Some considerations of operations of PV inverters in Electric Power Systems

Nokhum Markushevich

Smart Grid Operations Consulting

www.smartgridoperations.com

1. Introduction

High penetration of renewable generation in the Electric Power Systems (EPS) will introduce significant new monitoring objects and controllable variables in the realm of EPS operations. These variables will also constitute some of the aggregated variables to be monitored and controlled by both distribution and transmission applications, and thus will need to be included in the Transmission Bus model [1]. In this white paper, we discuss some aspects related to the operations of renewable distributed resources with inverters capable of generating/absorbing reactive power, mostly to the photovoltaic (PV) generation, in the area of voltage and var control. Although, according to [2], Distributed Energy Resources (DER) are not supposed to actively regulate the voltage at the Point of Common Coupling (PCC), they can be requested by the EPS to follow certain rules of voltage and var support for the EPS. In relation to Volt/var support, the possible modes of operations of conventional distributed generators are as follows:

- Constant active and constant reactive power (PQ mode), with or without voltage override
- Constant active power and constant voltage (PV mode)

Discussions on these and other modes of Volt/var control by inverter-based DER are presented in [3-6].

This paper is an attempt to supplement these publications with a discussion on the relationships between the volt/var modes of operations of DER and the variability of the active power of DERs. The solar and wind generators cannot be considered constant for any given extended time interval, because it depends on the ambient conditions. Therefore, the PQ and PV modes cannot be directly applied to these DR. The following modes of volt/var control can be suggested for such generators:

- Variable P and constant Q, with or without voltage override
- Variable P and constant Power Factor, with or without voltage override
- Variable P and constant voltage at a given bus.
- Variable P and maximum (minimum) Q, with or without voltage override

All these modes of operations of DER are constrained by the DR capability curves, which present relationships between the reactive and active powers and the voltage.

The following three aspects in relations to these modes are discussed in this white paper:

1. The capability curves
2. The behavior during intermittent operations
3. The impact on the models of loads with embedded DERs.

The following assumptions are made for this discussion:

- The operations of the inverter are limited by the AC current
- The current limit is referenced as a base (1 pu). It means that with the rated voltage equal 1 pu, the rated active power is equal to the rated Power Factor (PF). It also means that the capability curve is symmetrical for the inductive and capacitive modes of inverter operations.

Other constraints of the invertors operations are possible [e.g., 7]. Also, the impact of filtering out the higher harmonic components [8] was not taken into account in these analyses. However, we believe that the conclusions derived in this paper are conceptually applicable to the three aspects addressed in this paper.

2. Capability of PV inverter as a reactive resource

The capability curve of an inverter expressed as a dependency on the AC voltage is presented in Figure 1. As seen in the figure, the reactive power capability changes in a wide range dependent on both active power and voltage. Under no or small active power generation, the reactive power capability may exceed 1, when the voltage is above the rated level. When the voltage is low, even under active power below the rated value, the reactive power capability may significantly drop.

If the inverter is set into a constant reactive power mode, it can be executed until the voltage is above a certain level and the active power is below a certain value. For instance, as follows from Figure 1, the setpoint of Q=0.5 under P=0.9 can be met as long as the voltage is above 1.04, and if P=0.8, the voltage should be above 0.95.

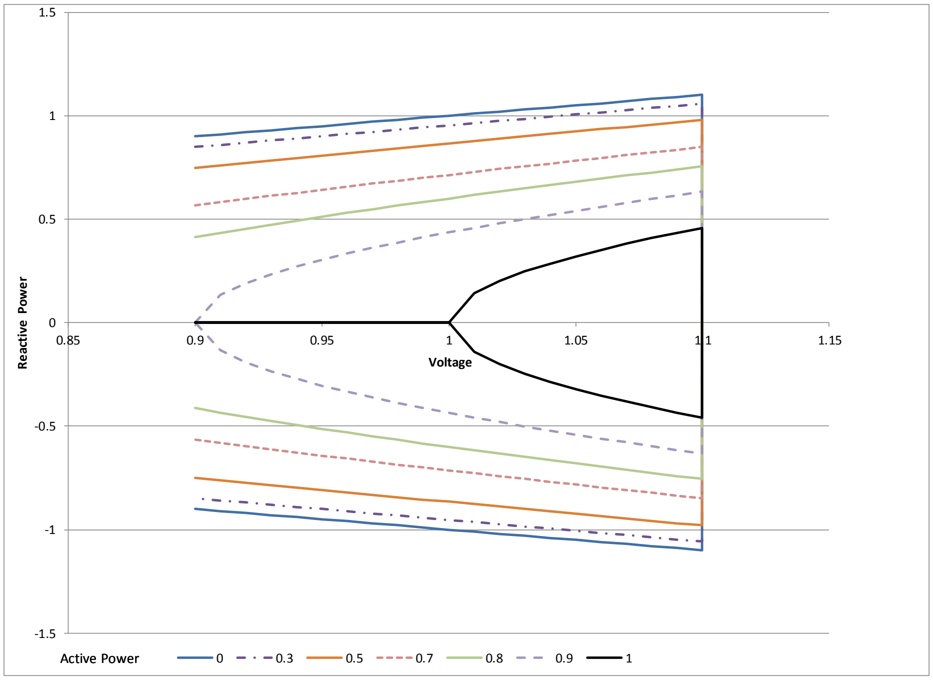

Figure 1. Capability curves of an inverter

Figure 2 presents a graph of the dependency of the reactive power of an inverter in the constant Q mode with voltage override, when the initial Q=0, derived based on the capability curves presented in Figure 1. As seen in the figure, under some levels of active power and voltages, the desired setting cannot be executed. The execution of such setting be much more restricted, if initially Q>0 (Figure 3).

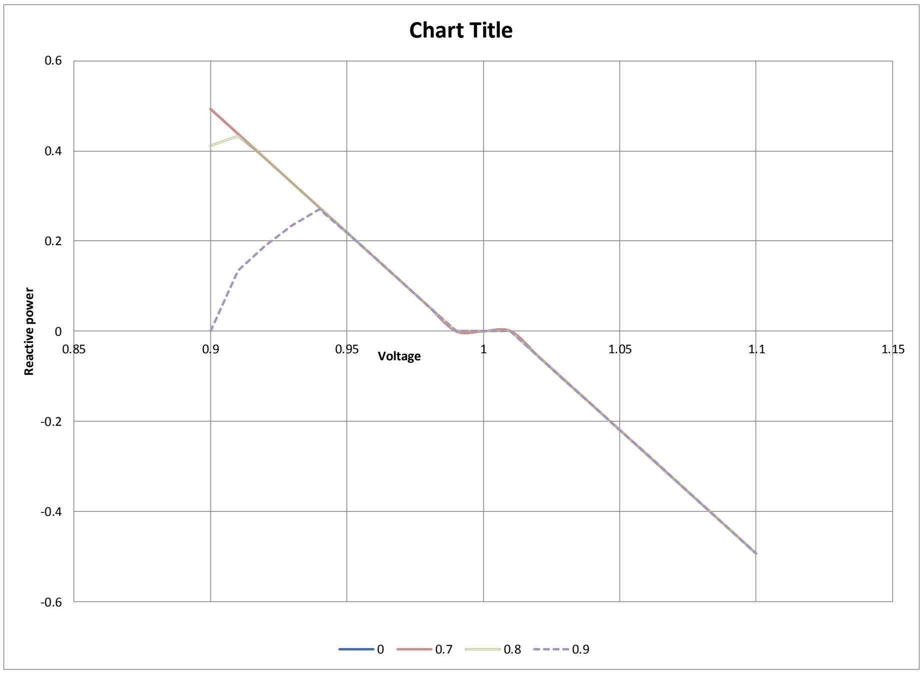

Figure 2. Q=f (V) dependency of inverter in Q=const mode with voltage override. Initial reactive power = 0

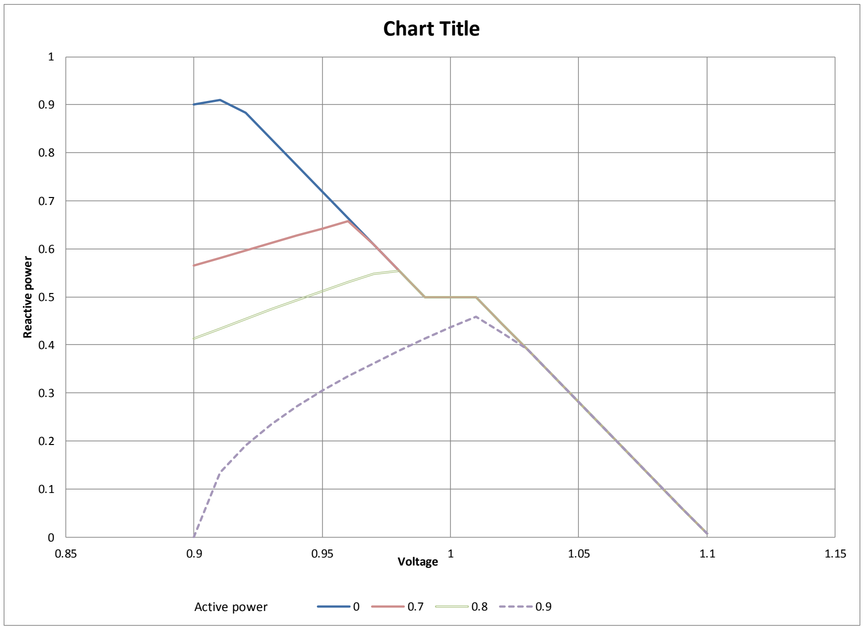

Figure 3. Q=f (V) dependency of inverter in Q=const mode with voltage override. Initial reactive power = 0.5

Figure 4 displays the impact of the capability curve on the behavior of the inverter in constant voltage mode. In this example, there are two scenarios: a) the initial voltage is low (0.95), and the inverters tries to raise the voltage to the target voltage = 0.99, and b) the initial voltage is high (1.05), and the inverter tries to reach the target voltage = 1.01. The initial Q=0 in both cases. As seen in the figure, the inverter is a little short of reaching the target voltages due to the limited reactive power capability under the corresponding voltages.

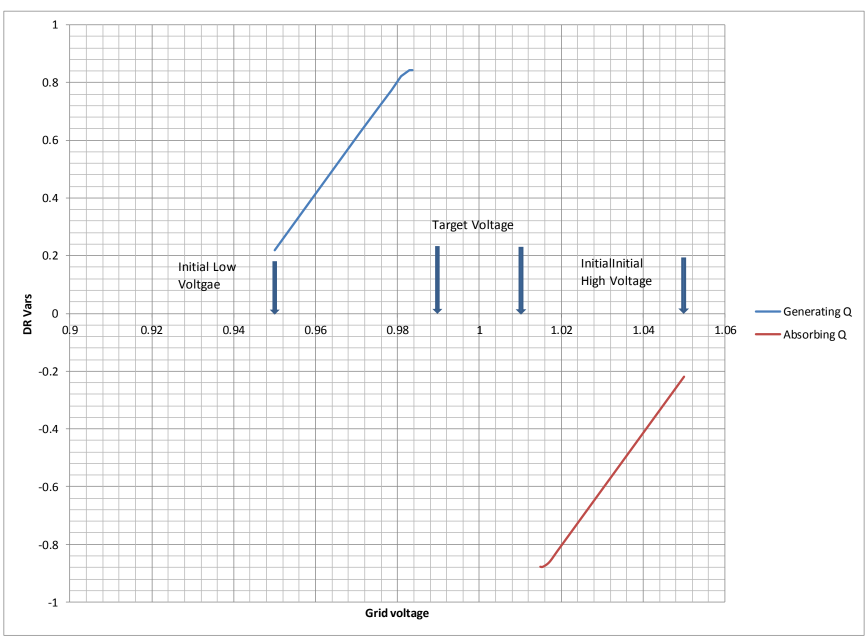

Figure 4. Inverter in constant voltage mode. Voltage setting = 0.99 – 1.01. The initial voltage in low voltage scenario is 0.95. The initial voltage in high voltage scenario is 1.05. P=0.6; Short Circuit ratio = 0.04.

The effectiveness of the constant voltage mode depends on the distance of the DER from the slack bus. Figure 5 displays a case, when the electric distance is two times smaller than in the previous case. As seen in the figure, the target voltage is more out of reach then it was in the previous example.

If the active power of the inverter is 0.9, the target voltage cannot be reach either, even at the large distance from the slack bus (see Figure 6).

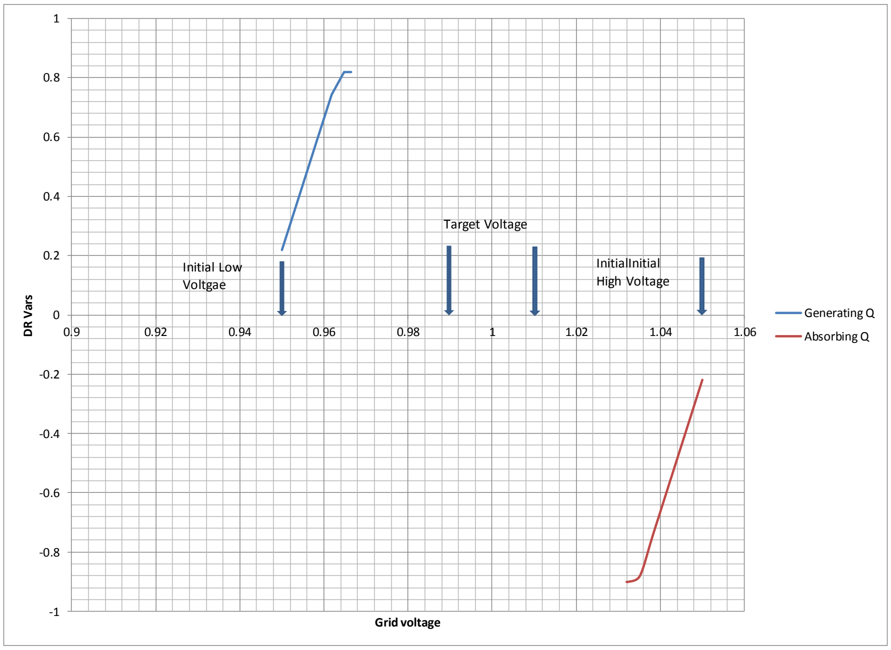

Figure 5. . Inverter in constant voltage mode. Voltage setting = 0.99 – 1.01. The initial voltage in low voltage scenario is 0.95. The initial voltage in high voltage scenario is 1.05. P=0.6. Short Circuit ratio = 0.02.

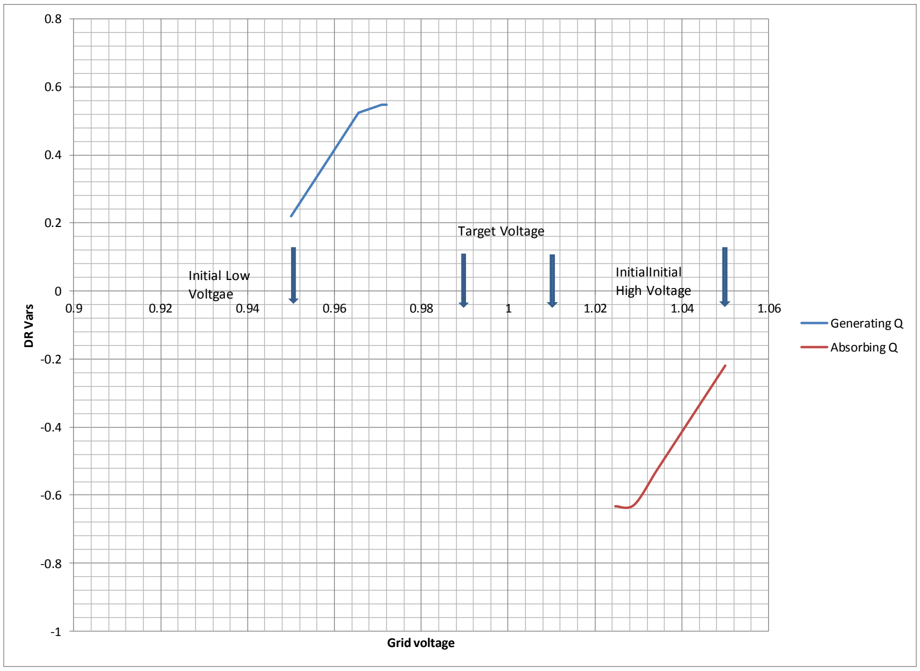

Figure 6. Inverter in constant voltage mode. Voltage setting = 0.99 – 1.01. The initial voltage in low voltage scenario is 0.95. The initial voltage in high voltage scenario is 1.05. P=0.9; Short Circuit ratio = 0.04.

3. Modes of intermittent operations

The intermittent changes of active power of PV (and Wind) generation cause voltage fluctuations in the EPS circuits, which sometimes may be unacceptable. One of the objectives of volt/var control by the DER is to compensate these fluctuations by corresponding changes of reactive power. It should be noted that the voltage fluctuations at a particular node of the EPS can be caused by intermittent operations of a DER in this or close node, as well as by combined intermittent operations of other DERs in remote nodes. One of the ways to compensate the voltage fluctuations caused by a DER in the same node is to set the inverter in a constant absorbing PF mode (see e.g. [9]). The change of the reactive power ΔQ needed to compensate the voltage fluctuation caused by a change of active power ΔP is defined as follows:

$$\Delta Q \approx -\Delta P \times \frac{R}{X} \qquad (1)$$

where R and X are the total resistance and reactance between the slack bus and the point where the constant voltage is desired. Based on this relationship, the desired power factor is

$$PF = \cos(\operatorname{atan}\frac{R}{X}). \quad (2)$$

We call the ratio of actual reactive power change to the change according to equation (1) the compensation factor.

Figure 7 through Figure 10Figure 9 illustrate the compensation factors for different $\frac{R}{X}$ ratios and different power factors settings. These examples present cases when the change of active power is the same (0.7), but in different ranges: from P=0 through P=0.7; from P=0.1 through P=0.8; from P=0.2 through P=0.9; and from P=0.3 through P=1.

As seen in the figures, if the power factor setting does not match equation (2), the compensation factor differs from unity, i.e., the fluctuation caused by the change of active power is not compensated by the change of reactive power (the compensation factor is smaller than 1 in Figure 8 and Figure 10). The compensation factor may also be smaller than 1, when the setting is correct, but the reactive power is constrained by the capability curve. Such cases can be seen in Figure 7 and Figure 9, when the changes of active power are from P=0.2 through P=0.9 and from P=0.3 through P=1.0, and the voltages are below some levels. If the setting of the power factor is lower than in (2), the compensation factor will be greater than 1, and the fluctuation will be overcompensated.

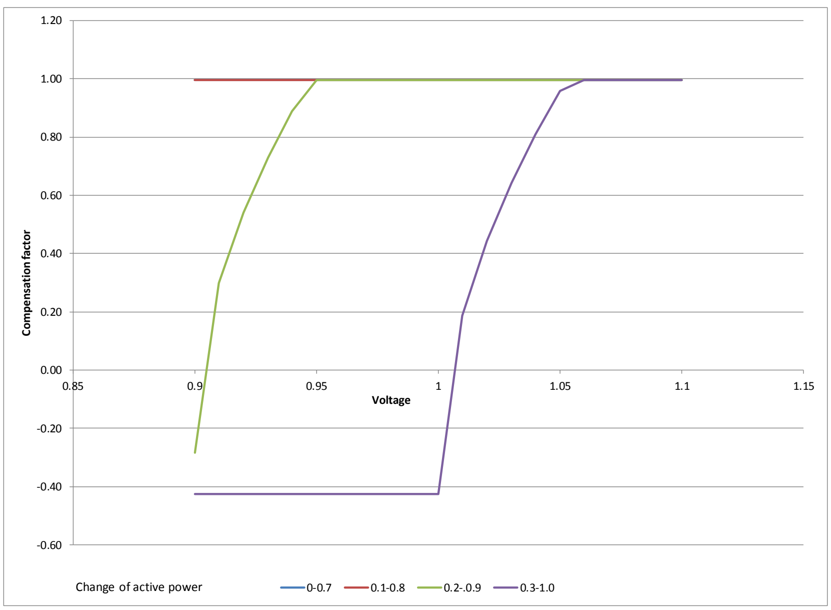

Figure 7. Compensation of voltage fluctuations caused by change of active power with inverter in constant capacitive PF mode. x/r ratio = 3, PF = 0.95

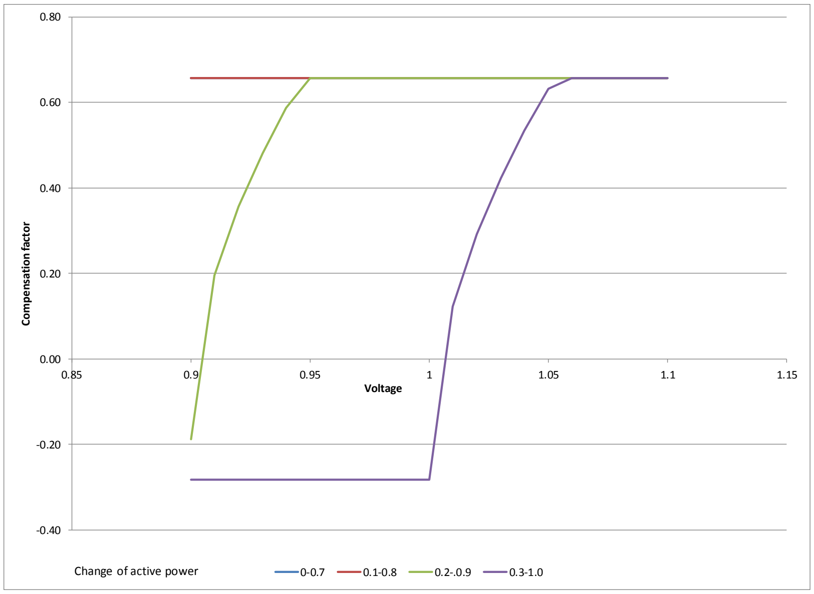

Figure 8. Compensation of voltage fluctuations caused by change of active power with inverter in constant capacitive PF mode. x/r ratio = 2 Rated PF=0.95

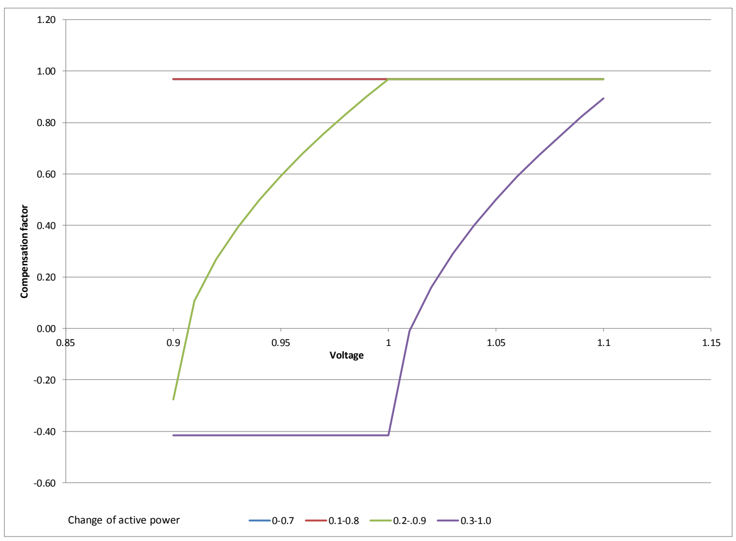

Figure 9. Compensation of voltage fluctuations caused by change of active power with inverter in constant capacitive PF mode. x/r ratio = 2, Rated PF=0.90

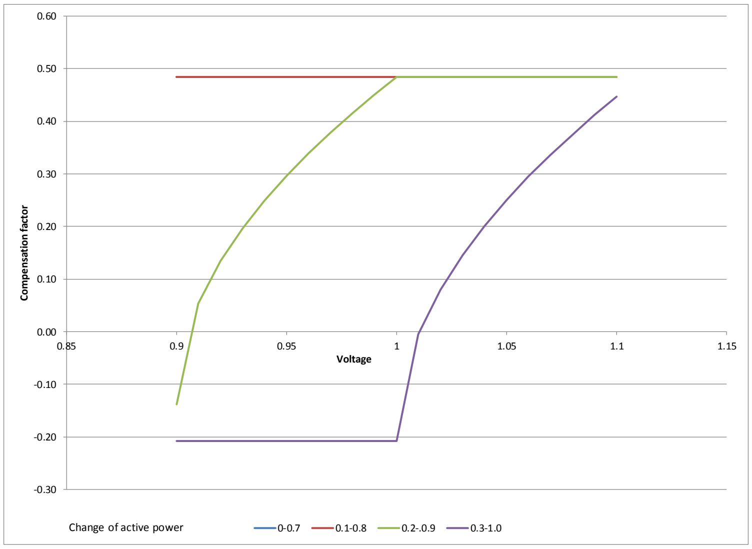

Figure 10. Compensation of voltage fluctuations caused by change of active power with inverter in constant capacitive PF mode. x/r ratio = 1, Rated PF=0.90

When the active power is smaller, the inverter may have the capability to operate with a smaller power factor than the one defined by power factor setting. This capability can be utilized, if the inverter is in the constant voltage mode. Such examples are presented in Figure 11 through Figure 13.

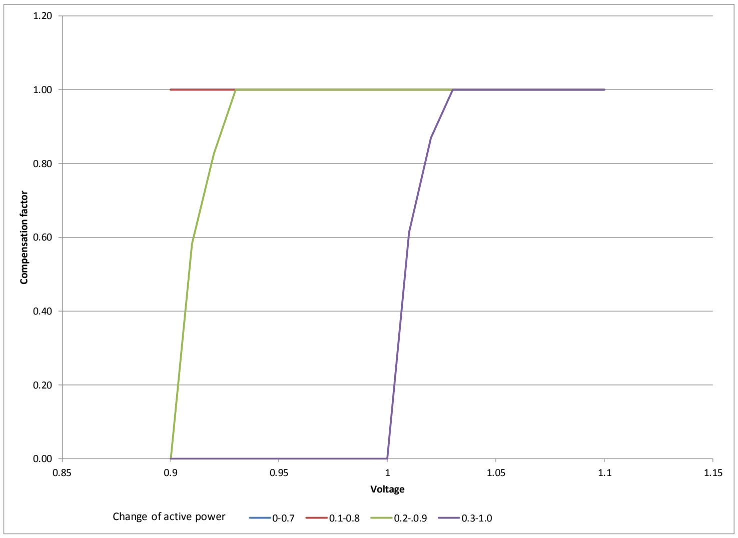

Figure 11. Compensation of voltage fluctuations caused by change of active power with inverter in constant voltage mode. x/r ratio = 3. Rated PF=0.95

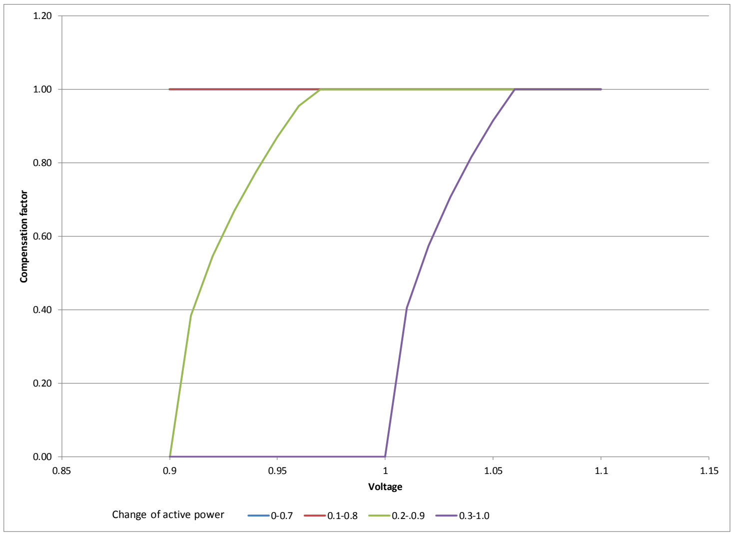

Figure 12. Compensation of voltage fluctuations caused by change of active power with inverter in constant voltage mode. x/r ratio = 2. Rated PF=0.95

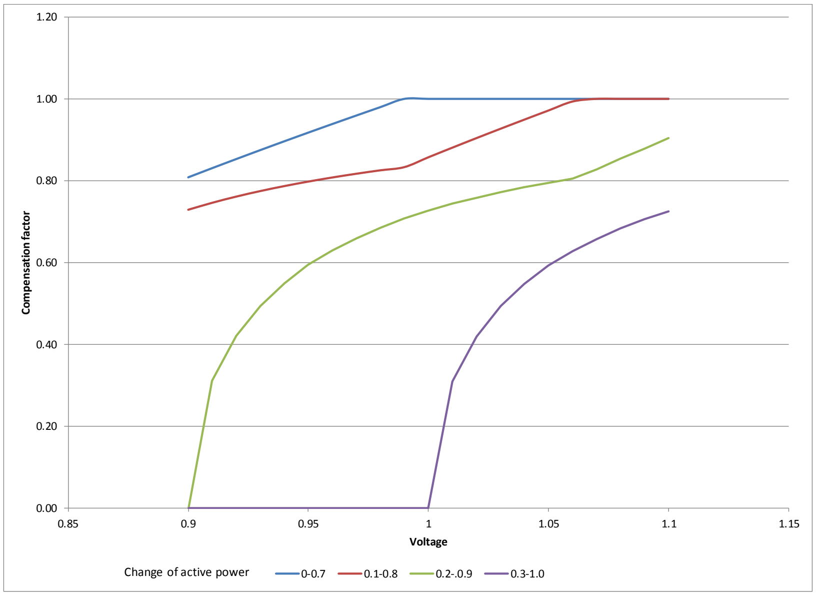

Figure 13. Compensation of voltage fluctuations caused by change of active power with inverter in constant voltage mode. x/r ratio = 1. Rated PF=0.90

Note 1: The above illustrations are based on the assumption that each inverter compensates the voltage fluctuations caused by the change of the real power of the same inverter. In reality, the voltage fluctuations in any node of the distribution network are caused by the combined impacts of many inverters connected to the same network.

Note 2: The settings for the constant voltage control mode may not be the same for the steady-state and for the intermittent conditions. While the settings in the former case are based on the need to provide a particular voltage at a given bus, the requirement in the latter case is to prevent unacceptable voltage fluctuations.

4. Impacts of PV resources embedded in load on aggregated load models

In this section of the paper, we address the reactive load-to-voltage dependences of loads with embedded PV resources, as seen by the monitoring and controlling applications of EPS. The changes of the load with embedded PV due to voltage changes are significantly different due to several reasons, such as:

- the inverter is in inductive mode or it is in capacitive mode
- different active loads of the PV
- different modes of operations of the inverter
- constraints of the inverter capabilities
- the change of the reactive load of the inverters is not proportional to the changes of the natural loads.

Figure 14 through Figure 20 illustrate different reactive load-to-voltage dependences of loads with embedded PV with inverters capable of generating/absorbing reactive power for the mentioned above conditions.

As seen in the figures, the differences in the load models in these cases may be considerably significant.

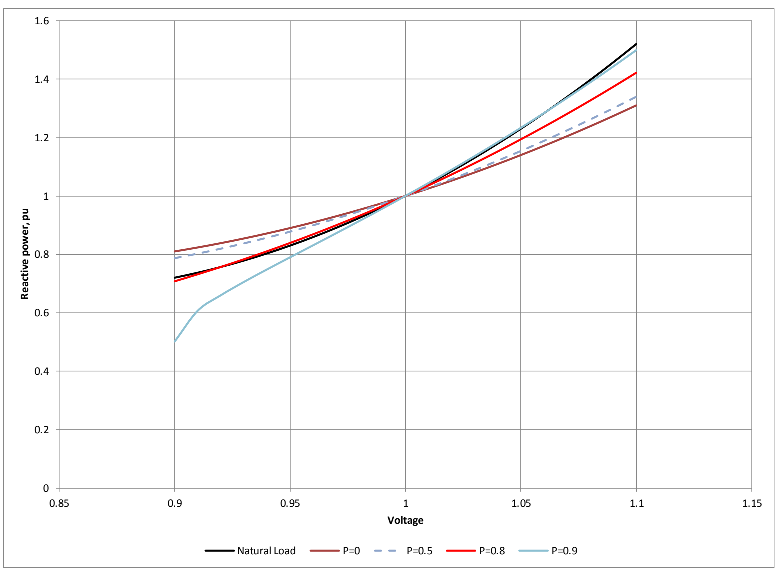

Figure 14. Reactive load-to-voltage dependency of load with embedded PV inverter in maximum inductive mode

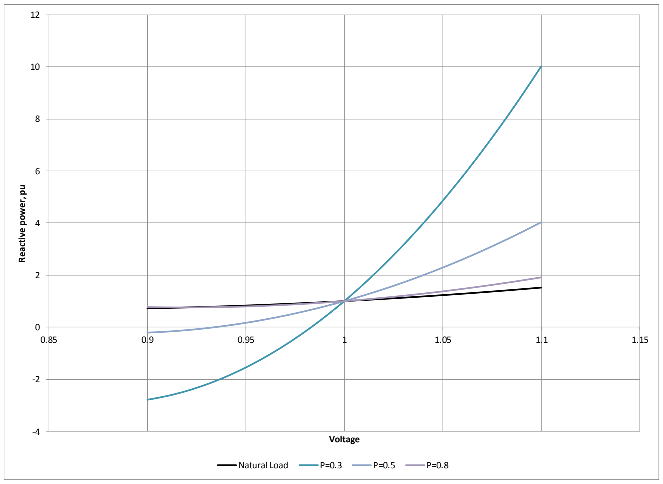

Figure 15. Reactive load-to-voltage dependency of load with embedded PV inverter in maximum capacitive mode

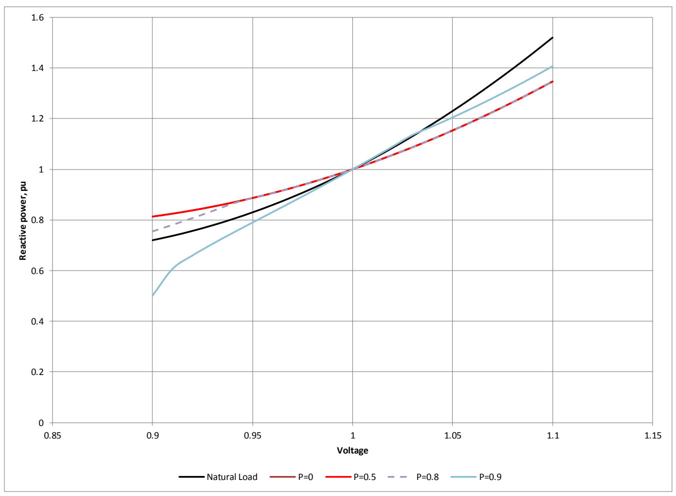

Figure 16. Reactive load-to-voltage dependency of load with embedded PV inverter in constant inductive Q mode

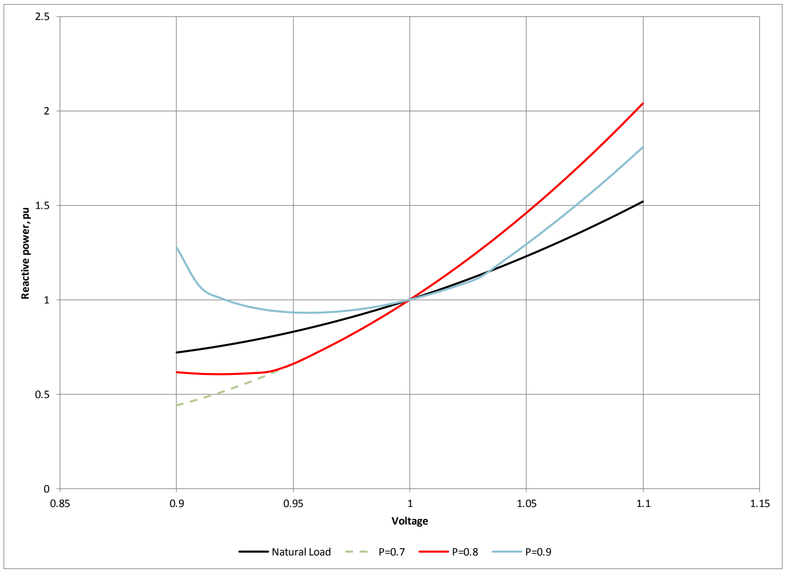

Figure 17. Reactive load-to-voltage dependency of load with embedded PV inverter in constant capacitive Q mode

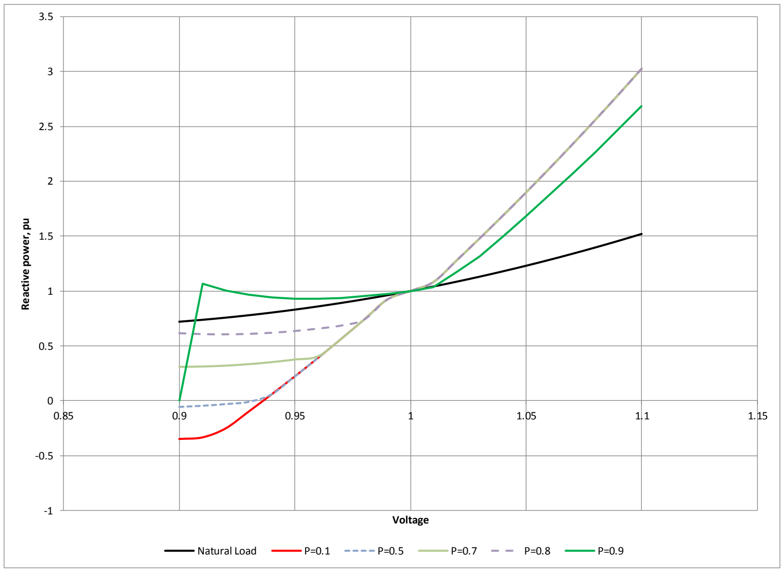

Figure 18. Reactive load-to-voltage dependency of load with embedded PV inverter in constant Q mode with voltage override

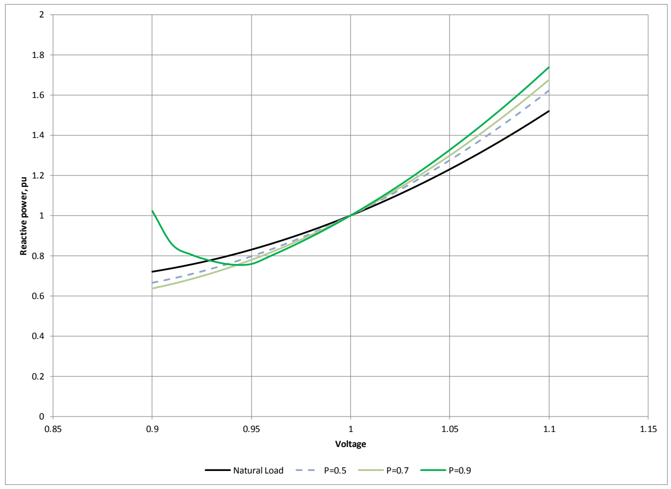

Figure 19. Reactive load-to-voltage dependency of load with embedded PV inverter in constant leading Power Factor mode

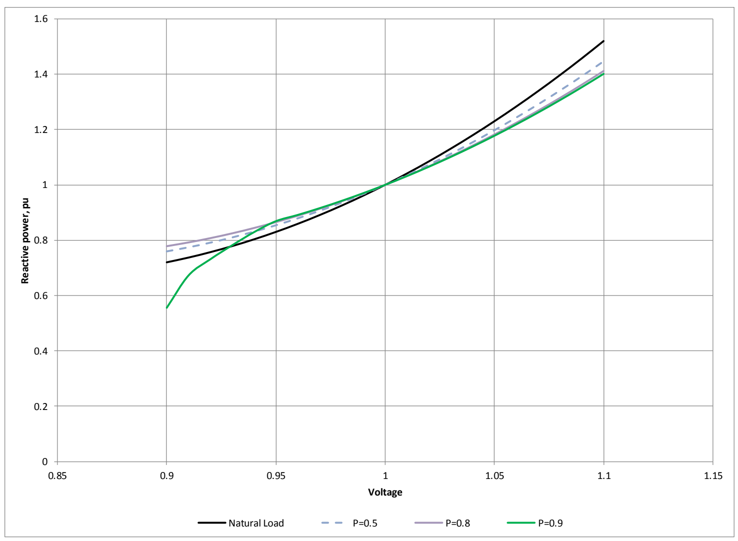

Figure 20. Reactive load-to-voltage dependency of load with embedded PV inverter in constant legging Power Factor mode

5. Conclusions

1. The capability curves of distributed energy resources are significant attributes of the DER object model. They should be included in the manufacturer's specifications of the products. The corresponding interoperability standards should support DER object models including the attributes of the capability curves.
2. The simulation and optimization applications of EPS should include models of the DER capability curves to adequately represent the reactions of DERs to the changing operating conditions of the DERs itself and of the EPS.
3. The method of compensation of the voltage fluctuations caused by the intermittent operations of DER is more efficient, if it is based on a close-loop control scheme targeted at voltage stabilization.
4. The load-to-voltage dependences of loads with embedded DER may significantly change depending on the operational state and behavior of the DER. The object models of loads with embedded DER should include the attributes of the DER

describing the operational states of DER, which may significantly impact the models of the aggregated loads.

5. The higher level of models [1] of load composed from individual load models with and without embedded DER and used in EPS applications and in the models of Virtual Power Plants should include composite aggregated load characteristics, based on the DER capability curves and states of DER operations. Representation of DER generation/absorption as simply subtracted or added load will introduce inaccuracies of the models leading to unsatisfactory operating conditions, uncertainties in the situational awareness, and loss of benefits from optimization procedures.

6. References

1. Nokhum Markushevich, Transmission Bus Load Model – the Bridge for Cross-Cutting Information Exchange between Distribution and Transmission Domains, Available: http://collaborate.nist.gov/twiki-sggrid/pub/SmartGrid/TnD/SGOC_presentation_to_SGIP_03-30_-2011a.pdf
2. IEEE P1547-2003: IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
3. Advanced Power System Management Functions for Inverter-based DER Devices, Draft v.9b. Available: http://collaborate.nist.gov/twiki-sggrid/pub/SmartGrid/PvInverter/Advanced_Functions_for_DER_Inverters_v9b.docx
4. B. Seal, "Standard language protocols for photovoltaics and storage grid integration," EPRI 1020906, Tech. Rep., 2010. Available: http://my.epri.com/portal/server.pt?Abstract id=000000000001020906
5. Petr Sulc, Konstantin Turitsyn, Scott Backhaus, Michael Chertkov, "Options for Control of Reactive Power by Distributed Photovoltaic Generators". Available: http://arxiv.org/PS_cache/arxiv/pdf/1008/1008.0878v1.pdf
6. E. Liu and J. Bebic, "Distribution system voltage performance analysis for high-penetration photovoltaics," NREL/SR-581-42298, Tech. Rep., 2008. Available: http://www1.eere.energy.gov/solar/pdfs/42298.pdf
7. Reactive power control for Wind Power Plant with STATCOM, Master Thesis, Project group: WPS 1051, Available: http://projekter.aau.dk/projekter/files/32251172/MasterFINAL.pdf
8. Alexander Osnach, A New Approach to Reactive Power Calculation of the Static Var Compensator, Available: http://www.leonardo-energy.org/webfm_send/1181
9. Reigh Walling and Gao Zhi, Eliminating voltage variation due to distribution-connected renewable generation, DistribuTech 2010.