of the challenges associated with VRE penetration in a distribution feeder are:

- Maintaining a flat voltage profile across the feeder
- Avoiding rapid voltage changes
- Complying with applicable voltage criteria

Conventional voltage support devices, such as regulators and capacitors can help address some of these voltage management challenges, as long as the issues at hand do not require a dynamic response and frequent operations.

If these voltage management challenges can be properly addressed, then not only does the hosting capacity of a feeder improve, but also the following benefits can be realized:

- Reduced regulator and switched capacitor bank operations
- Deferment of large capital projects for voltage management
- Improved conservation voltage reduction (CVR) capabilities

In this paper, case studies are presented to show how a STATCOM solution provides the dynamic voltage regulation needed to address issues introduced by high penetration of VRE. The examples covered are based on experiences in North America, but the same technical concepts should apply to utility scale VRE projects in India and other parts of the world.

In the next section, a representative distribution feeder is reduced to the major items that influence voltage drop in order to demonstrate their relative importance and constraints. In Sections III and IV, case studies from two VRE projects are presented. The paper concludes with key takeaway in Section V.

II. CHARACTERISTICS OF A DISTRIBUTION FEEDER

A radial feeder has seven relevant components shown in Figure 1 that aid in a discussion of hosting capacity and voltage management:

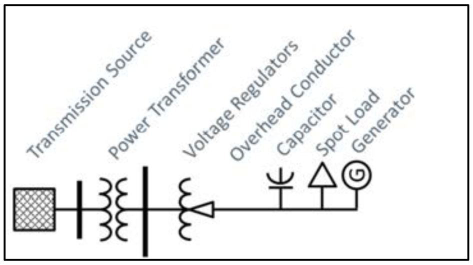

Figure 1. Simplified 25 kV Feeder

The Transmission Source and Power Transformer impedances define the short circuit capability available at the distribution bus. The Overhead Conductor impedance and X/R ratio defines the magnitude of voltage drop or rise that can be induced by a Capacitor, Spot Load, or Generator.

Consider as an example, a 100 KM long 25 kV feeder with 2.5 MVA of load at 92% power factor distributed evenly across its length. The combined load draws approximately 1000 kVAR supplied from the substation bus. The conductor is capable of carrying 385 Amps and has an X1/R1 ratio of 1.26. The Fault MVA (voltage stiffness) is 178 MVA at the substation 25 kV bus but quickly drops off down the feeder as the cumulative conductor impedance increases. Without any mitigation, the voltage profile across the feeder would follow the unacceptable yellow profile shown in Figure 2.

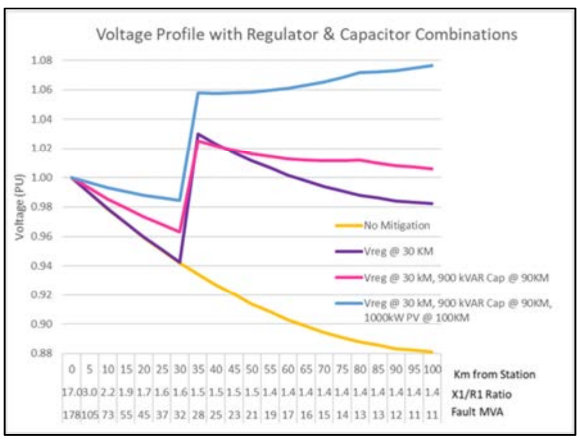

Figure 2. Voltage Profile with Regulator and Capacitor

Trying to address the voltage profile problem with a single voltage regulator, the purple profile in Figure 2, only succeeds in raising the voltages in front of the regulator to an acceptable level. In doing so, the regulator reaches its maximum boost tap.

Addressing the voltage profile problem with a combination of a regulator and a capacitor yields an overall flatter profile across the feeder and the regulator only needs to raise by 12 tap positions. In addition, the average power factor measured at the feeder breaker has been improved to near unity, reducing losses.

The combination of regulator & capacitor, however, presents a problem if a 1 MW VRE is added to the end of the circuit. Variability of the generator will induce unacceptable overvoltages near the end of the circuit before the regulator and capacitor have time to respond as shown in the blue profile in Figure 2.

An alternative would be to replace the 900 kVAR capacitor with a ±1000 kVAR distribution STATCOM capable of ramping its output in less than a second. The STATCOM can provide the same power factor correction as the capacitor when the VRE is at low output but ramp down quickly and even begin to absorb VARs as needed to help maintain a healthy voltage profile on the feeder. The dark blue profile in Figure 3 shows the STATCOM's ability to suppress voltage rise caused by the VRE.

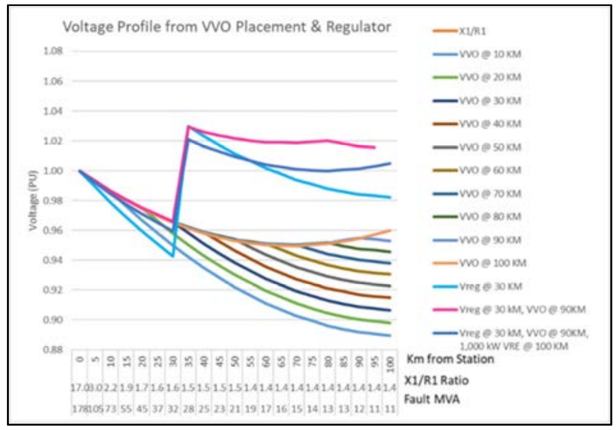

Figure 3. Voltage Profile with VVO and VVO with Regulator

III. CASE STUDY #1: EFFECT OF WIND VARIATION ON A 25 KV DISTRIBUTION FEEDER

The following voltage profiles are from a 25 kV distribution feeder extending radially for approximately 72 KM. The voltage plots show all 25 kV nodes for the feeder include single phase taps. Approximately 43 kilometers (27 miles) from the substation is a cluster of six wind turbines with a total nameplate capacity of 3,780 kW. The Utility was reporting both high and low voltages in the vicinity of the wind turbines depending on the non-coincident states of circuit load and VRE. Load flow analysis confirmed undervoltage conditions during maximum load with all VRE off as shown in Figure 4 and also confirmed overvoltage conditions during minimum load when all VRE was at full output as shown in Figure 5. The yellow highlight denotes the target voltage window in both figures.

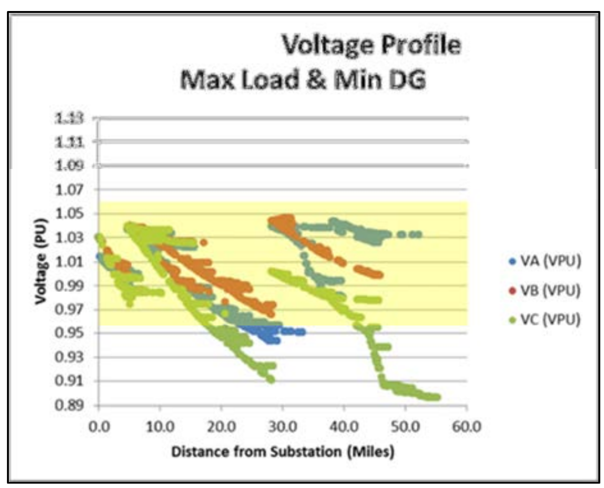

Figure 4. Voltage Profile during Max Load, Min VRE

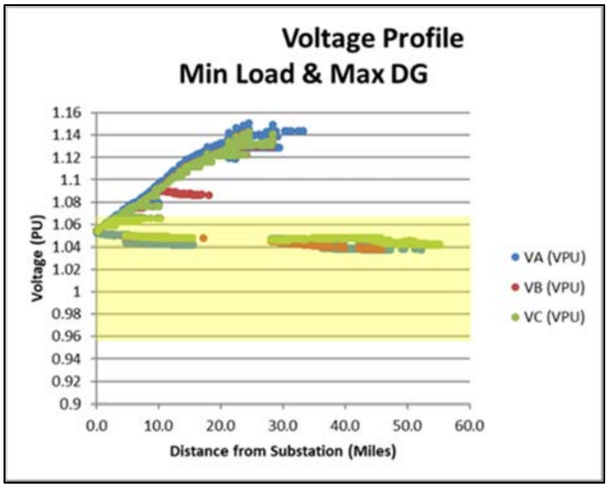

Figure 5. Voltage Profile during Min Load, Max VRE

These two voltage extrema cases were then plotted together in Figure 6 illustrating the wide range of voltages across the feeder. Regulator A is shown to be incapable of maintaining voltage within the desired range. In addition, Regulator B is traveling across almost its full tap range and likely to be experiencing excessive mechanical wear.

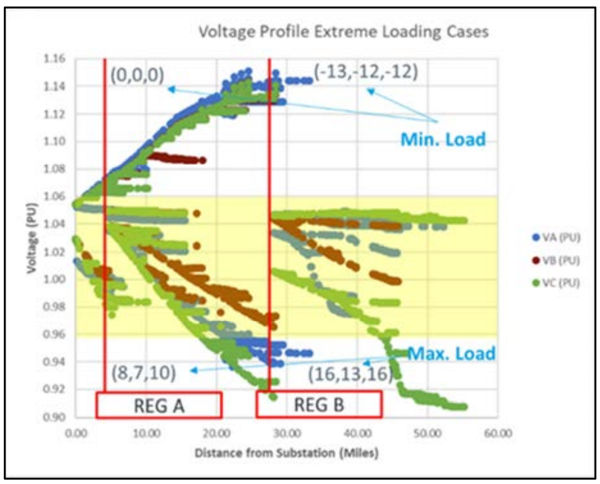

Figure 6. Voltage Maximum and Minimum Profiles Combined

Adding a third regulator between the existing two was not an option since the Utility's standard practice was to have no more than two regulators in series. Instead, two distribution STATCOMs were installed in the vicinity of the wind turbines and set to boost voltage during heavy load and buck voltage during light load by dynamically adjusting their reactive power output. The two STATCOMs, in combination with lowering the first regulator's voltage target by two volts, were able to regulate the majority of the feeder's voltage within the desired operating range as shown in Figure 7. As an additional benefit, the second regulator tap range of travel was significantly reduced suggesting that its mechanical wear will be slowed by the inclusion of the distribution STATCOMs.

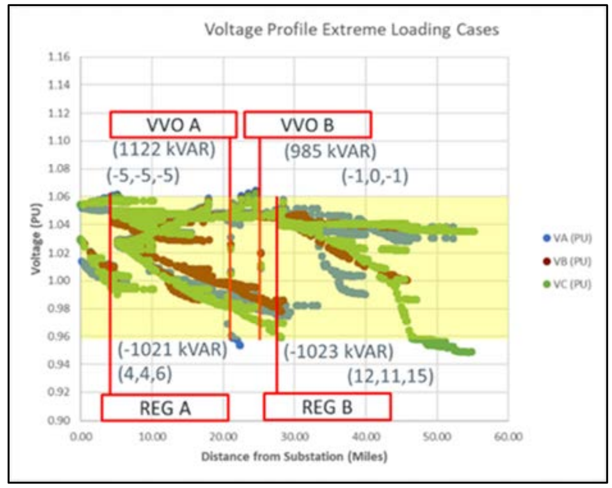

Figure 7. A Two VVO Solution for Mitigating VRE Induced Voltage Variations

IV. CASE STUDY #2: EFFECT OF WIND VARIATION ON A 15 KV DISTRIBUTION FEEDER

As an example of potential voltage fluctuations that can be observed in a real distribution feeder, loadflow analysis for addition of two wind turbine generators is presented in this section. The feeder studied is given in Figure 8. Pink numbers represent the buses where voltage values are captured in loadflow analysis. Addition of the two 1200 kW wind turbines at the end of the feeder present some voltage management challenges as the wind output changes throughout the day.

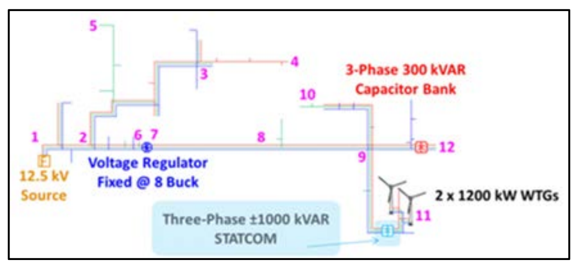

Figure 8. Feeder one-line diagram

Comparison of wind output during a steady-windy day and a variably-windy day is shown in Figure 9.

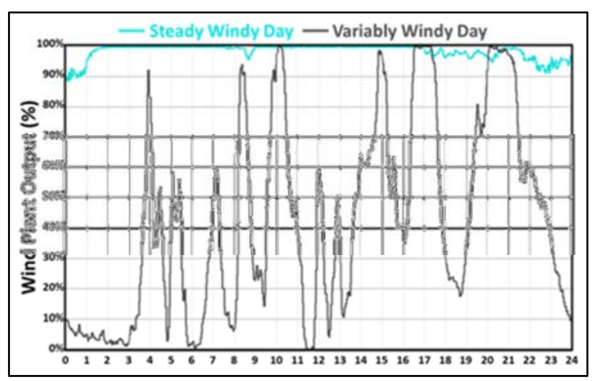

Figure 9. Field Measurements of Wind Generation

To represent the changes in the variably windy day, four different wind output levels are plotted in Figure 3:

1. Full output, 2400 kW: blue bars
2. 50% output, 1200 kW: orange bars
3. 25% output, 600 kW: pink bars
4. No wind, 0 kW: green bars

The percentages on top of the bars in Figure 10 denote the maximum voltage difference, which correspond to the difference between the full wind and no wind cases. The worst case voltage fluctuation (6.2%) is seen at bus 11.

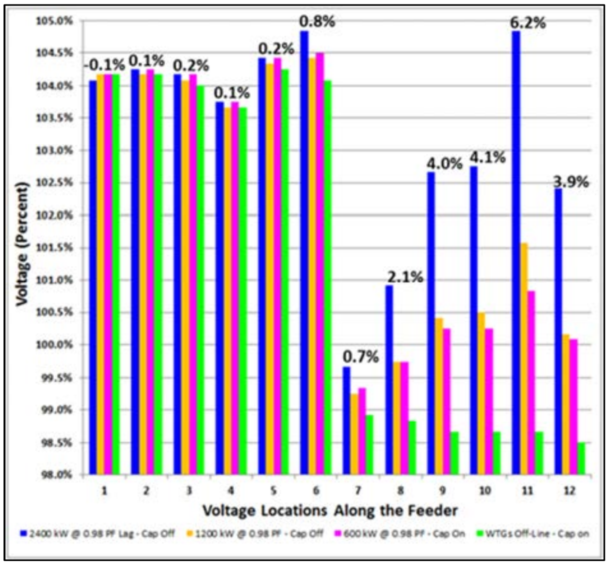

Figure 10. Voltage vs. Wind Output at Different Buses along the Feeder (pre-STATCOM case)

Since the response times (usually several minutes) of the conventional voltage regulation devices (voltage regulators and capacitor banks) would not be fast enough to mitigate these voltage fluctuations, a device with dynamic reactive power capability is needed. Installing a 1000 kVAR STATCOM close to bus 11 as shown in Figure 8 is simulated in loadflow. The results in Figure 11 demonstrate the improvement provided by the STATCOM. The worst case voltage fluctuation of 6.2% at bus 11 is reduced to 1.3% after the addition of the STATCOM.

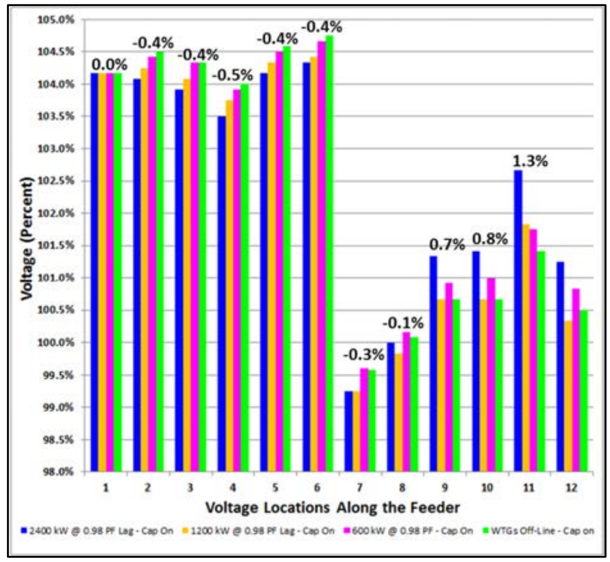

Figure 11. Voltage vs. Wind Output at Different Buses along the Feeder (post-STATCOM case)

V. CONCLUSION

As one of the most limiting factors of hosting VRE in distribution feeders, a study of voltage regulation problem has been presented in this paper. Case studies from real world feeders were used to show how a STATCOM solution can provide the dynamic voltage regulation needed to address voltage management issues introduced by high penetration of VRE. Even though the examples covered are based on experiences in North America, similar approaches can be used to analyze utility-scale VRE projects in India and other parts of the world.

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[3] "1547.7-2013 – IEEE Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection," IEEE Std 1547.7(TM), Feb. 28, 2014.