

Analysis to Inform CA Grid Integration: Methods and Default Settings to Effectively Use Advanced Inverter Functions in the Distribution System

EPRI REPORT:
3002007139, December 2015

Integration of Distributed Energy Resources
Program (174)

EPRI Project Manager
J. Smith



DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER ... SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2015 Electric Power Research Institute, Inc. All rights reserved.

ACKNOWLEDGMENTS

The Electric Power Research Institute (EPRI) prepared this report.

Principal Investigators

H. Li

M. Rylander

J. Smith

This work is sponsored, in part, by the CPUC California Solar Initiative (CSI) Research, Development, Demonstration, and Deployment (RD&D) #4 and EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Analysis to Inform CA Grid Integration: Methods and Default Settings to Effectively Use Advanced Inverter Functions in the Distribution System. EPRI, Palo Alto, CA: 2015. 3002007139.

ABSTRACT

- Advanced inverters are not smart enough to determine which settings to use in a given set of conditions. Additional analysis is needed to determine which settings are most appropriate given local feeder conditions. Although rigorous, detailed analyses can provide the “best” settings for a particular set of conditions, more efficient methods of analysis are needed to determine appropriate settings that can be applied to a wide range of feeder and distributed energy resources (DER) scenarios.
- In addition to efficient methods for determining settings, it is also beneficial to establish sufficient default settings for advanced inverters. As such, regardless of where the DER are located, these functions can be leveraged by utilities without any additional analysis. Both efficient analysis methods and default settings are essential to ease the adoption and use of advanced inverter functions.
- This report presents three methods to determine appropriate advanced inverter power factor settings that reduce voltage impact on the distribution system from inverter-based DER. The three methods presented vary in computational complexity, data requirements, and effectiveness. The simulation results show that although the three methods vary in effectiveness, they all help reduce the voltage rise and therefore the potential overvoltage.
- This report also presents a proposed default volt/volt-ampere-reactive (VAR) setting that has provided beneficial response based on detailed analyses. The benefit from this default setting will be shown to further improve in combination with additional inverter functions.

Keywords

Distributed energy resources, Inverter, Performance, Photovoltaics, Power factor, Voltage deviation

CONTENTS

	Slide
Chapter 1: Introduction	Slide 6
Chapter 2: Methods for Determining Power Factor Settings	Slide 12
Chapter 3: Default volt-var Setting	Slide 35
Chapter 4: Combined Functionality of Common Functions	Slide 48
Chapter 5: Conclusion	Slide 55
Appendix: References	Slide 57

Chapter 1: Introduction

Chapter 1 – Introduction

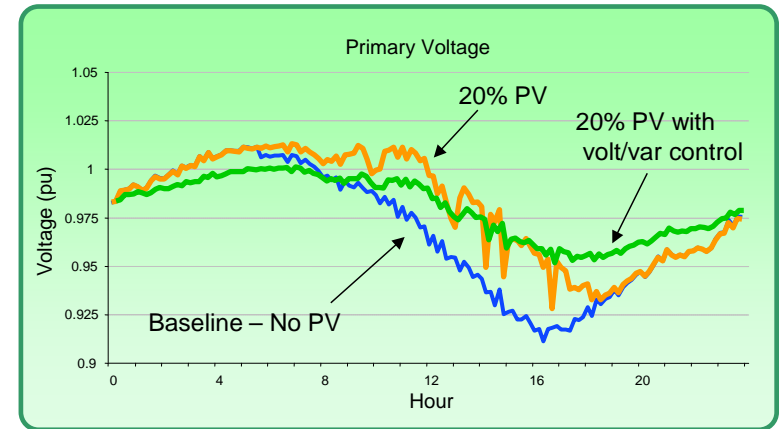
This chapter provides background on advanced inverters. The chapter discusses advanced inverters and their potential benefits with use of reactive power, as well as importance of sufficient inverter capacity and appropriate settings.

- Section 1 Advanced Inverters Can Have Significant Advantages
- Section 2 Importance of Reactive Power Capacity
- Section 3 Inverter Settings are Critical
- Section 4 Summary

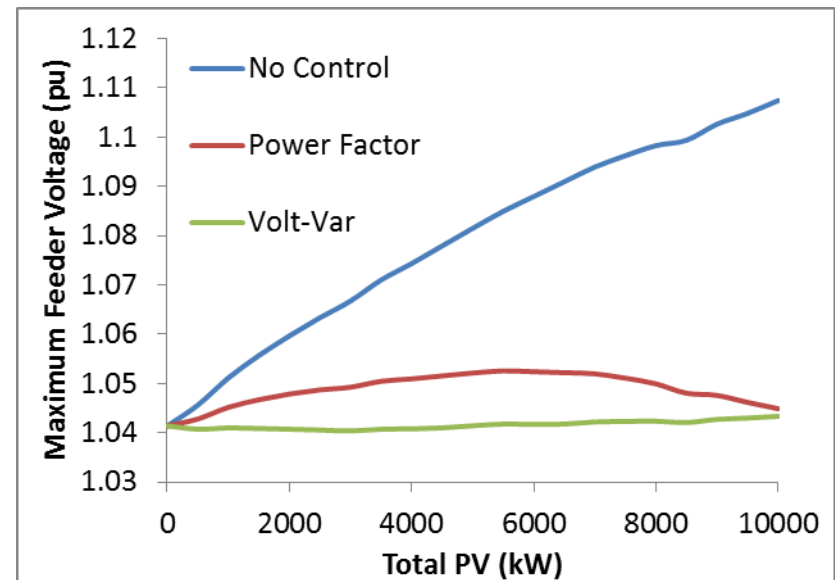
Advanced Inverters Can Have Significant Advantages

Advanced inverters can improve integration of DER by reducing some of the adverse impacts from DER.

- Voltage issue
 - Voltage-related issues can be the most limiting issues regarding integrating DER
- Least-cost solution
 - In many cases, use of advanced inverters can be the least cost solution for mitigating voltage related issues due to DER
- Increased hosting capacity
 - EPRI has shown advanced inverters can increase the amount of DER that can be accommodated



24 Hour Simulation



Importance of Reactive Power Capacity

Any reactive power (var) related inverter function used to mitigate adverse voltage impacts from DER requires sufficient inverter capacity.

Issue

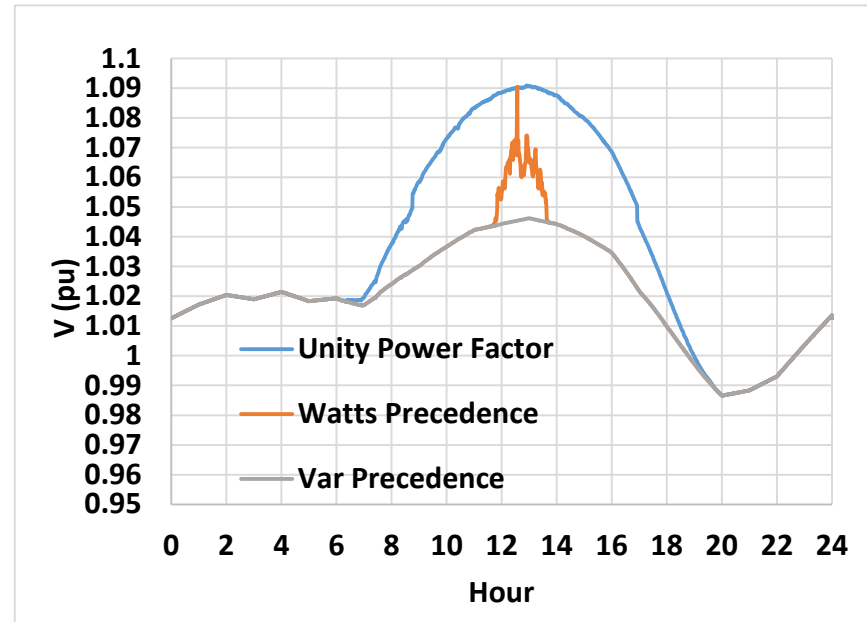
- Inverters are rated smaller than the PV panel, or
- Inverters give precedence to watts, but do not have capability to provide reactive power at full output

Result

- Inverters cannot provide reactive power at full output when the reactive power is needed most
- May result in unacceptable voltage rise

Solution

- Simulation results indicate that DER providing a minimum of +/- 0.9 power factor at full output allows for sufficient inverter var control



Voltage comparison with different inverter var scenarios

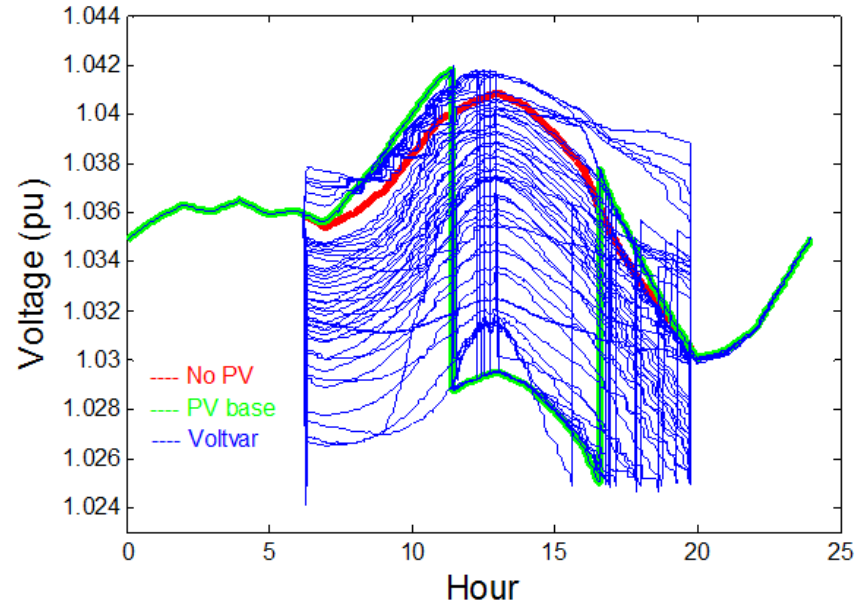
Reactive power control may not be needed now, but as penetration levels increase so does the necessity of reactive power control

In a watts-precedence setting, as the active power increases to near full output, the inverter's capability to provide reactive compensation decreases, thus also decreasing the ability to provide overvoltage mitigation.

Inverter Settings are Critical

Appropriate settings are critical to ensure advanced inverters provide the response that is desired.

- Reactive power controls, such as volt-var, are capable of significantly altering the feeder voltage
- There are numerous possible inverter settings
- A DER system with wrong settings can actually worsen grid performance beyond that seen if the DER is operating at unity power factor



Variety of Voltage Responses Resulting from Different Volt-var Settings

Summary

Objective

- Easing use of advanced inverters for distribution engineers
- Maximizing use of advanced inverters to improve integration

Inverter Functions

- Power factor control
- Volt-var control
- Combinations of existing controls

Approach

- Utilize advanced inverter controls modeled in OpenDSS to analyze range of feeders and DER locations
- Evaluate methods for determining appropriate settings
- Evaluate possible default settings
- Determine impact on voltage mitigation

Specific Issues Being addressed

- Both simple and advanced methods for determining most effective power factor settings that provide the maximum benefit based upon feeder characteristics, DER deployments and DER locations
- Identifying locations where advanced inverter control are most effective – and when they're not
- Evaluating default volt-var settings that are applicable across a wide range of potential conditions.

Chapter 2: Methods for Determining Power Factor Settings

Chapter 2 – Determining Power Factor Settings

This chapter discusses power factor control settings. The chapter provides a “how to” for determining settings for both single and multiple systems on a feeder.

- Section 1 Power Factor Control Background
- Section 2 DER Power Factor Voltage Impacts
- Section 3 Power Factor Settings for Single DER System
- Section 4 Location Does Matter
- Section 5 Methods to Determine Power Factor Settings for Multi-DER Systems
- Section 6 Simulation Results
- Section 7 Summary

Power Factor Control Background

The most common approach used for mitigating voltage rise from distributed DER is applying non-unity (inductive) power factor control.

■ Positive Characteristics

- Power factor control can mitigate many voltage rise issues
- Relatively easy to estimate “best” setting to use for a single DER system

■ Negative Characteristics

- Always works to draw reactive power from grid, even when it doesn't need to
- Reactive power must be “sourced” from somewhere
- When multiple DER systems are on the same feeder, potentially large amounts of reactive power can be drawn, thus resulting in adverse voltage impacts along the feeder

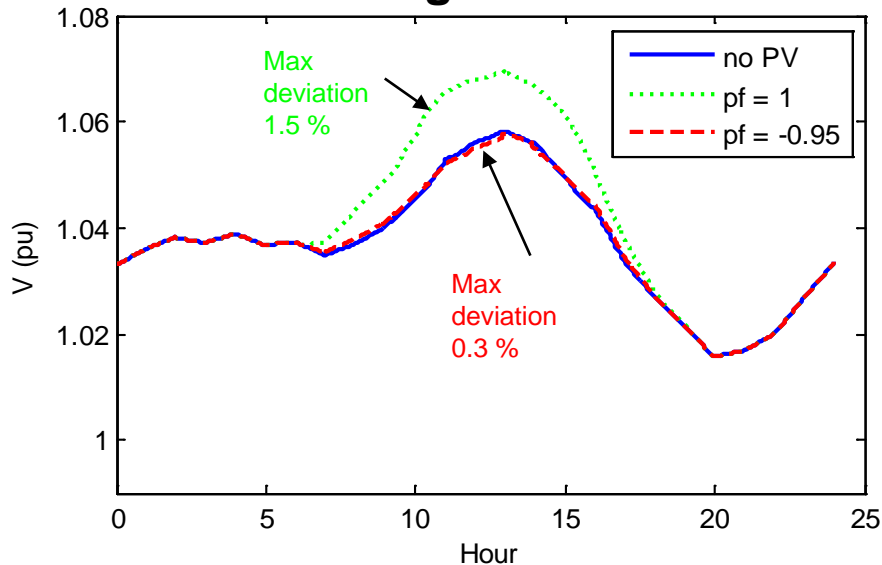
■ Requirements

- Sufficient inverter capacity is needed to provide reactive power at all active power output levels

DER Power Factor Voltage Impacts

Power factor settings can be easily calculated to mitigate voltage rise when there is a single system on the feeder. Multiple DER on a feeder using settings calculated without consideration for other DER can often result in overcompensation of the voltage rise (multiple DER absorbing reactive power). Settings need to be properly tuned for the multiple DER scenario.

Single DER

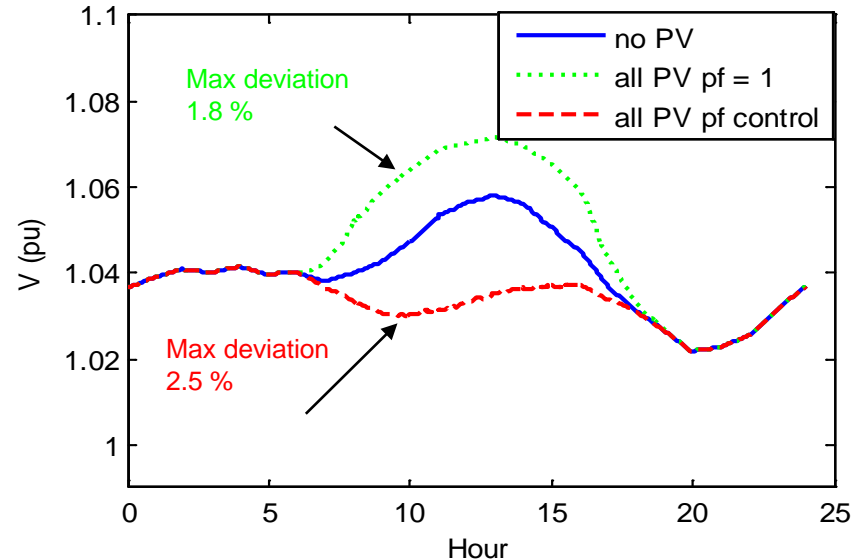


Voltage at POI of a Single DER

Appropriate power factor settings can be easily calculated for one DER

- The calculated power factor setting successfully mitigates the voltage rise (red curve) and keeps the voltage very close to the no-DER condition (blue curve)

Multiple DER

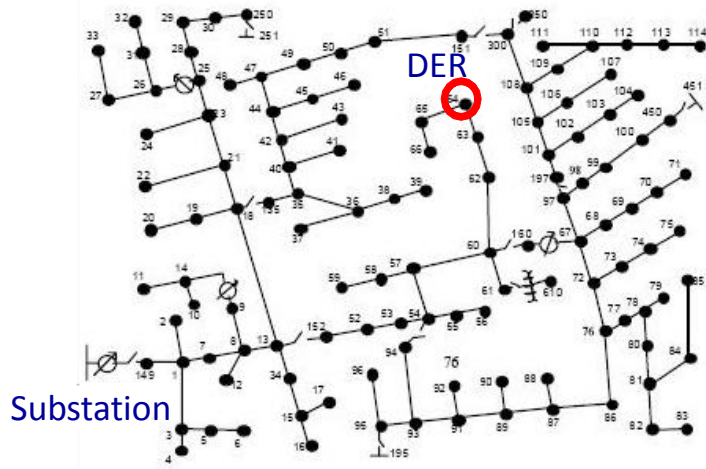


Voltage at the same POI with Multi-DER systems

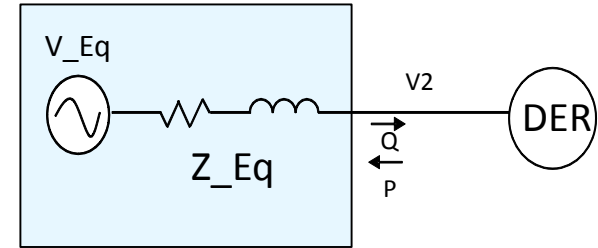
Appropriate power factor settings can Not be easily calculated for multiple DER

- Power factor settings can overcompensate for voltage rise (red curve) and actually cause voltage reductions to occur.

Power Factor Settings for Single DER System



Thévenin equivalent circuit



$$\Delta V_{pu} \cong \frac{R \times P + X \times Q}{V}$$

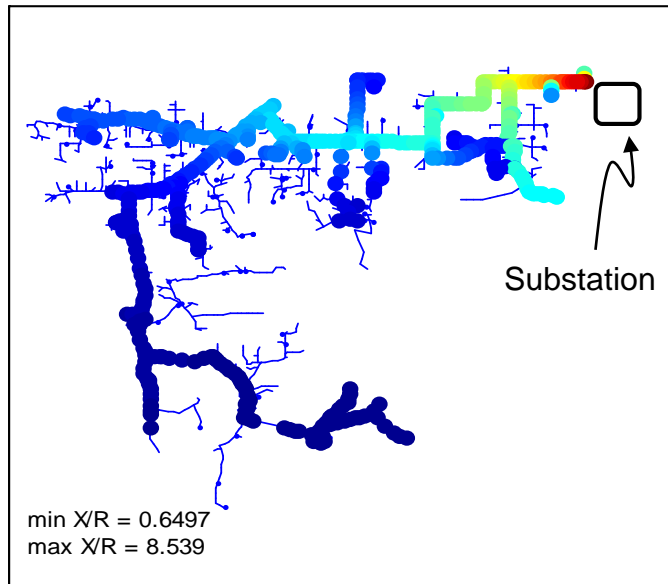
Let $\Delta V_{pu} = 0$, and yields $\frac{X}{R} \cong \frac{-P}{Q}$

$$\text{Power Factor} \cong \frac{\frac{X}{R}}{\sqrt{\left(\frac{X}{R}\right)^2 + 1}}$$

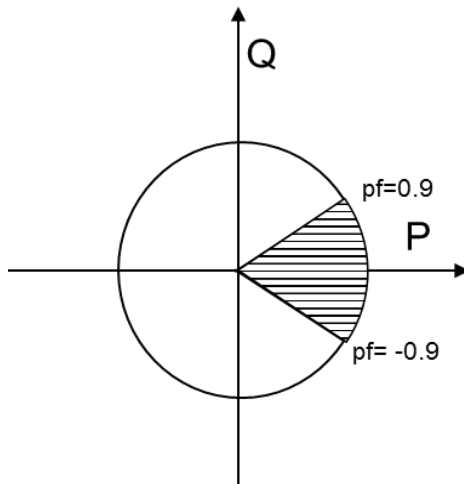
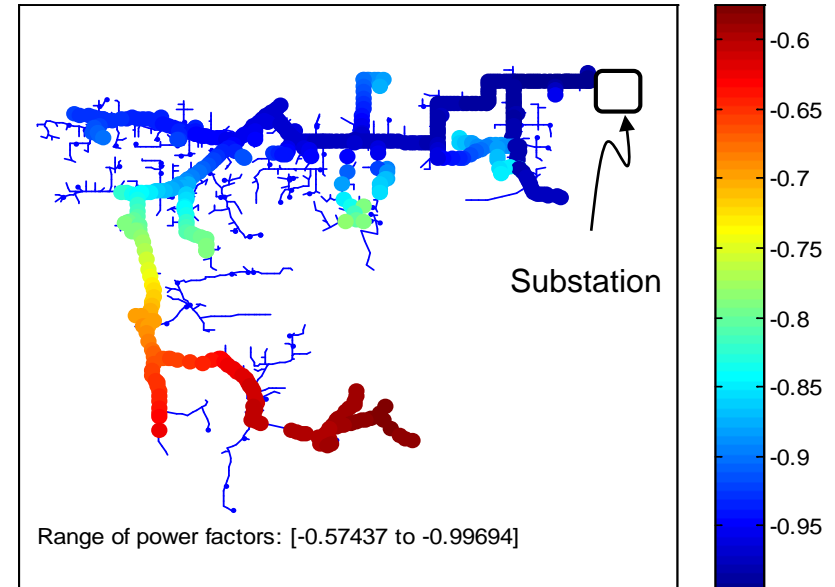
Where ΔV_{pv} is the DER-induced voltage change; V is the base voltage; X , R are the equivalent reactance and resistance at point of interconnection (POI) primary side; P , Q are the DER active power and reactive power.

Location Does Matter – Power Factor Settings

X/R ratio



Calculated DER Power Factor

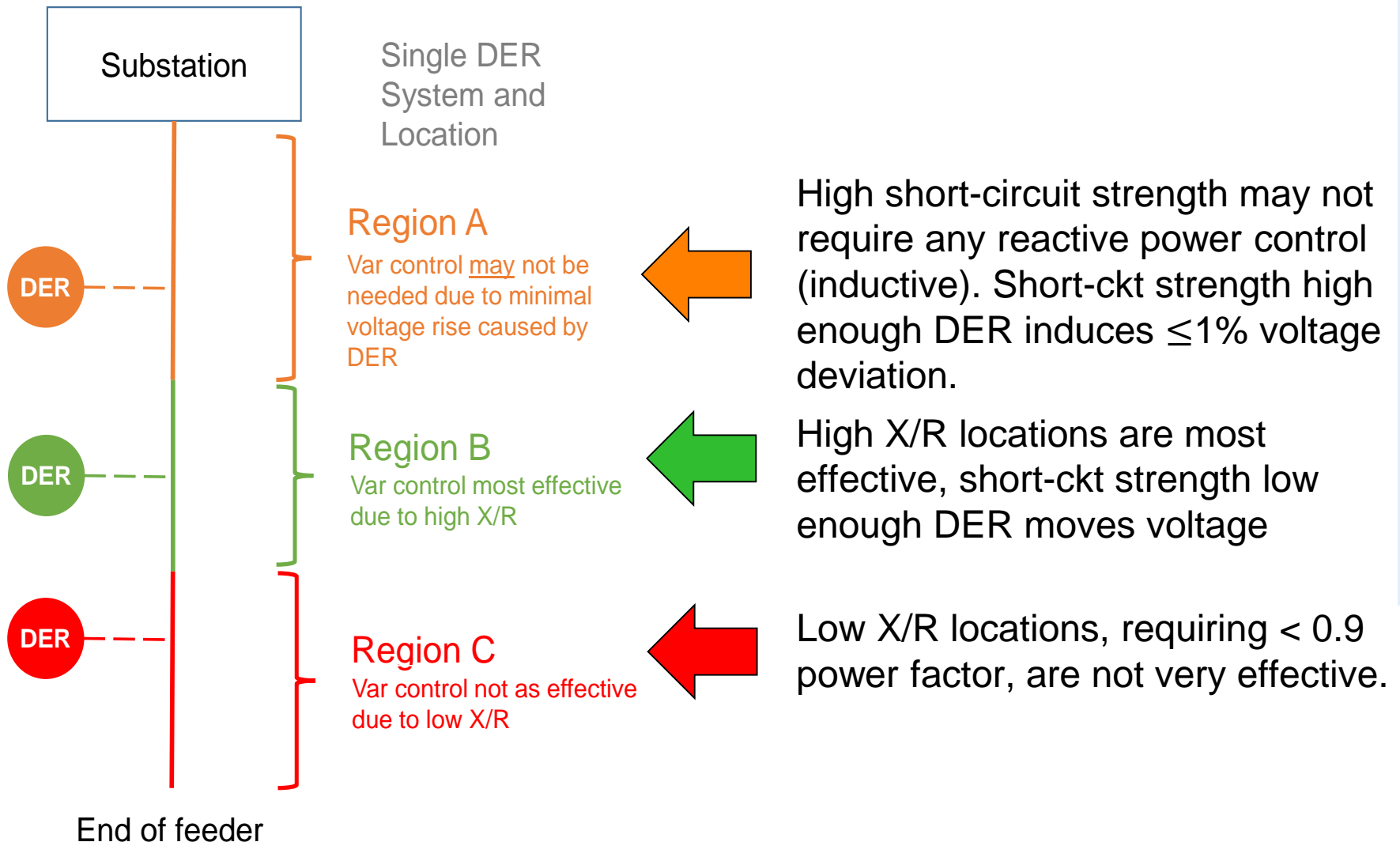


Using the previous equation, associated DER power factor needed to prevent voltage rise can be calculated

- Power factor setting is close to unity power factor near the substation and drops toward the feeder end
- Low X/R ratio has low power factors and needs to absorb a large amount of reactive power to mitigate voltage rise (alternative solutions are necessary)
- A DER location associated w/ X/R of ≥ 1.833 requires a DER power factor of ≥ 0.90 to effectively mitigate overvoltage.

*Assuming interconnection transformer $x=5.67\%$, $R_s=0.673\%$

Location Does Matter – Reactive Power Control Effectiveness



Methods to Determine Settings for Multiple Utility-Scale DER Systems

There are three methods identified to determine more appropriate power factor settings when multiple systems exist on a feeder. Additional description and detail are provided on the next slides.

1. Median X/R ratio

- “Hand” calculation equating X/R to power factor

2. DER Point of Interconnect X/R

- “Spreadsheet” calculation using weighted average size of DER and POI X/R

3. Sensitivity-based algorithm

- Iterative, load flow-based method

Goal is to determine efficient and effective methods for determining settings



Description of Methods

#	Method	Calculation Method	Data Requirements	Grid Performance	Power Factor Setting
1	Median Feeder X/R to determine power factor	Hand calculation	average primary voltage X/R on feeder	Limited improvement based on actual DER location.	Single Setting on each feeder
2	Weighted Average X/R @ DER Location	Spreadsheet calculation	Requires calculation at DER point of interconnect	Effective for single DER system. Limited improvement for the multi-DER scenario.	Single Setting on each feeder that takes into consideration the location of single or multiple DER systems on the feeder to obtain one single setting tailored to the location of those systems.
3	Sensitivity -Based Algorithm	Algorithm using iterative load flows	Load flow model	Effective approach for single or multiple systems	Customized setting for each site and deployment

Method 1 – Median Feeder (X/R) Ratio

$$\text{Power factor} \cong \frac{(X/R)_{\text{median}}}{\sqrt{\left((X/R)_{\text{median}}\right)^2 + 1}}$$

1. Calculate median X/R.
2. Calculate power factor by applying the X/R ratio calculated in step 1 in the power factor setting formula for single DER system. If the calculated power factor setting is below 0.9, set it to 0.9.
3. DER systems in Region A that induce minimal impact (less than 1% voltage rise at its POI @unity power factor in single DER scenario) is set to unity power factor. The other DER systems are set to the power factor calculated in 2.

Method 2 – Weighted Average X/R Ratio

		$=(C2*D2+C3*D3+C4*D4+C5*D5+C6*D6)/SUM(C2:C6)$						
	A	B	C	D	E	F	G	H
1		bus	PV_size	X/R	V_rise_singel PV	weighted Avg X/R	Calculated pf	Pf
2	PV1	PV1bus	0.1	6.149	0.002	1.537977778	-0.86	1
3	PV2	Pv2bus	0.5	2.385	0.011			-0.9
4	PV3	PV3bus	0.3	1.905	0.015			-0.9
5	PV4	PV4bus	0.6	1.965	0.016			-0.9
6	PV5	PV5subs	3	1.121	0.017			-0.9

Minimal impact

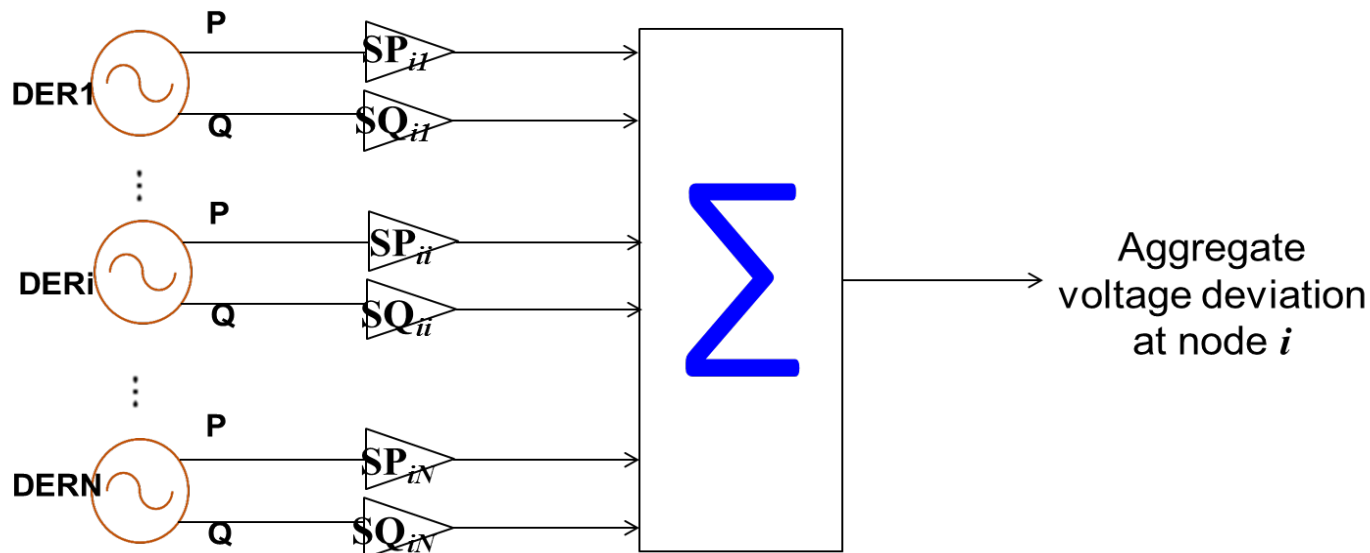
1. Calculate the DER size weighted average X/R.
2. Calculate power factor by applying the X/R ratio calculated in step 1 in the power factor setting formula for single DER system. If the calculated power factor setting is below 0.9, set it to 0.9. (Negative sign denotes inductive var)
3. DER systems in Region A that induce minimal impact (less than 1% voltage rise at its POI @unity power factor in single DER scenario) is set to unity power factor. The other DER systems are set to the power factor calculated in 2.

Method 3 – Sensitivity Analysis Based Method

- Requires feeder model and DER locations and sizes
- Approximates the aggregate impacts from all the DER systems on the voltage deviation of a particular node by linearization
- Minimizes the voltage deviations of DER systems by optimization procedure

Method 3 – Approximation of Aggregate Voltage Deviation

Aggregated voltage deviation based on voltage sensitivities



$$\Delta V_i = (SP_{i1}P_1 + SQ_{i1}Q_1) + (SP_{i2}P_2 + SQ_{i2}Q_2) + \dots (SP_{iN}P_N + SQ_{iN}Q_N)$$

Where ΔV_i is the voltage deviation at node i ; P_1, \dots, P_N and Q_1, \dots, Q_N are the active and reactive power of the DER at node 1 to N respectively; SP_{i1}, \dots, SP_{iN} and SQ_{i1}, \dots, SQ_{iN} are the sensitivities of voltage at bus i with respect to the active power and reactive power of the DER at node 1 to N respectively.

Method 3 – Voltage Sensitivities

Voltage Sensitivity Matrix to P

$$[SP] = \begin{bmatrix} SP_{11} & SP_{12} & SP_{13} & SP_{14} & SP_{15} & \cdots & SP_{1N} \\ SP_{21} & SP_{22} & SP_{23} & SP_{24} & SP_{25} & \cdots & SP_{2N} \\ SP_{31} & SP_{32} & SP_{33} & SP_{34} & SP_{35} & \cdots & SP_{3N} \\ SP_{41} & SP_{42} & SP_{43} & SP_{44} & SP_{45} & \cdots & SP_{4N} \\ SP_{51} & SP_{52} & SP_{53} & SP_{54} & SP_{55} & \cdots & SP_{5N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ SP_{N1} & SP_{N2} & SP_{N3} & SP_{N4} & SP_{N5} & \cdots & SP_{NN} \end{bmatrix}$$

$SP_{ij} = \frac{\Delta V_i}{\Delta P_j}$

Resulting voltage change at node i due to ΔP_j
 DER P Change at node j

Voltage sensitivity at node i w.r.t. P generation at node j
Only P at bus j changes and all the other P and Q injections are locked.

Voltage Sensitivity Matrix to Q $[SQ]$ has similar definitions:

$$SQ_{ij} = \frac{\Delta V_i}{\Delta Q_j}$$

Resulting voltage change at node i due to ΔQ_j
 DER Q Change at node j

Method 3 – Minimization of Voltage Deviations

$$\Delta V = SP * P + SQ * Q$$

Where $\Delta V = [\Delta V_1, \Delta V_2, \dots, \Delta V_N]^T$ Voltage deviations at DER systems nodes;
 $P = [P_1, P_2, \dots, P_N]^T$ and $Q = [Q_1, Q_2, \dots, Q_N]^T$ Active and reactive power of DER systems

Objective: $\min \sum_{i=1}^N \Delta V_i^2$



$$\min \sum_{i=1}^N (SP_{i1}P_1 + SQ_{i1}Q_1 + SP_{i2}P_2 + SQ_{i2}Q_2 + \dots + SP_{iN}P_N + SQ_{iN}Q_N)^2$$

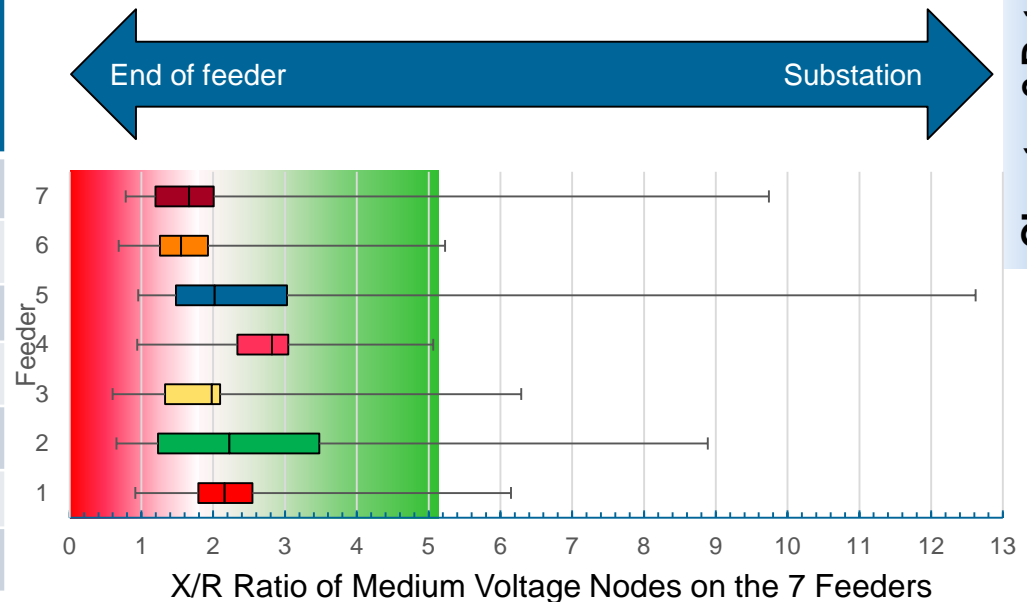
Constraints: $\left| \frac{Q_i}{P_i} \right| \leq 0.4843, i = 1 \dots N$ ← $PF_i \in [1, \pm 0.9]$

Power factor setting for each DER system can be easily calculated once the reactive power variables are solved through the optimization.

Feeders Selected for Analyzing Power Factor Setting Methods

Several feeders have been identified based on very different characteristics and impacts from DER. The application of the three power factor methods will be analyzed on each the feeders described below. The variables in this analysis and the results from the application of the three methods are described on the following slides.

Feeder #	Impact	Nominal Voltage (kV)	Peak Load (MW)	Voltage Regulators	Capacitors (kvar)	Feeder-End Impedance
1	High	4	2	0	0	2
2	High	12	6	1	2400	16
3	Moderate	12	8	0	4800	9
4	Low	21	13	0	9600	8
5	Low	12	6	0	1200	3
6	High	12	10	2	6000	9
7	Moderate	12	4	0	1200	8



Simulation Results for a High Impact Feeder – Feeder 1

Location Matters:

- As shown in the figures, from the substation towards the feeder end the short-circuit impedance increases while X/R ratio decreases
- Voltage rise induced by the same sized DER is small near the substation and increases toward the feeder end, illustrated in Table 1.
- Required power factor setting for a single DER system is close to unity power factor near the substation and drops toward the feeder end, illustrated in Table 1.

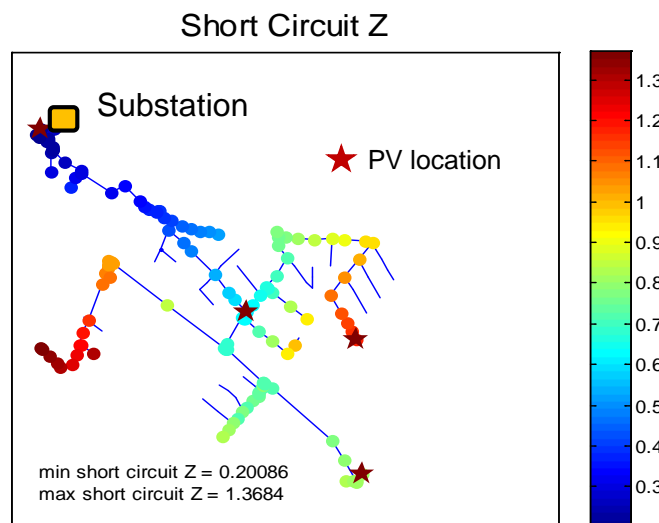
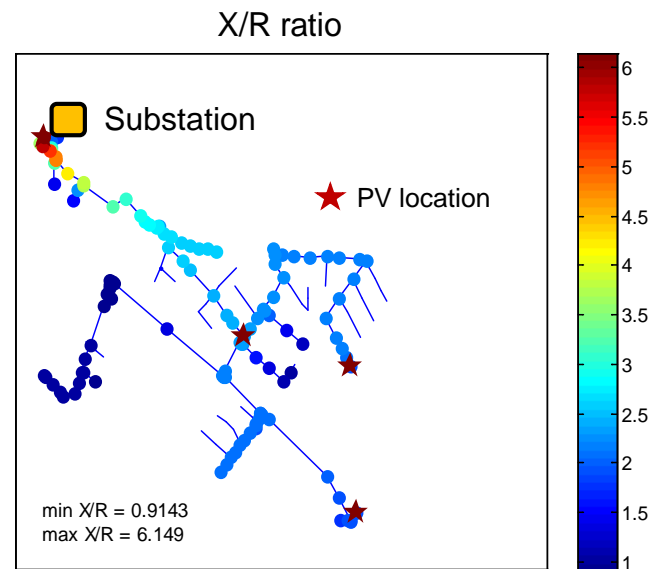


Table 1. Potential PV Sites on 4 kV feeder

PV	X/R	Z1	Size	Calculated PF	POI voltage rise due to single PV @unity pf
PV1	6.149	0.2	1MW	-0.992	0.0014
PV2	2.385	0.61	1MW	-0.943	0.0123
PV3	1.965	1.18	1MW	-0.921	0.0274
PV4	1.905	0.82	1MW	-0.913	0.0202

Voltage Rise without Power Factor Control

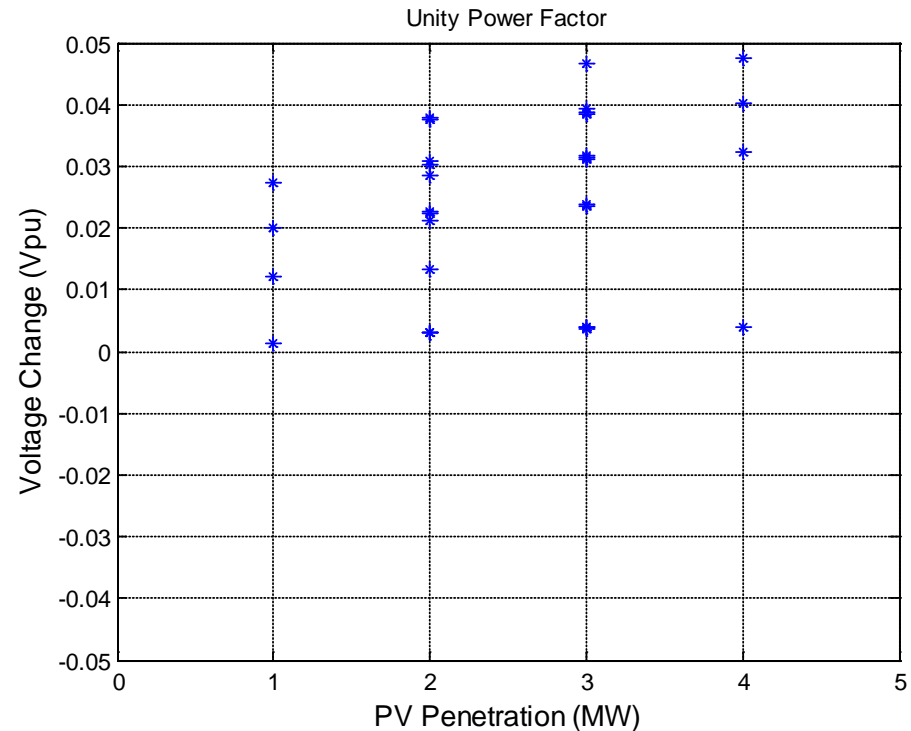
Case List

(1: PV is connected ,0: PV is not connected)

Case #	Total PV (MW)	PV1	PV2	PV3	PV4
1	1	1	0	0	0
2	1	0	1	0	0
3	2	1	1	0	0
4	1	0	0	1	0
5	2	1	0	1	0
6	2	0	1	1	0
7	3	1	1	1	0
8	1	0	0	0	1
9	2	1	0	0	1
10	2	0	1	0	1
11	3	1	1	0	1
12	2	0	0	1	1
13	3	1	0	1	1
14	3	0	1	1	1
15	4	1	1	1	1

The combinations of the four 1 MW PV systems make fifteen PV deployments.

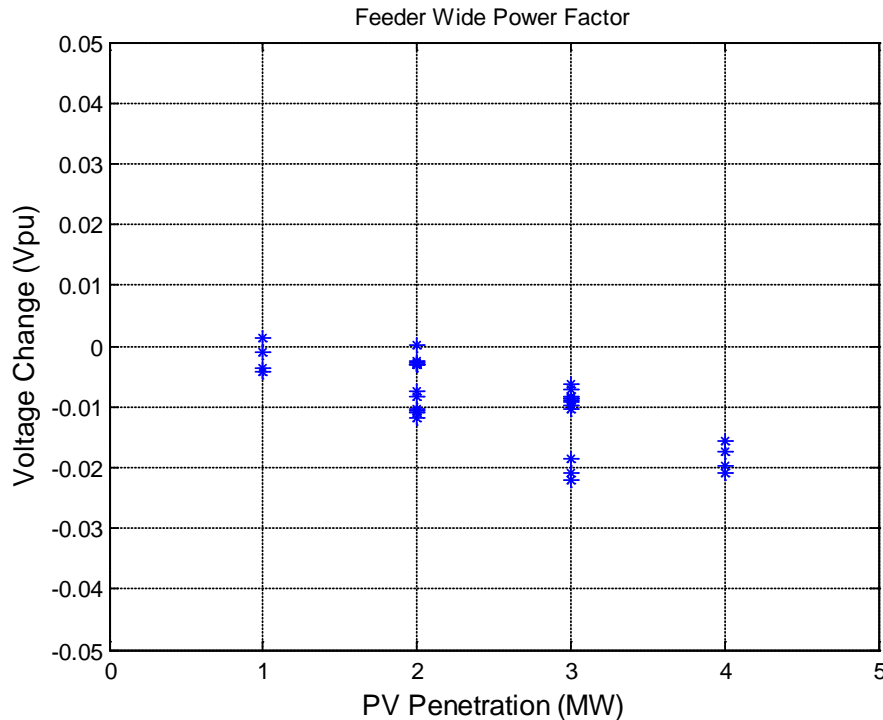
Voltage Response for Each Case (Voltages Measured @ POI)



The voltage rise due to the connected PV @ unity power factor increases with the increase of PV penetrations. The highest voltage rise is approximately 5% when all the four PV systems are connected.

Voltage Rise after Applying Method 1

Method 1	Power Factor
Median Feeder X/R	No PF control for PV1 All other PV use pf of -0.92



- This power factor is applied to all PV systems, other than PV1 which does not require power factor control due to minimal PV-induced voltage rise at that location.
- In some higher penetration levels this power factor setting over-mitigates the voltage rises and causes a 2% voltage drop.

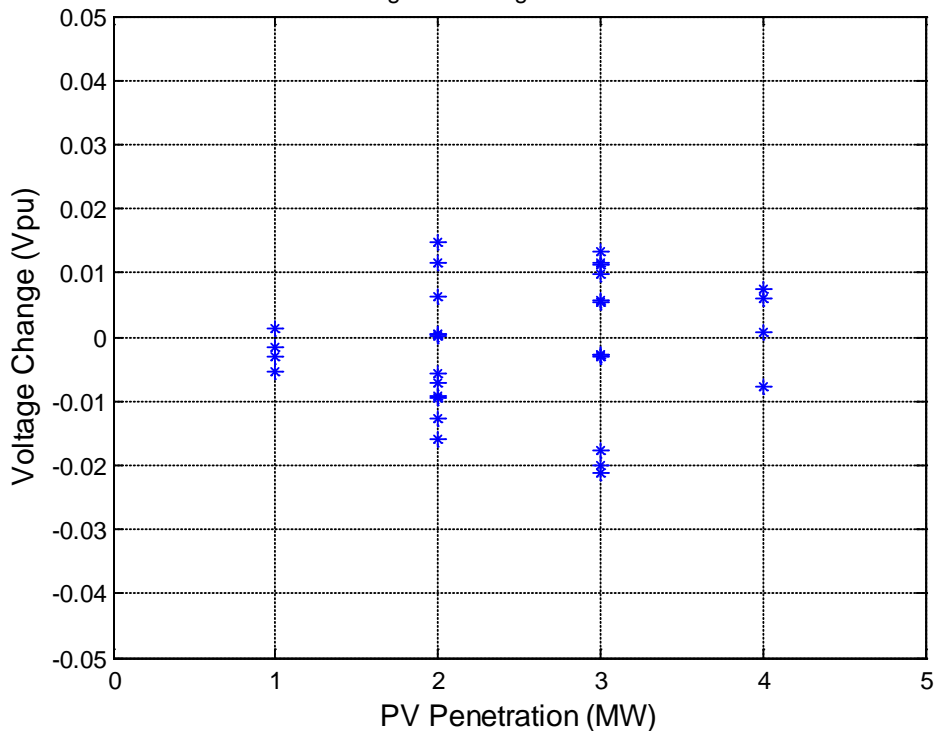
Voltage Rise after Applying Method 2

Method 2	Power Factor
X/R @ DER Location	No PF control for PV1 All other PV use the weighted average X/R based pf

Power Factors list (blank: no PV)

Case No.	PV1_PF	PV2_PF	PV3_PF	PV4_PF
1	1			
2		-0.93988		
3	1	-0.98302		
4			-0.90686	
5	1		-0.9806	
6		-0.92578	-0.92578	
7	1	-0.97303	-0.97303	
8				-0.91215
9	1			-0.98093
10	0	-0.92777		-0.92777
11	1	-0.97337		-0.97337
12			-0.90956	-0.90956
13	1		-0.97047	-0.97047
14		-0.92157	-0.92157	-0.92157
15	1	-0.96529	-0.96529	-0.96529

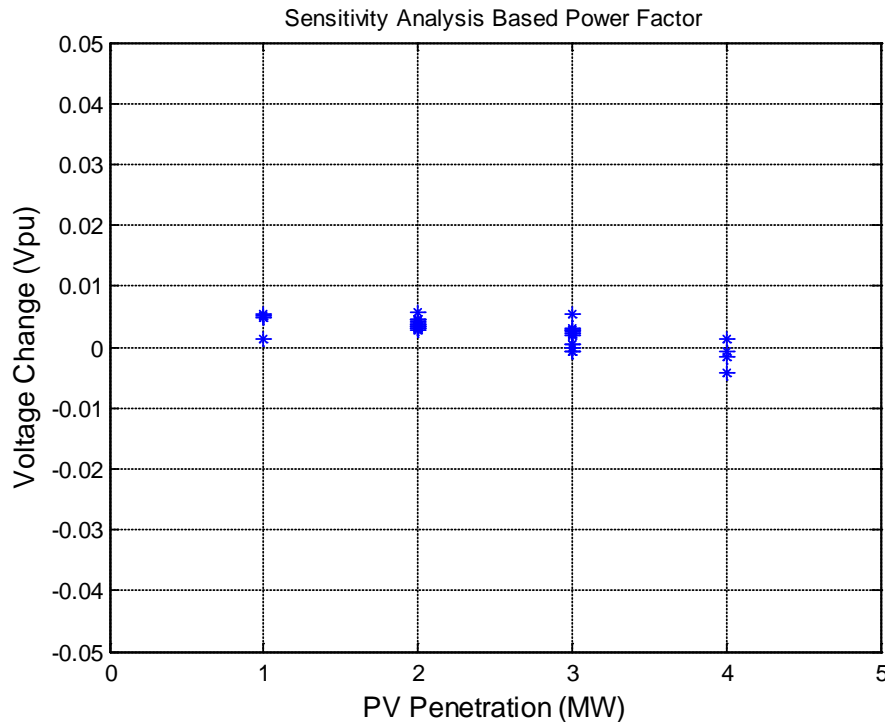
Weighted Average Power Factor



- In single PV scenarios (1 MW penetration) Method 2 yields similar results to Method 1.
- Using the aggregate DER location can still over-mitigate or under-mitigate the DER impacts yet the impact straddles the x-axis
- Impact improved in highest penetration scenarios.

Voltage Rise after Applying Method 3

Method 3	Power Factor
Sensitivity-Based Algorithm	Location and deployment dependent power factors



Power Factors list (blank: no PV)

Case No.	PV1_PF	PV2_PF	PV3_PF	PV4_PF
1	-0.99264			
2		-0.95216		
3	0.987535	-0.92363		
4			-0.92692	
5	1		-0.9	
6		1	-0.9	
7	1	-0.99806	-0.9	
8				-0.93621
9	0.97898			-0.91751
10	0	-0.98991		-0.90604
11	0.91627	-0.94827		-0.90752
12			-0.93905	-0.94643
13	0.973449		-0.9	-0.93391
14		1	-0.9	-0.90872
15	0.987867	-1	-0.9	-0.9109

- The voltage deviations are well within 1% band for all penetration levels.
- Most effective method although most complex

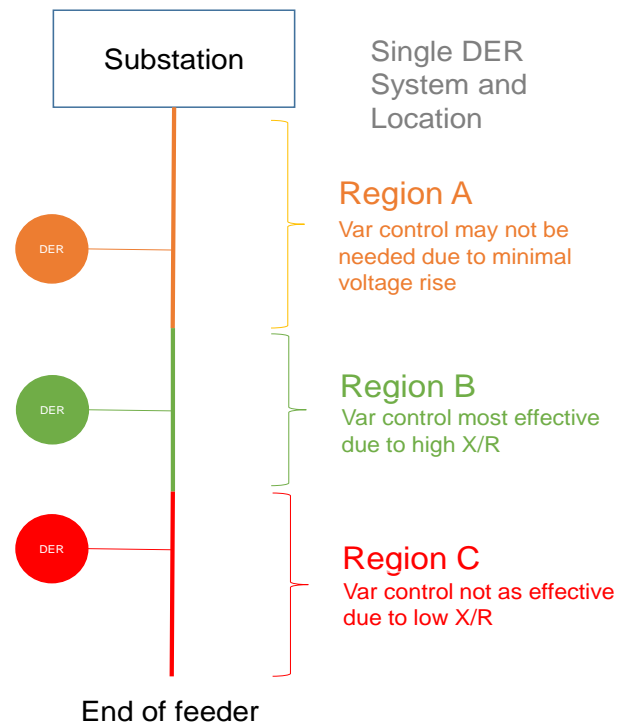
Summary Results for All Feeders

- Three methods were applied to all seven feeders and similar responses were observed.
 - Method 1
 - Limited improvement based on actual DER location
 - Method 2
 - Effective for single DER system
 - Limited improvement for the multi-DER scenario
 - Method 3
 - Effective approach for single or multiple systems

Summary of Findings for Determining Power Factor Settings

- **A single setting for feeder with multiple utility-scale DER does not work**
 - Can mitigate some voltage rise, but not very effective long term
 - Must customize settings based upon location
- **Single DER systems are simple**
 - Site-specific setting based upon POI X/R ratio is effective
- **Multiple locations require more care**
 - Simple techniques using aggregate location of DER can be used to help mitigate overvoltage
 - Sensitivity based approaches are most effective

- **Location does matter**
 - High short-circuit strength may not require any reactive power control
 - High X/R locations more effectively use reactive power control



Chapter 3 – Default Volt-Var Settings

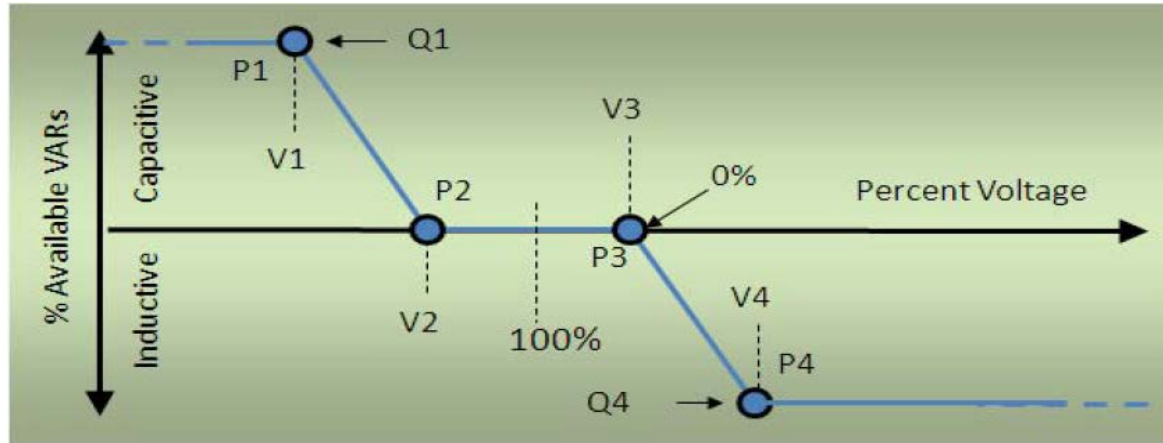
Chapter 3 – Default Volt-Var Settings

Power factor control can help reduce the voltage rise from distributed generation but may reduce voltage rise when it is not necessary.

The advanced inverter with the volt-var function can also reduce voltage rise but when set properly will only do so when necessary. This chapter examines a proposed default volt-var setting that provides effective compensation in a range of feeder conditions.

- Section 1 Background
- Section 2 Volt-var Function with the Proposed 1547 Draft Default settings
- Section 3 Sample Results
- Section 4 Summary

Background



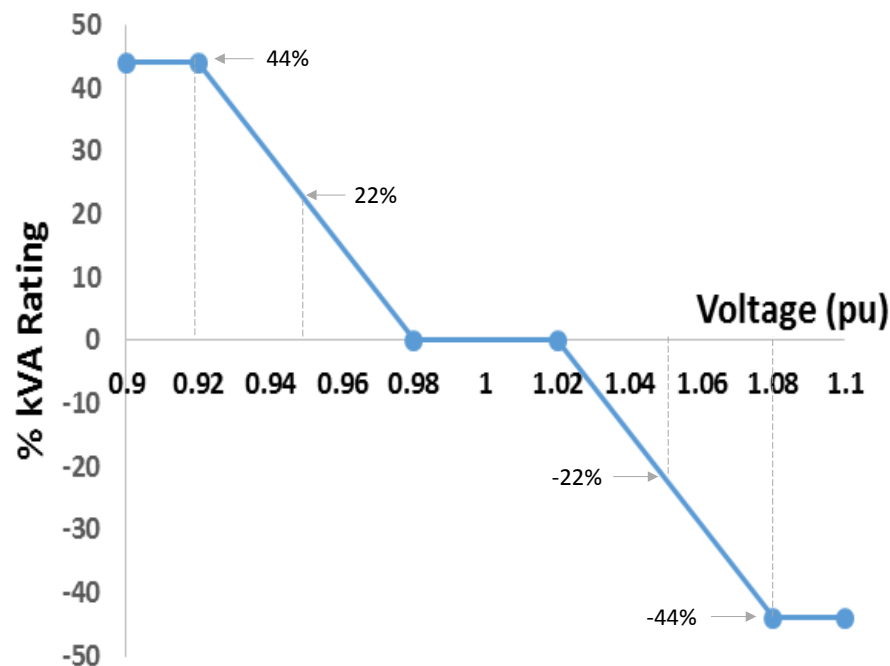
Volt-var Function

- Primary objective of a default volt-var setting is to help mitigate unacceptable voltage conditions caused by the DER, which include both minimizing overvoltage conditions and, in the case of variable generation such as solar and wind, minimizing the voltage variations
- Proposed default settings must be effective across a wide range of distribution system conditions
 - Should work in any given scenario without further engineering studies
 - Should not cause any adverse impact to the grid

Default Volt-Var Setting

Proposed by IEEE 1547 Voltage Regulation Subgroup

- The IEEE 1547 VR Subgroup has proposed a default volt-var curve as shown.
- The maximum reactive capacity is approximately 44% of the inverters kVA rating, equivalent to operating at +/- 0.9 power factor at full active power output
- Inside the deadband (0.98pu to 1.02pu) the inverter would effectively provide no reactive power
- Outside of the deadband however, the inverter is importing/exporting reactive power based upon the voltage
- Reactive power increases as voltages move further from the deadband
- At ANSI range of 1.05 and 0.95 pu, 22% of kVA rating is used
- Maximum reactive power would only occur with voltages at/below 0.92 Vpu or at/above 1.08 Vpu



IEEE Voltage Regulation Subgroup Proposed Volt-Var Settings

Default Setting Analysis Procedure

Approach: The proposed default setting is analyzed in a time-series simulation using OpenDSS. The seven feeders used in the power factor analysis are used once again here.

- Distribution Feeder Types chosen based upon
 - Feeder characteristics
 - DER feeder impact
 - Range of regulation equipment
- Inverter-Based Generation (Solar PV)
 - Size (dependent on feeder)
 - Low penetration
 - High penetration
 - Locations
 - Near substation
 - Near feeder-end
 - Solar Profile
 - Highly variable day
 - Sunny day
- Feeder Load Conditions
 - Light load
 - Peak load

Feeder #	Impact	Nominal Voltage (kV)	Peak Load (MW)	Voltage Regulators	Capacitors (kvar)	Feeder-End Impedance
1	High	4	2	0	0	2
2	High	12	6	1	2400	16
3	Moderate	12	8	0	4800	9
4	Low	21	13	0	9600	8
5	Low	12	6	0	1200	3
6	High	12	10	2	6000	9
7	Moderate	12	4	0	1200	8

High Impact Feeder Characteristics – Feeder 2

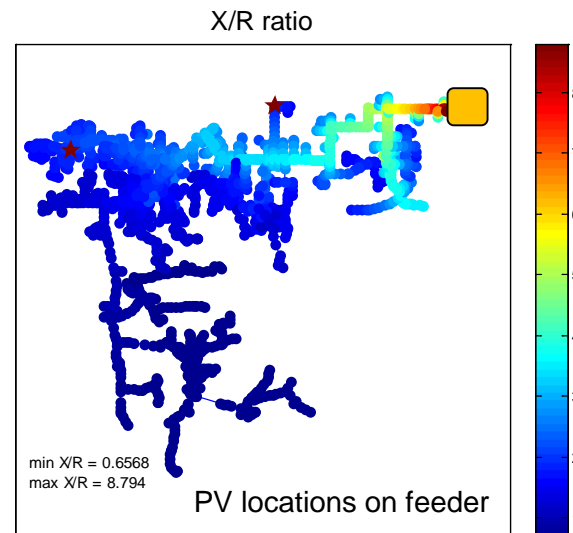
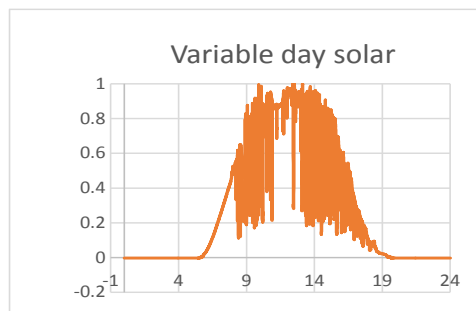
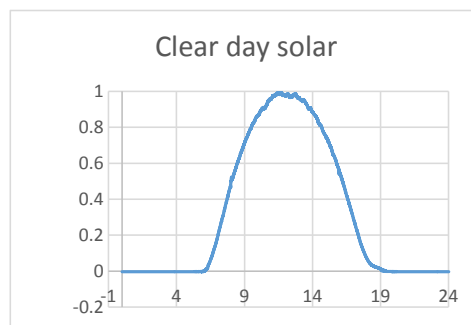
This is a more detailed description of one of the high impact feeders. The next few slides illustrate the voltage improvement using the proposed volt-var settings.

- 12 kV circuit
- 72 primary ckt miles
- 11 miles to feeder end
- Load/Customers
 - 1107 residential/ 132 commercial
 - Peak load 6.2 MW
- Feeder regulation
 - LTC at sub
 - Line regulator
 - Cap banks, voltage controlled
 - Low voltage due to conservation voltage reduction control

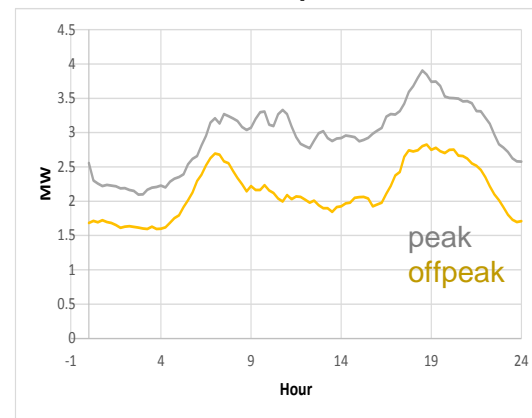
Simulated PV

PVs	Z	X/R
PV1	5.34	1.97
PV2	3.69	1.84

Solar profiles



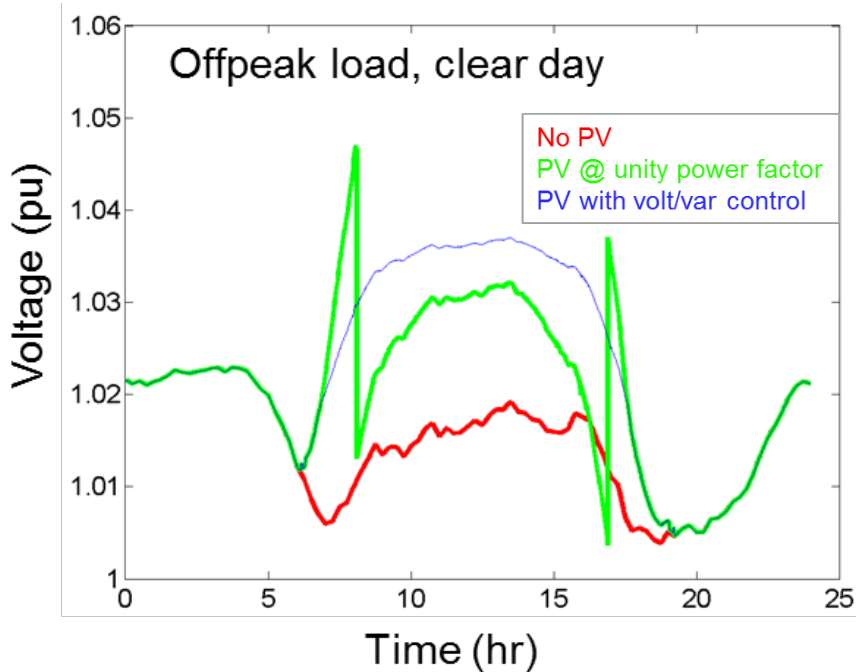
Load profiles



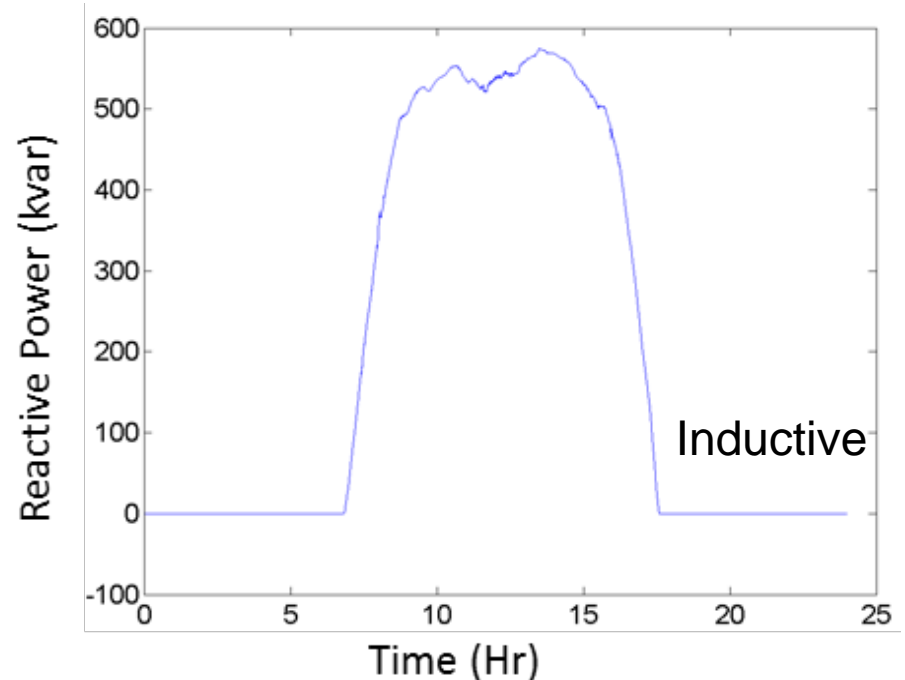
High Impact Feeder Voltage Response

– Offpeak Load, Clear Day

Voltage



Reactive Power

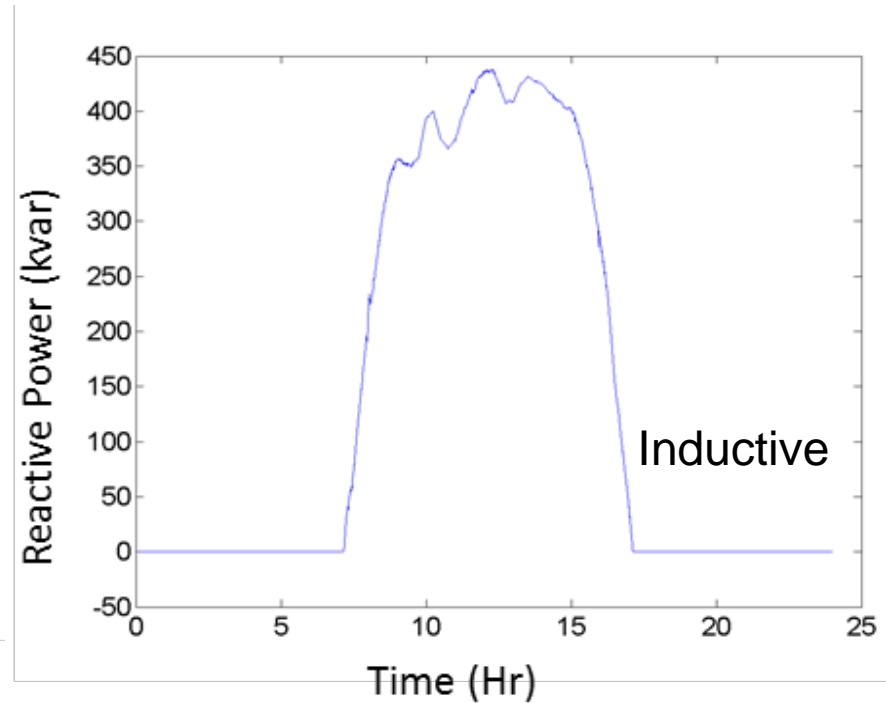
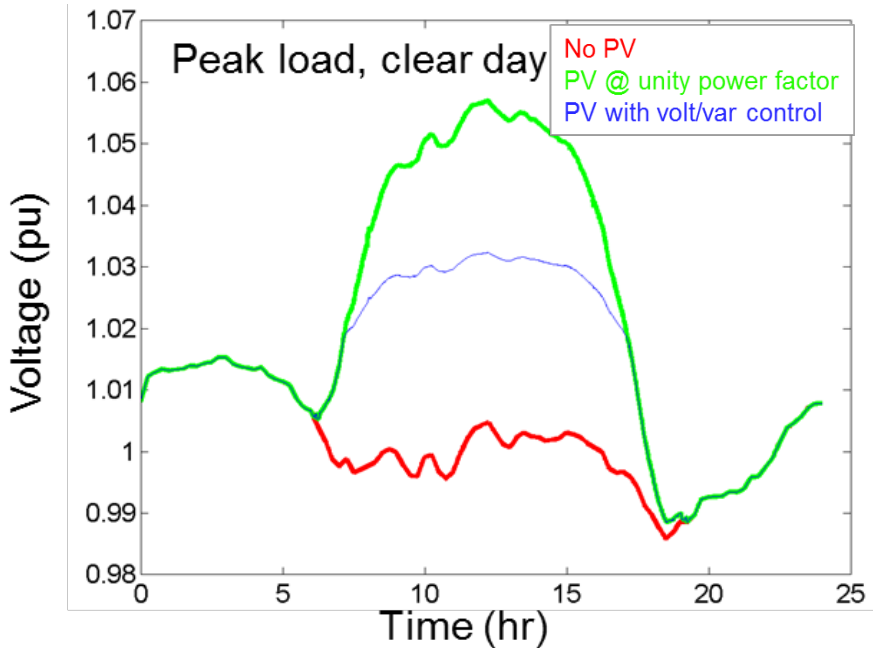


Volt-var control with the default setting reduce the capacitor banks switch.

High Impact Feeder Voltage Response – Peak Load, Clear Day

Voltage

Reactive Power

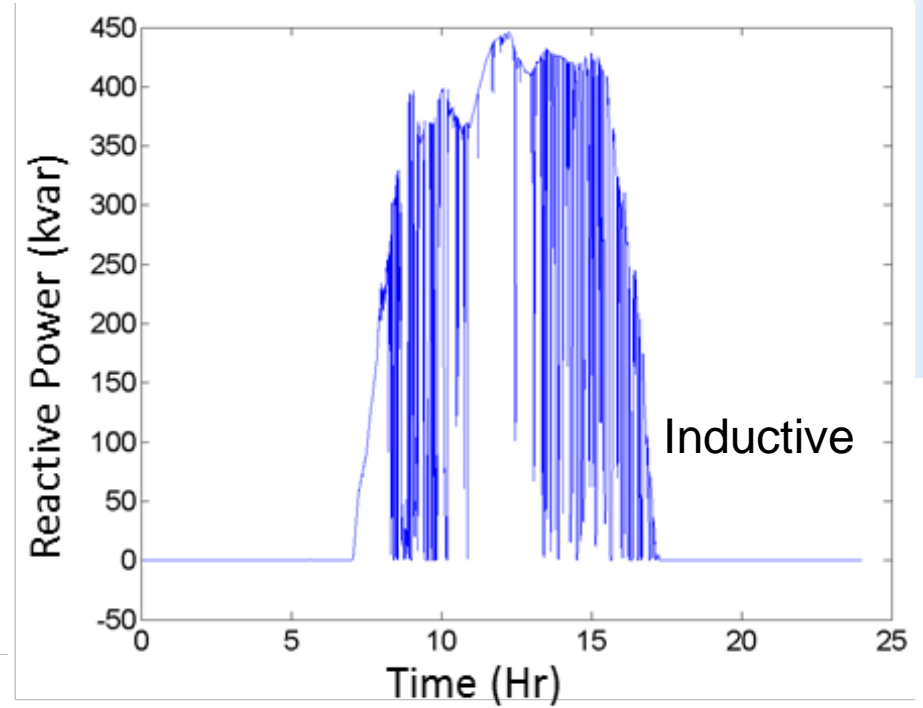
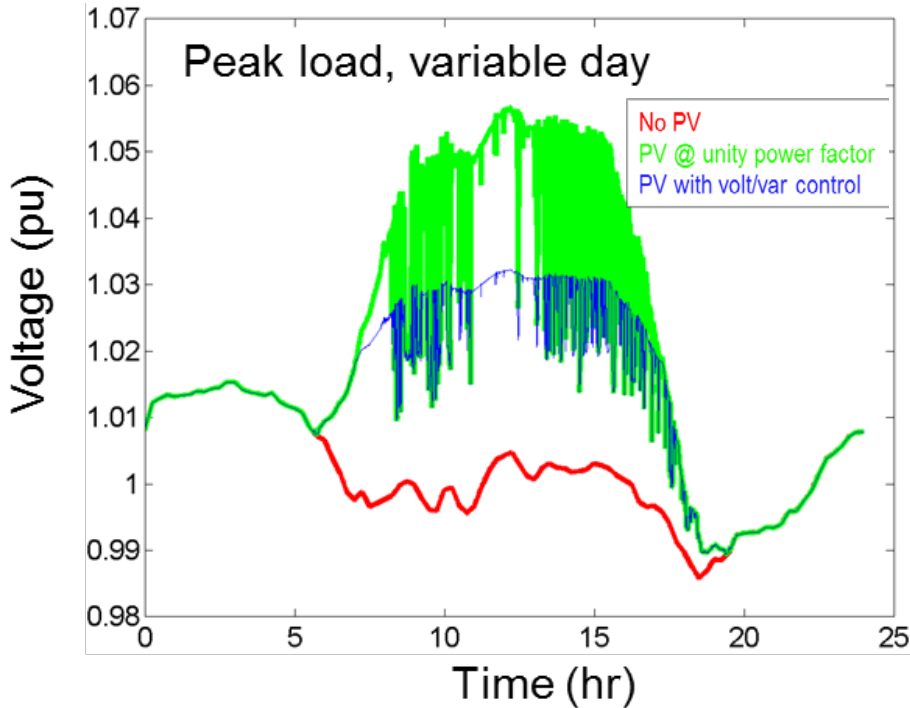


Volt-var control with the default setting mitigates overvoltage.

High Impact Feeder Voltage Response – Peak Load, Variable Day

Voltage

Reactive Power



Volt-var control with the default setting significantly reduces voltage fluctuations.

High Impact Feeder Line Regulator and LTC Operations

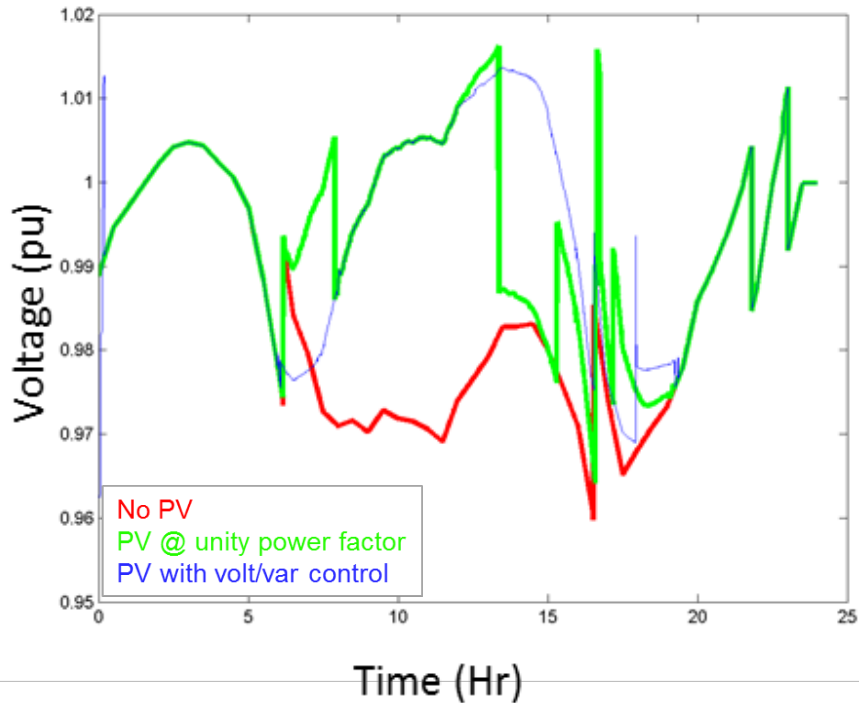
Total daily LTC and line regulator tap operations

		Clear Day		Variable Day	
Load	No PV	Unity power factor	Volt-var	Unity power factor	Volt-var
Peak	1	5	1	4	0
Offpeak	0	5	0	67	0

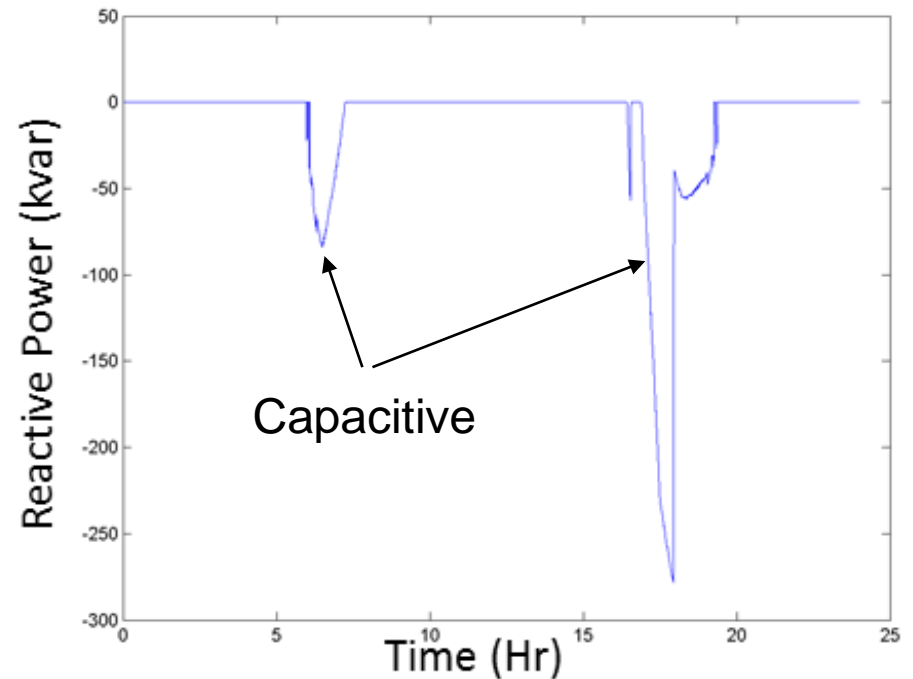
Taps operations are reduced through use of the default volt-var control

Voltage Response of Another Example Feeder – Feeder 3

Voltage



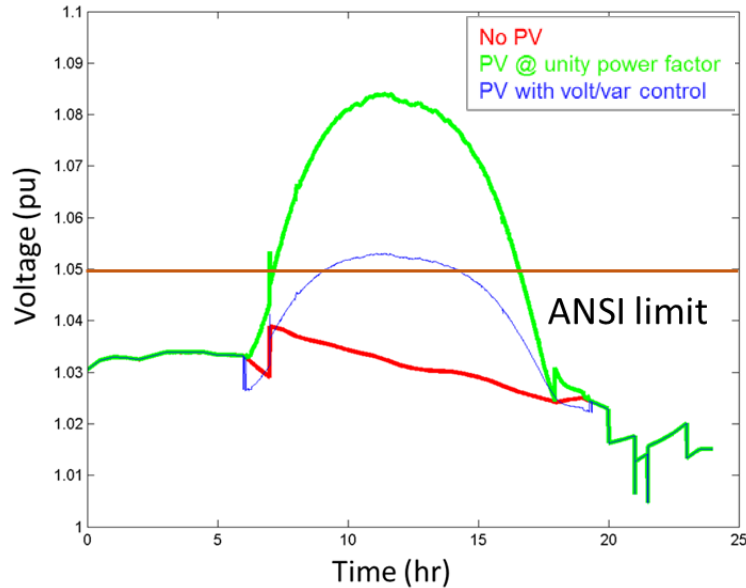
Reactive Power



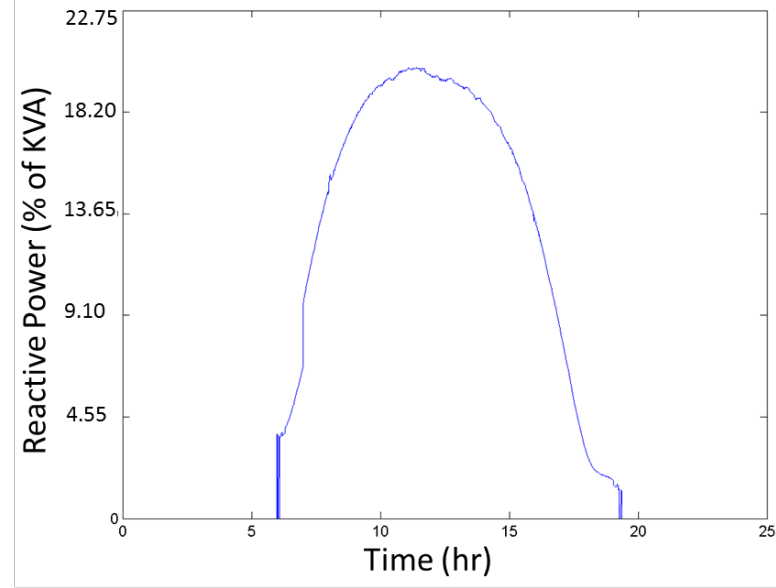
Volt-var control with the default setting also helps support feeder voltage by injecting capacitive reactive power during low voltage conditions.

Voltage Response of Another Example Feeder – Feeder 4

Voltage



Reactive Power



In this case, the volt-var control provides some mitigation for overvoltage, however the non-aggressive slope of the volt-var curve limits the reactive power output.

Summary

- All seven unique feeders simulated are found to have similar responses in which voltage rise and voltage variability induced by the PV is reduced with the proposed default volt-var curve.
- The comparison is made to the inverter operating at unity power factor. Although voltage rise and variability is found to reduce in all scenarios, that does not imply that all overvoltages can be eliminated with the default setting
- More aggressive settings (requiring more than 20% reactive power at the ANSI limits of 0.95 and 1.05 Vpu) may be needed to reach some feeder/DER scenarios where voltage rise on the feeder may be more significant requiring additional reactive compensation

Chapter 4 – Combined Functionality of Common Functions

Chapter 4 – Combined Functionality of Common Functions*

The proposed default volt-var setting in the previous chapter compensates for voltage rise based on the current point of interconnect voltage. This chapter illustrates the additional benefit that can be attained from advanced inverters if the default volt-var function is combined with another common function specifically designed to compensate for voltage variability.

- Section 1 Combining Smart Inverter Functions
- Section 2 Feeder Response with volt-var Combined with additional Function
- Section 3 Summary

**Common Functions for Smart Inverters, Version 3. EPRI, Palo Alto, CA: 2013. 3002002233.*

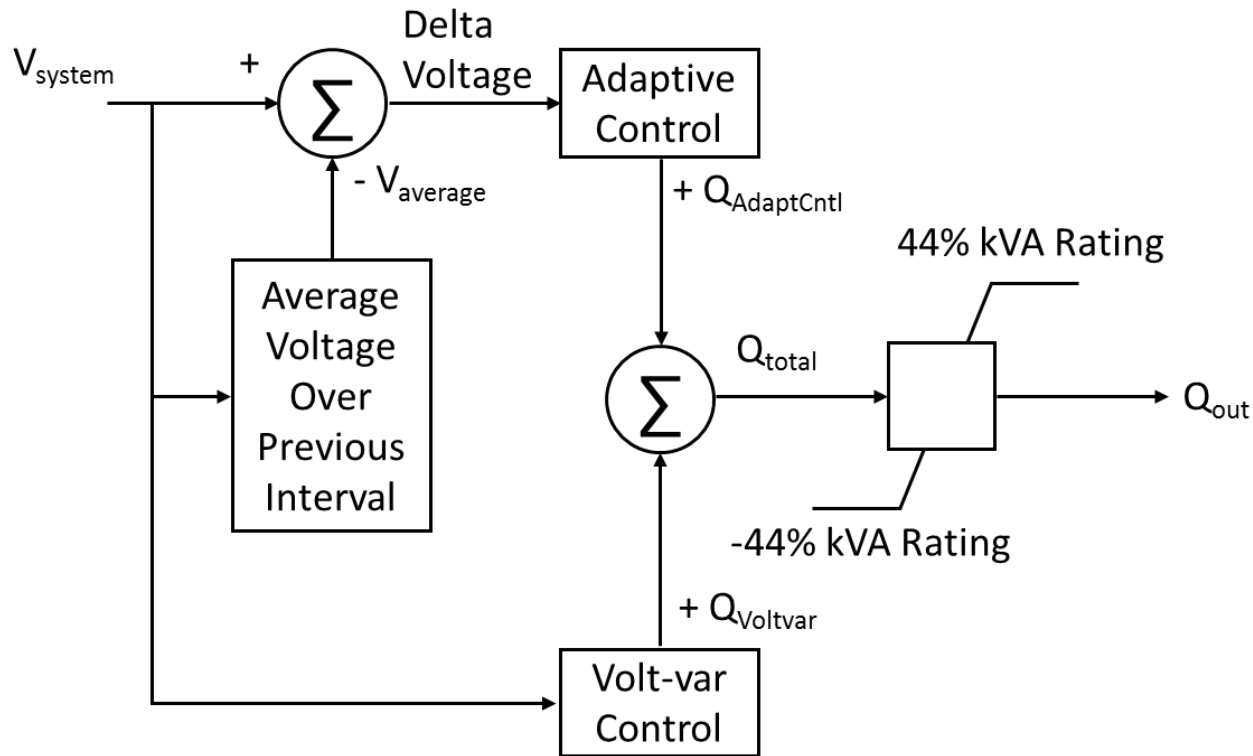
Combining Volt-Var with Adaptive Control

The Common Functions* document outlines a function called Dynamic Reactive Power. The function adjusts reactive power output to compensate for the change in measured voltage. To prevent confusion on how the function relates to dynamic events, the function is renamed here as Adaptive Control.

- Volt-var Control
 - Fixed voltage points
 - Shown to be very effective at mitigating overvoltages
- Adaptive Control
 - Adaptive control compensates for change in voltage, not absolute voltage magnitude. The Adaptive Control's reactive output is a function of deviation in voltage
 - Known as Dynamic Reactive Current in Common Functions Documentation*
- Volt-var can help compensate for voltages at ANSI limits, while Adaptive Control can adapt to daily changes in voltage and respond accordingly
- Combining these functions can effectively mitigate overvoltage and voltage fluctuations

**Common Functions for Smart Inverters, Version 3. EPRI, Palo Alto, CA: 2013. 3002002233.*

Control Diagram of Combined Functionality



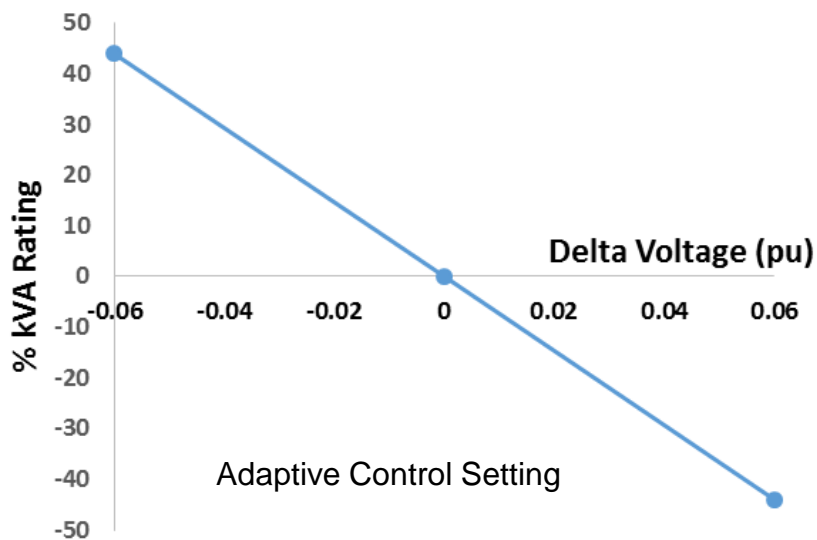
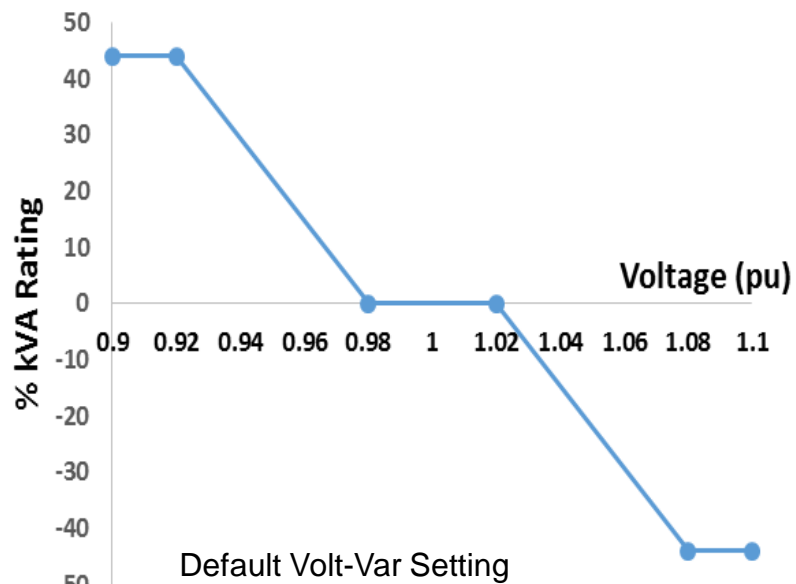
Control Diagram of Combined Functionality

Volt-var can help improve voltages near ANSI limits, while the Adaptive Control function can adapt to daily changes in voltage and respond accordingly.

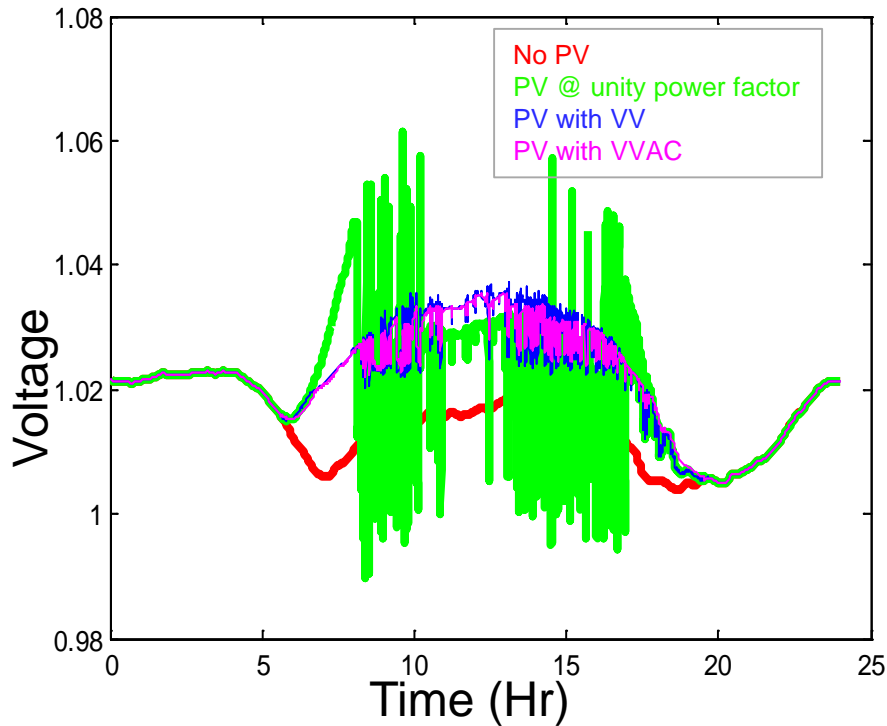
Volt-Var with Adaptive Control Settings

These control settings are applied in the simulation results shown on the following page.

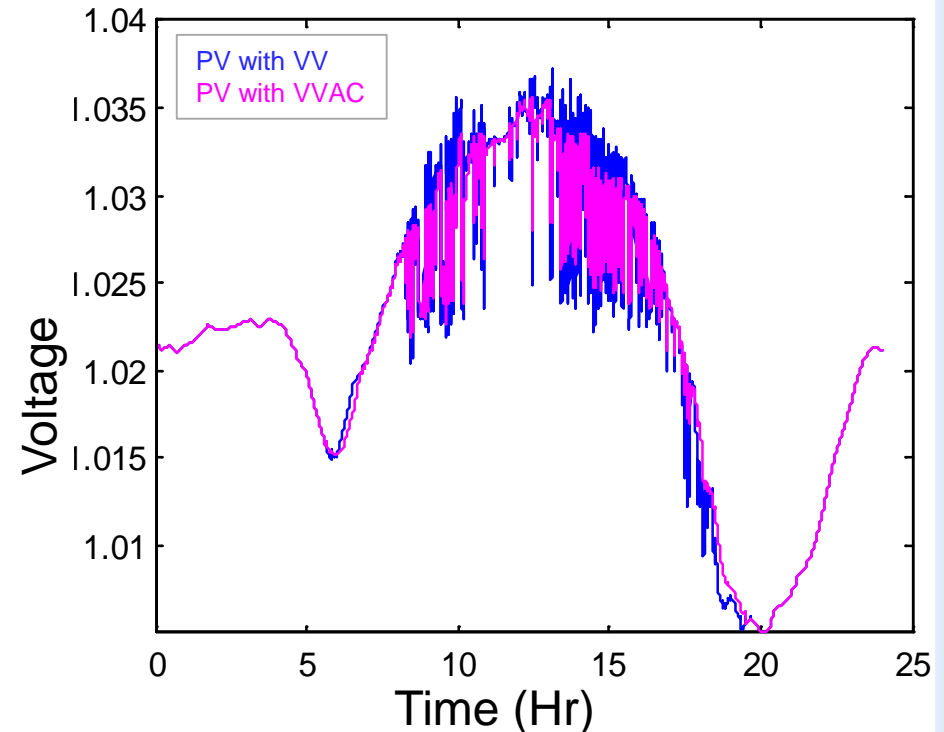
- Volt/var
 - Proposed default 1547 volt-var curve
- Adaptive Control
 - Curve: same slope as volt-var default setting
 - Voltage averaging window: 5 minutes



Feeder Response from Default Volt-var with Adaptive Control



Voltage Comparisons



Closer comparison of 1) volt-var and 2) volt-var with Adaptive Control

- Combined volt-var and Adaptive Control further reduce the voltage variations

Summary

- Volt-Var with Adaptive Control is NOT a custom function
 - It is a combined response using common functions previously defined through industry collaborative (Volt-Var and Dynamic Reactive Current)
- Default 1547 volt-var settings with Adaptive Control achieves improved response over Volt-var alone

Volt-var with adaptive control updated in OpenDSS and available for download in latest release

Chapter 5 - Conclusion

Chapter 5 – Conclusion

Main Points

■ Power Factor Methods

- Determining a setting for feeder with single DER is effective and simple to calculate
- Simple calculations are less effective for feeders with multiple utility-scale DER
- Sensitivity based approaches are most effective when multiple DER systems are present

■ Default Volt-var Settings

- Results indicate improved integration of DER
- Results indicate no adverse impacts found
- Effective “out-of-the-box” setting
- “Non-aggressive” curve improves voltage in all simulations but does not take advantage of full reactive power capability of DER

■ Volt-var with adaptive control

- Default 1547 volt-var settings with adaptive control achieves improved response over default volt-var alone
- Uses Common Functions – not custom functions

Additional Considerations

■ Custom settings are most effective

- Custom settings can be “tuned” based upon conditions
- Can yield higher hosting capacities
- More use of reactive power control

■ Proper sizing of inverter is critical

- 110% above DC rating for PV is sufficient (+/- 0.9 power factor @ full output)

■ Location does matter

- High short-circuit strength may not require any var control (inductive)
- High X/R locations are most responsive to reactive power
- Low X/R may require other methods to mitigate voltage issues

Appendix – References

References

- Analysis Method and Results for Determining Optimal Inverter Settings for Improved Integration of Solar PV. EPRI, Palo Alto, CA: 2015. 3002007131
- Alternatives to the 15% Rule: Modeling and Hosting Capacity Analysis of 16 Feeders. EPRI, Palo Alto, CA: 2015. 3002005812.
- Rylander, M., Abate, S., Smith, J, Li, H., "Integrated Control of Photovoltaic Inverters to Improve Distribution System Performance", accepted for presentation at CIGRE Canada 2014 Conference, September 2014.
- "Smart Grid Ready PV Inverters with Utility Communication Quarterly Report", DOE, DE-EE0005337, July 2014
- A. Samadi, R. Eriksson, L. Söder, B. G. Rawn and J. C. Boemer, " Coordinated Active Power-Dependent Voltage Regulation in Distribution Grids With PV Systems ", IEEE Transactions on Power Delivery, 2014
- Grid Impacts of Distributed Generation with Advanced Inverter Functions: Hosting Capacity of Large-Scale PV Using Smart Inverters. EPRI, Palo Alto, CA: 2013. 3002001246.
- Modeling High-Penetration PV for Distribution Interconnection Studies: Smart Inverter Function Modeling in OpenDSS, Rev 2. EPRI, Palo Alto, CA: 2013. 3002002271.
- Modeling of Inverter Control with Distribution Management System for Distributed Energy Resources. EPRI, Palo Alto, CA: 2013. 3002001243.
- Field Verification of High-Penetration Levels of PV into the Distribution Grid with Advanced Power Conditioning Systems, Phase III, Dept of Energy (DOE) Award No. EE0004681, 2012-2013.
- Advanced Voltage Control Strategies for High Penetration of Distributed Generation: Emphasis on Solar PV and Other Inverter-Connected Generation. EPRI, Palo Alto, CA: 2010. 1020155.
- Smith, J., Sunderman, W. Dugan, R., Seal, B., "Smart Inverter Volt/Var Control Functions for High Penetration of PV on Distribution Systems," IEEE PES Power Systems Conference and Exposition, Phoenix, AZ, 2011
- Smith, J., Seal, B., Key, T., "Facilitating Higher Penetration Of Photovoltaics On Distribution Networks With Advanced Inverter Controls," CIGRE Symposium, Electric Power System of the Future, Bologna, Italy, 2011.
- Smith, J., Seal, B., Sunderman, W., Dugan, R., "Simulation of Solar Generation with Advanced Volt-Var Control," 21st International Conference on Electricity Distribution, CIRED, Frankfurt, Germany, 2011
- Smith, J., Rylander, M., Sunderman, W., The Use of Smart Inverter Controls for Accommodating High-Penetration Solar PV, Distributech Conference and Exhibition, San Diego, CA, Jan 2013

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

3002007139