VOLTAGE CONTROL CHALLENGES AND POTENTIAL SOLUTIONS FOR LARGE-SCALE INTEGRATION OF PV RESOURCES IN LV NETWORKS

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ABSTRACT

In this paper we illustrate PV single inverter response to voltage rise in LV networks and simulate multiple PV cascading that may result from inverter's response. We then address potential solutions to mitigate the drawbacks of simplistic control approaches, such as reinforcing the network, shifting supply phases, and implementing enhanced control processes. We elaborate on the framework of such control processes and identify main implementation challenges to make them effective.

INTRODUCTION

The integration of photovoltaic (PV) micro-generation in low-voltage (LV) networks is expected to increase significantly in the next few years [1]. It is known that the large-scale integration of PV in conventional low-voltage (LV) networks poses many challenges and that simplistic voltage regulation strategies such as disconnecting PV when phase-voltages rise above a defined threshold cannot respond adequately to such challenges [2].

One of the major impacts of PV in quality of service is caused by voltage rise. The resource output of PV is expected to be high at midday off-peak hours, which may lead to node voltages higher than acceptable in weak networks. In practice, utilities are avoiding unacceptable voltage rise in a simple way. They require the inverter to be programmed to disconnect the PV from the grid when the local voltage rises above acceptable values (typically 1.1pu). This is an on/off voltage control approach but is far from being adequate, especially under large-scale penetration of distributed resources.

In this paper, we analyse the drawbacks of on/off control approaches and identify their risks. From the resource owner point of view drawbacks are obvious – they get disconnected, lose income by being disconnected, and may be compelled to switch On and switch Off frequently, which may shorten the inverter lifespan. From the utility point of view, the risks are not so obvious. In this paper, we focus on the problems that yield from the unbalanced nature of LV loads and their corresponding neutral return currents. Neutral currents, when important, can be responsible for hard-to-predict phase-to-neutral voltages behaviour that can make PV cascade after single inverter tripping.

The paper illustrates inverter response to single-phase voltage rise in laboratory environment. It also shows how inverter tripping may cause cascading of other resources of the same network feeder.

The paper then address potential solutions to mitigate the drawbacks of on/off control approaches, such as reinforcing the network, shifting supply phases, and implementing enhanced control processes. It elaborates on the framework of such control processes and states the minimum observability requirements necessary to make them effective. Based on that, control limitations and possible solutions to overcome such limitations are discussed.

CONTROL CHALLENGES

In LV networks, the R/X ratio of the feeder lines/cables is very high. That makes node voltages almost insensitive to reactive power injection and very sensitive to active power injection instead.

In LV networks, load unbalance is significant. That makes neutral currents to be significant too. Significant neutral currents make complex changes in phase-to-neutral voltages: the phasor of the neutral wire voltage drop depends on the argument of the neutral current phasor, which depends on the sum of the three phasor currents, one for each phase.

Together, the high sensitivity to active power and the complex relationship between single phase injection and 3-phase voltage changes make the voltage control problem in LV networks a very challenging one.

In the following, we illustrate the inverters response to voltage rise in a week distribution feeder. We first show how output voltage changes with injected current to illustrate that switching-off and switching–on times depend on network voltage. Then, we simulate voltage rise in a network with several inverters to illustrate that the switching-off of a single inverter may cause the cascading of several and make the network voltage behaviour very hard to predict.

Single inverter response to voltage rise

Single phase PV inverters are programmed to be connected/disconnected from the grid when a predefined set of conditions is satisfied. Some of these conditions can be parameterized onsite or remotely.

We tested a commercial PV single-phase inverter under standard parameterization in laboratory environment. The inverter was connected to a week four-wire resistive network with balanced load. When single phase power is injected into the network, voltage rises at the inverter phase. We studied the voltage evolution that resulted from the on/off control approach preprogrammed on the inverter. Three situations were studied for three different settings of the network's initial voltage (without PV injection). Results on the voltage evolution are depicted in Fig. 1. The figure shows three sequences of voltage steps that result from the same amount of injected power at different network initial voltages: 250V, 245V and 240V. The figure illustrates that higher network voltage make the inverter switch less frequently and stay connected for less time. Fig.1 also show that there are occasional voltage spikes resulting from unstable connection decisions.

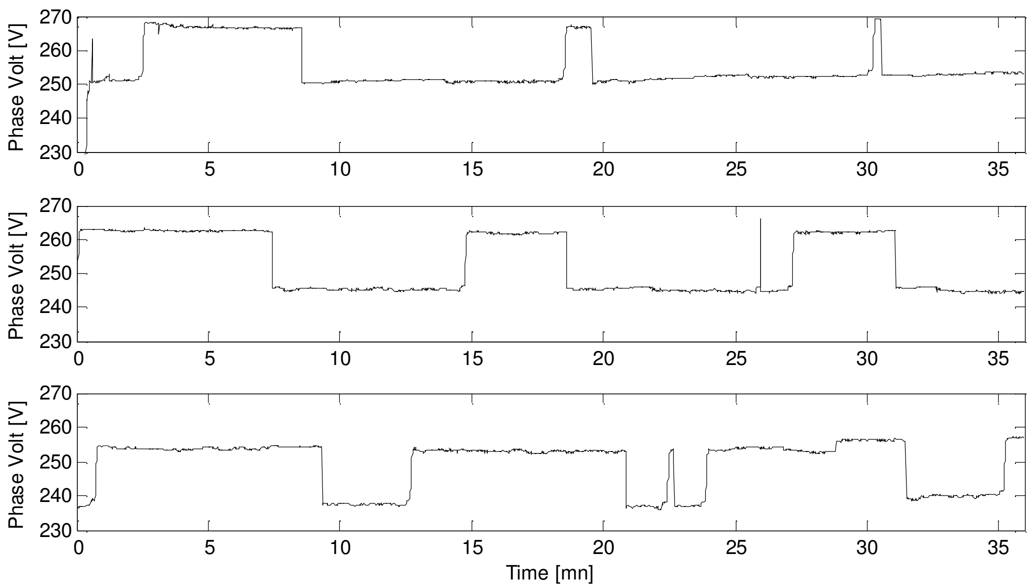


Fig. 1. On/off inverter controller response to voltage rise. Three sequences of single-phase voltage steps that result from the same injected power are presented for three different network initial voltages: 250V, 245V and 240V respectively at the above, middle and below subfigures.

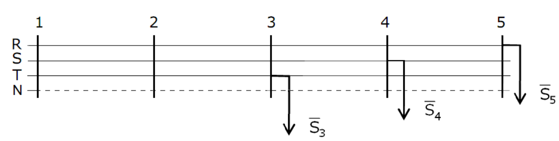
Multiple PV cascading due to inverter response

By decreasing active power injection in one phase one will decrease voltage in the injection phase (positive sensitivity value) but may increase voltage in the other two phases (negative sensitivity values). Voltage-to-power sensitivity results on a very simple test network can be used to illustrate this. Take the network of Fig. 2 and the corresponding sensitivity matrix.

By reducing active power in node '3' on about 20% to avoid irregular voltages in phase T one will:

- Decrease voltage in phase T of node '3' by 10%, but
- Increase voltages in phases S and R of nodes '4' and '5' by 2.7% and 2.9%, respectively.

Supposing that node '4' or '5' would be already at a high voltage, one might be creating a new problem when trying to solve the former. Moreover, because inverters' response to irregular voltage consist in switching-off the PV from the grid, the sequence of former problem solving and new problem creation might become harmful to the system static stability and may cause the cascading of the PVs in a feeder.

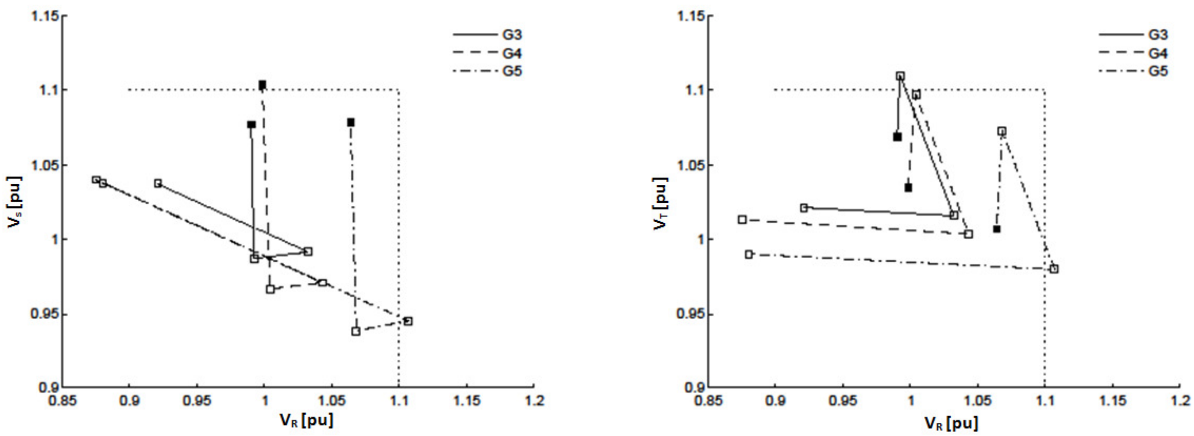


	∂P_{3T}	∂P_{4S}	∂P_{5R}
∂V_{3T}	0.513	−0.137	−0.144
∂V_{4S}	−0.109	0.752	−0.220
∂V_{5R}	−0.151	−0.198	1.025

Fig. 2. LV test network with 3 identified injections in 3 different phases together with the 3×3 voltage-to-power sensitivity matrix. Results were obtained for a particular loading situation. Other situations would lead to qualitatively different results.

In Fig. 3 we illustrate the voltage evolution at the nodes 3T, 4S and 5R during a cascading failure of all three PVs nodes triggered by the irregular voltage of node 4S. As a consequence of the irregularly high voltage in 4S, the inverter switches-off G4 and the voltage at node 4 drops to acceptable values. However, by switching-off G4 the voltage at G3 rises above 1.1pu (see V_T axis in subfigure (b)). Again, the control procedure switches-off G3 and the voltage at node 3 drops to acceptable values. However, by switching-off G3 the voltage at G5 rises above 1.1pu (see V_R axis in subfigure (a) or (b)), which will lead to switching-off G5 as well.

The cascading failure can be more complex if any of the switched-off inverters (G4 or G3) decide to re-connect to the grid before de end of the process. Theoretically, the process can take an infinite number of steps as the on/off inverter controller response is itself very much dependent on voltage magnitude (as seen illustrated in Fig. 1).



(a) (b)

Fig. 3. Voltage evolution for three different nodes in three different phases caused by the tripping of generator G4 in phase-*b* (G3 is connected to phase-*a* and G5 to phase-*c*). Solid squares represent the initial voltage state; blank squares represent the voltage state evolution.

POTENTIAL SOLUTIONS

There are several possible solutions to mitigate the drawbacks of on/off control approaches, namely:

- Reinforcing the network
- Shifting phases to balance the loads
- Controlling PV power injection

Reinforcing the network is an obvious one. If one strengthens the network to avoid voltage changes induced by changes in injected power, one avoids the problem.

Balancing the loads can also contribute to mitigate the risk of having problems. If loads and generation are balanced, return neutral currents are small and the risk of cascading is mitigated. However, with few connected customers it is not possible to guarantee a balanced load in LV networks. Single-phase customer behaviour is too random for balancing to be an effective solution to the problem.

Controlling active power injection seems to be the most promising solution to the problem. By controlling power injection one controls voltage and avoids switching-off the inverter. There are many ways to implement active power control. Here we propose a very simple autonomous approach, which only requires occasional interaction between PV controllers.

Optimal PV curtailment

If we represent the LV network by its voltage sensitivities to the active power injection for the nodes with PVs (as exemplified in Fig. 2), we may compute the optimal generation curtailment using linear programming. The linear programming (LP) problem can be formulated as in the following:

$$\min_{\Delta P_i} \sum_{i=1}^{g} -\Delta P_i$$

s.t.

$$[k].[\Delta P] - [\Delta V^*] \leq 0$$
$$\Delta P_{i_{min}} \leq \Delta P_i \leq \Delta P_{i_{max}}.$$

Where, k is the sensitivity matrix and ΔP and ΔV^* are the power changes and the required voltage changes, respectively.

The overall LP solution implementation would be quite simple from the algorithmic point of view but would require centralized coordination and, therefore, adequate communications. The k matrix is a full matrix as voltage in each node/phase is in fact dependent on the injection in any other node/phase.

Local iterative PV curtailment

We may neglect cross dependence between voltages in one node/phase and injection in other node/phase if we allow control to be iterative, i.e., if each inverter is allowed to observe its own voltage and correct it successively until no irregular voltage is detected. The iterative control approach can be described as in the following algorithm:

Step 1: *Compute* $\Delta V_i^* = V_{i_{max}} - V_i - \varepsilon_V, \forall_i$;
Step 2: *Compute* $\Delta P_i = \Delta V_i^*.k_{ii}^{-1}, \forall_i$;
Step 3: *Update:* $P_i = P_{i_0} + \Delta P_i, \forall_i$.
Step 4: *Obtain*$[V] = f([P])$.
If $V_i - V_{i-1} > \varepsilon_\delta, \forall_i$, *return to* Step 1; *Else,* stop.

Where k_{ii} refers to the diagonal element of the sensitivities matrix k and f is the power-flow function.

In practice, only the first three steps have to be implemented as the fourth step represents the network's voltage response to the power injection update. If we simulate such response with a three-phase unbalanced power-flow function [3] for the test network of Fig. 2 during a day, then the iterative voltage control output looks like Fig. 4.

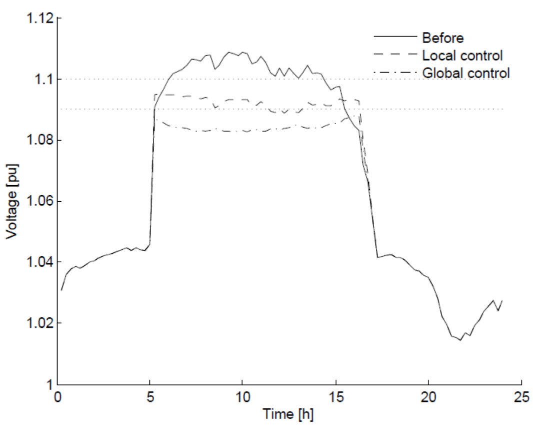


Fig. 4. Daily voltage profile at node 3T for local and optimal control for 3 PVs on different phases (R,S,T). The solid line represents the situation without control; the dashed line represents the iterative local control; and dashed-dotted line the LP optimum control. The horizontal dotted lines refer to the taken voltage limit and corresponding threshold ε of Step 1.

The local control approach is not always an effective one. It is iterative and convergence can be compromised. It can be compromised by the number of iterations being limited in practice and so the result may become far from optimal. It can also be compromised by the convergence process being oscillatory or even unstable.

This is a practical difficulty as successive updating of local curtailments may cause significant voltage perturbations during a significant period. The oscillatory and possible instability behaviour of the local control approach can be avoided if one scales the updating rule for curtailment in Step 3 in an adequate manner. To do that, the local convergence process can to be approximated by a discrete-time linear dynamic system [4], which may be undertaken by approximating the power-flow output in Step 4 by the output of the sensitivities matrix. The scaling of the updating rule is out of the scope of the present paper and will be presented in the future [5].

CONCLUSION

The paper illustrates inverter's response to single-phase voltage rise in laboratory environment and simulates network voltage bouncing from multi inverter response. It also shows that inverters on/off control may cause cascading of other resources of the same network feeder.

The paper discusses potential solutions to mitigate the drawbacks of on/off control approaches. A simple autonomous approach to active power injection control is proposed. The basic framework is iterative and requires parameterization to be effective. The main implementation challenges are discussed together with possible solutions to overcome such limitations.

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