SMART GRID INVERTERS TO SUPPORT PHOTOVOLTAICS IN DISTRIBUTION SYSTEMS

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ABSTRACT

With increasing penetration levels of solar PV, the need for inverter technology to provide grid support has become more and more critical. Since 2009, EPRI and industry partners have been working to establish a common set of functions that can provide such capability. The development of a common set of functions is complete, however, very little work to date has addressed the impact these common functions will have on grid performance, especially at the distribution level. At the same time, EPRI has established a method for determining the PV hosting capacity of distribution feeders using model analysis and simulation.

Present work combines these two efforts to provide a better understanding of the impact of grid supportive inverters on distribution feeders through hosting capacity. This paper summarizes analysis to determine the additional amount of PV that distribution feeders can accommodate with the use of smart inverters.

INTRODUCTION

The analysis in this paper focuses on the impact of three different smart inverter functions[1]- power factor, volt-var, volt-watt- on four feeders in the Northeastern United States. Four feeders were chosen with varying characteristics, and the three different functions were applied to determine the possible increase in hosting capacity utilizing these smart inverter functions.

FEEDER CHARACTERISTICS

Two of the feeders were relatively short in overall primary circuit distance, and two were relatively long in overall circuit distance. All four feeders were 15 kV class feeders.

The primary voltages of the four feeders are 13.2 kV. Two feeders have exclusively 13.2 kV primary voltage. The other two feeders have multiple primary voltages. Feeder N3 has 13.2 kV and 4.16 kV, while the N4 feeder has 13.2 kV wye, and 4.8 kV un-grounded sections. The peak loads of the four feeders range from 9 MW for Feeders N1 and N2 down to 7 MW for feeder N3.

The lengths of the feeders vary from 9 total circuit miles for feeder N2 up to 138 total circuit miles for feeder N4. Two of the feeders are relatively short (N1 and N2), while the other two (N3 and N4) are relatively long 15 kV class feeders. The maximum short circuit impedances of feeders N1 and N2 are 6.7 Ω and 2.7 Ω, respectively. Feeders N3 and N4 which are much longer feeders have higher maximum short circuit impedances of 19.3 Ω and 27.6 Ω.

Feeder N1 has a substation three-phase load tap changer (LTC) that supplies a 13.2 kV (line-line) nominal feeder. Its' set-point is 123V (on a 120V base) and it has a bandwidth of 3V. It is configured with line drop compensation with a potential transformer (PT) ratio of 63.5V:1V and a current transformer (CT) primary rating of 1200 amperes. The line drop compensation R value is set to 3V and the X value is set to 5V. There are three fixed feeder capacitors providing 2700 kvar total compensation.

Feeder N2 has an LTC that supplies a circuit whose nominal voltage is 13.2 kV (line-line). The set-point of the LTC is 124.5V (on a 120V base). It has a bandwidth of 3V. There are two feeder capacitors, totaling 900 kvar. One capacitor is switched and the other is fixed. The capacitor that is switched, is switched on current with voltage over-ride.

Feeder N3 has three single-phase regulators at the head of the feeder. The voltage setpoint is 122V with a 2V bandwidth. Each regulator has line drop compensation enabled with R=2V and X=0V. There are 5 line voltage regulators that vary between a single-phase regulator and three single-phase regulators. Four out of the 5 line voltage regulators have line drop compensation enabled, with various settings. The fifth voltage regulator does not have line drop compensation enabled. There are three feeder capacitors in-service with 2400 kvar total compensation. Two banks are fixed, and the largest bank (1200 kvar) is voltage controlled with 120/126V on/off settings.

Feeder N4 has a substation three-phase LTC with a setting of the 120V for the voltage setpoint with a two-volt band. The LTC does not have line drop compensation enabled. There are 7 line voltage regulators out on the feeder. They range from single-phase voltage regulators to three single-phase voltage regulators. Some of the line voltage regulators have line drop compensation enabled, while others do not. There are numerous step-down and step-up transformers that connect the 13.2 kV sections of the feeder with 4.8 kV un-grounded sections. There are six single-phase feeder capacitors (in-service) comprising a total of 315 kvar of reactive compensation. There are five three-phase feeder capacitors providing 1350 kvar total reactive compensation. All the capacitor banks are fixed banks.

A voltage profile under peak load for one of the short feeders, N1, is shown in Figure 1.

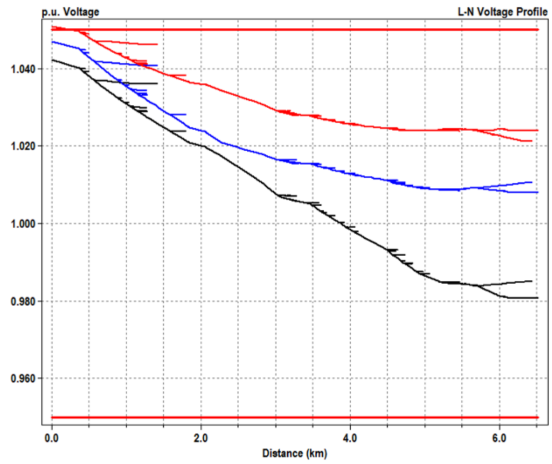


Figure 1: Voltage profle for Feeder N1 under peak loading.

A voltage profile under peak load for one of the long feeders, N3, is shown in Figure 2.

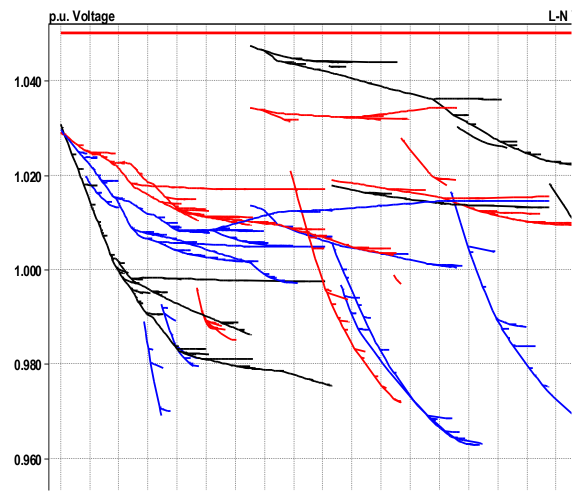


Figure 2: Voltage Profile for Feeder N3 under peak loading.

SCENARIO DEVELOPMENT

The simulation cases in which PV inverters don't have the advanced functions to regulate voltages are referred to as the 'No Control' or 'Base-Line' cases. Each customer is identified as a probable point of interconnection for small-scale PV. The customers each have a peak loading, and the size of the PV (if the customer is chosen to have PV for a given case) is either the maximum active power demand of the customer, or it is chosen from a statistical distribution of small-scale PV sizes. Customers are classified by type as either residential or commercial/industrial and a separate statistical distribution is used for the customer type, with commercial/industrial customers having an opportunity, generally, for larger size small-scale PV installations.

The hosting capacity methodology [2,3] applied for this study looks at such items as primary bus overvoltages and voltage deviations (at primary buses and at voltage regulating devices, including capacitors). 5000 PV deployments were generated for the small-scale PV. Both peak-loading and off-peak loading (both at solar noon) conditions were analysed.

A smaller number of PV deployments (4000) were generated for large-scale PV (500 kW to 10 MW). The same hosting capacity methodology was applied, and the same two loading conditions were analysed, as well.

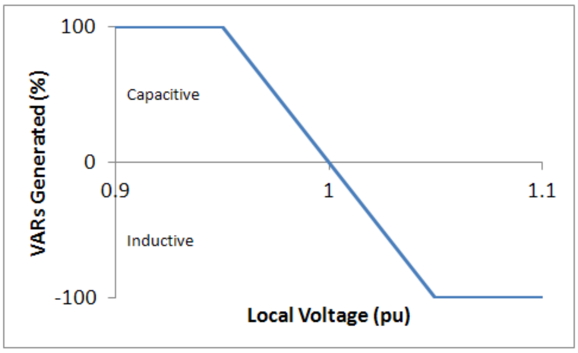
Each feeder was analysed with the PV inverters under a no-control scenario (unity power factor), two fixed power factor settings (0.98 inductive power factor, 0.95 inductive power factor), two volt-var curve settings, and two volt-watt curve settings.

ANALYSIS RESULTS

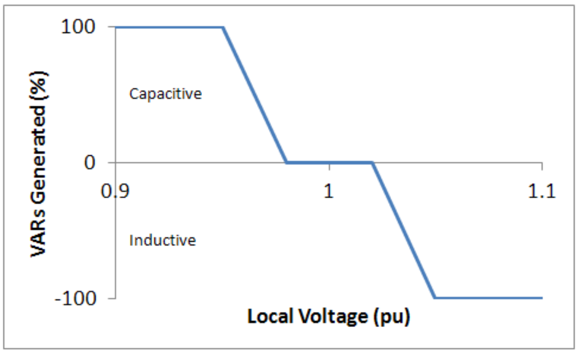
As mentioned previously, three smart inverter functions are considered for the analysis, including:

- Power factor control
- Volt-Var control
- Volt-Watt control

The volt-var curves utilized are shown in Figure 3.



a)

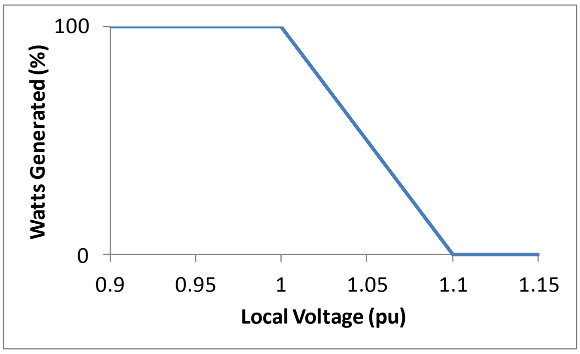


b)

Figure 3:Volt-Var Control: a) Volt-Var 1 b) Volt-Var 2

The volt-watt curves utilized are shown in Figure 4.

a)



b)

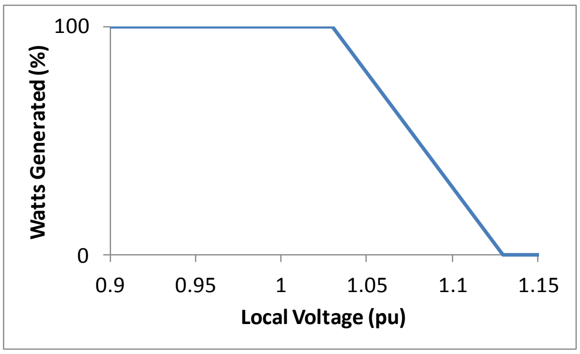


Figure 4: Volt-Watt Control: a) Volt-Watt 1 b) Volt-Watt 2

Within each of these smart inverter functions, the control is modified to test impact on feeder performance. This analysis calculated the change in PV hosting capacity for all four feeders under two different loading conditions. Each of the advanced inverter functions and control was applied to all PV systems considered. For example, when analysing any particular penetration level, it is assumed that all inverters have smart inverter capability and each inverter was operating with the same advanced control function.

This particular analysis considered both large, three-phase installations (large-scale PV), and small-scale PV, as applied at customers. The newly calculated hosting capacities was compared to the "No Control" hosting capacities where the PV systems utilized unity power factor.

To save space, we will show only the graphical results for the feeder (feeder N1) that showed the most improvement with advanced inverter functions. The hosting capacities for Feeder N1 are shown in Figure 5, for small-scale PV.

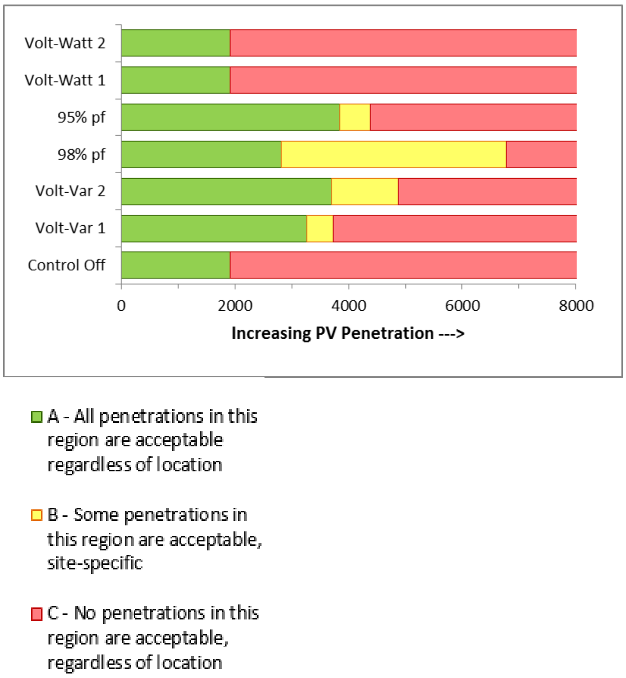


Figure 5 Hosting Capacity Results for Feeder N1, small-scale.

Similarly, for large-scale PV, Figure 6 shows the change in hosting capacities for different advanced inverter functions.

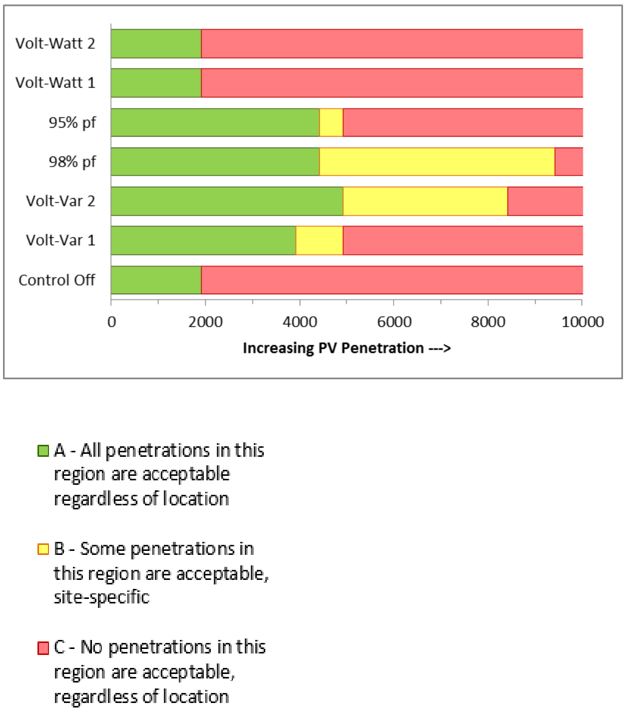


Figure 6 Hosting Capacity Results for Feeder N1, large-scale.

A summary of the hosting capacity changes for all four of the feeders is shown in Table 1a, for small-scale PV and Table 1b, for large-scale PV.

Table 1 Small-scale (a) and Large-scale (b) Increases in Hosting Capacity with Smart Inverters.

(a) Small-scale PV

	Average Hosting Capacity (kW)						Increase in Average Hosting Capacity with Smart Inverters (%)				
	N1	N2	N3	N4	Total		N1	N2	N3	N4	Total
None	1920	1652	710	0	4282		-	-	-	-	
98% pf	4792	3000	1137	0	8929		150%	82%	60%	-	109%
95% pf	4110	3000	973	0	8083		114%	82%	37%	-	89%
volt-var 1	3495	2339	499	24	6357		82%	42%	-30%	-	48%
volt-var 2	4288	3000	463	24	7775		123%	82%	-35%	-	82%
volt-watt 1	1920	2352	887	24	5183		0%	42%	25%	-	21%
volt-watt 2	1920	3000	786	0	5706		0%	82%	11%	-	33%

(b) Large-scale PV

	Average Hosting Capacity (kW)						Increase in Average Hosting Capacity with Smart Inverters (%)				
	N1	N2	N3	N4	Total		N1	N2	N3	N4	Total
None	1920	8250	349	250	10769		-	-	-	-	
98% pf	6920	10000	349	250	17519		260%	21%	0%	-	63%
95% pf	4670	10000	349	250	15269		143%	21%	0%	-	42%
volt-var 1	4420	7750	349	250	12769		130%	-6%	0%	-	19%
volt-var 2	6670	8250	349	250	15519		247%	0%	0%	-	44%
volt-watt 1	1920	8250	0	250	10420		0%	0%	-100%	-	-3%
volt-watt 2	1920	8250	0	250	10420		0%	0%	-100%	-	-3%

Feeder N4 showed a pre-existing violation, and therefore no results were obtained from it.

VOLT-VAR SETTINGS FOR LONG FEEDER

Feeder N4 showed no possible improvement in hosting capacity for small-scale PV or large-scale PV due to a pre-existing violation. It was thought that perhaps the default settings for volt-var, for instance, were not optimal for a long feeder.

A case was developed where there was 50% penetration of added PV on Feeder N4, or approximately 1241 kW of added PV with volt-var functionality (small-scale). A volt-var curve was developed that had a transition from capacitive to inductive vars taking place at a lower voltage, and to help in bringing down higher voltages, but also supporting lower voltages. The altered volt-var curve was successful in allowing a penetration of 1241 kW of small-scale PV without overvoltage violations. It is likely that the bandwidth on nearby voltage regulators will need to be widened to accommodate the large voltage deviations due to the volt-var curve.

CONCLUSIONS

Three distinct smart inverter functions were selected and hosting capacity calculations were performed with solar PV operating with each control function. Varying results were found across each of the feeders, and functions chosen. Feeder N1 showed the most improvement with smart inverter functions, with a maximum increase in hosting capacity of 260% of large-scale PV. Feeder N4 was able to accommodate higher levels of PV with a tailored volt-var curve. Smart inverter functions do have the capability, in many cases, to increase the hosting capacity of distribution feeders.

REFERENCES

[1] EPRI, *Common Functions for Smart Inverters, Version 2*. EPRI, Palo Alto, CA: 2012. 1026809.

[2] EPRI, *Stochastic Analysis to Determine Feeder Hosting Capacity for Distributed Solar PV*. EPRI, Palo Alto, CA: 2012. 1026640.

[3] Rylander, M., Smith, J., *Comprehensive Approach for Determining Distribution Network Hosting Capacity for Solar PV*, 2nd International Workshop on Integration of Solar Power Into Power Systems, Lisbon, Portugal, Nov 2012.