PROBABILISTIC ASSESSMENT OF P/V DROOP CONTROL OF PV INVERTERS

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ABSTRACT

This study evaluates the performance of the Voltage Based Droop (VBD) control in mitigating overvoltage due to photovoltaic units (PV) in Low Voltage (LV) networks. The benefit of this primary control of PV inverters, with respect to the on-off oscillations, the voltage level and the captured energy in LV networks, has been already demonstrated with deterministic "worst case" approaches on small networks and for restricted time periods. These approaches do not consider the intermediate network operation states but only the extreme ones (lowest expected consumption - highest PV generation) and they often lead to over dimensioned and costly technical solutions. In this paper, the P/V control (implemented in the VBD control) is evaluated with a probabilistic analysis framework that considers the time fluctuation of the PV generation and of the voltage at the MV/LV transformer as well as the randomness of the consumption loads. The nodal statistical profiles of these fluctuating parameters are based on 15-min smart meters' (SM) data recorded by the DSO. An existing LV network in Belgium is simulated in order to evaluate with a probabilistic approach the benefit of the proposed control.

Abbreviations

VBD	Voltage Based Droop
P	Ac-side active power [W]
V	Rms value of the network voltage [V]
$E_{inj,i}$	Total quarter-hourly (15-min) injected energy at node i (kWh)
$E_{cons,i}$	Total quarter-hourly(15-min) consumed energy at node i (kWh)
f_i	Time repartition factor of $E_{inj,i}$ or $E_{cons,i}$
P_{MPP}	Peak injected power at node i during the15-min interval [W]
k	Droop of P/ V controller
V_{nom}	Nominal voltage [V]
V_{up}	Reference voltage in the droop function [V]
f	Network frequency (Hz)
P_{rated}	Maximum (installed) active power of the PV unit
M	Total number of MC iterations
b	Constant-power band width (p.u.)

INTRODUCTION

Presently the PV power injections towards the network are solely subject to the maximum power point (MPP) of the PV units. In case of voltage violation, the PV inverters passively undergo the on-off control that is required by the standards, without considering the current network state [1-2]. These temporary cutoffs of the units affect the income of the PV producer, the network stability and the degradation of the inverters as they often lead to significant voltage and current transients.

In order to address this operational issue, the authors of [3] developed a fast-acting primary control scheme based on voltage droops. The droops are applied by P/V controllers requiring neither inter-unit communication nor voltage tracking for synchronization. The benefit of this P/V control with respect to the on-off oscillations, the voltage level and the captured energy in LV networks has been already demonstrated with a deterministic "worst case" approach. Although this approach is safe for protecting the electric system, it discards multiple intermediate network states as it doesn't take into account the time fluctuations of PV injection and consumption load. It is therefore not advisable for the long term techno-economic evaluation of voltage control strategies, such as the P/V control, since it can lead to less optimized, in terms of efficiency and cost, technical solutions.

In this paper the P/V control (implemented in the VBD control) is evaluated with a probabilistic Monte-Carlo (MC) framework that is based on 15-min SM data of energy flow at the nodes of a LV feeder [4-5]. This probabilistic framework considers multiple possible network states, sampled from the Cumulative Distribution Functions (CDFs) of the time variable parameters, in a fast optimized way. It therefore evaluates the P/V control taking into account the time variance of PV injection and consumption loads and of the voltage at the MV/LV transformer since these uncertain parameters influence the time-dependent power quality and therefore the implementation of the control [8]. The presented framework is applied in order to simulate an existing LV feeder with distributed PV generation in Belgium.

This paper is organized as follows. In §1 the interest of studying P/V control is outlined. In §2 the modelling of the control with the probabilistic framework is explained. Finally in §3 a LV feeder in Belgium is simulated considering the action of the P/V inverters for the overvoltage mitigation. The conclusions of this study are presented in §4.

1 CHALLENGES AND CONTRIBUTIONS OF THE STUDY

1.1. Droop control configuration

Voltage control in large power plants is often deployed by reactive power/terminal voltage (Q/V) droop controllers. The same strategy, with adapted Q/V droop functions, could be applied in distributed PV inverters connected to the distribution network. Nevertheless, due to high R/X-value of the distribution network lines, the voltage control should preferably be linked to active instead of reactive power [9-10]. Thus, P/V controllers are considered more straightforward in providing voltage support in the distribution network [11-15].
Considering the above reasons, the authors in [3] present a fast-acting primary control based on voltage droops. This strategy eliminates overvoltages while optimizing the capture of renewable energy compared to the conventional on-off control. Besides, the proposed VBD control obviates inter-unit communication and voltage tracking for synchronization.
Therefore the P/V controller (integrated in the VBD controller of [3]) modifies the injected active power of the PV unit in function of the local voltage in order to prevent and eliminate overvoltage situations. In this way total cutoffs of PV units, applied in the conventional on-off control, and their subsequent effects (voltage and current transients as well as significant PV power loss) are avoided. The P/V droop controller adapts P according to the scheme in figure (1). The Q/f –droop controller and V/V$_{dc}$–droop controller do not affect the PV active power that is injected into the network, and although they participate in the VBD control their description is out of the scope of this paper.
The authors, in [3], evaluate the benefit of the VBD control in a grid-connected microgrid with three DG units and six loads. As already mentioned, the analysis has

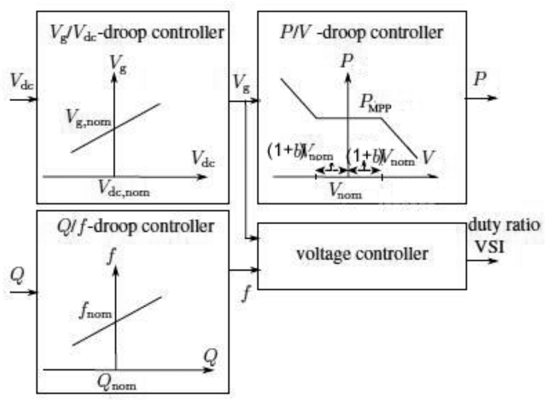

Figure 1: VBD control; active and reactive power control. Combined operation of the droop controllers to determine the set value of the grid voltage [3]

been done with a deterministic "worst-case" approach considering the lowest expected consumption and the highest PV generation. Therefore, that deterministic approach did not consider the uncertainty of the PV injection and the randomness of the consumption loads over time. For this reason, in the present paper, the P/V control is evaluated with the proposed probabilistic framework using real 15-min individual customers' SM data of energy flow in a LV feeder.

1.2. Integration of the droop control in the probabilistic framework

The probabilistic framework randomly samples a large number of different network states from the CDFs of the variable parameters [4-5]. For each sampled state, the network is characterized by the following values:

$$\{E_{\mathrm{cons,i}},\ E_{\mathrm{inj,i}},\ f_{\mathrm{i}}\} \text{ for nodes i} = 2{:}\mathrm{N}$$
$$\{V_{\mathrm{MV/LV}}\}\ for\ node\ \mathrm{i} = 1 \tag{1}$$

where $E_{\mathrm{cons,i}}$ is the 15-min energy consumption at node i, $E_{\mathrm{inj,i}}$ is the 15-min energy injection at node i, f_{i} is the time repartition factor of the consumed or injected energy at node i explained in [7] and $V_{\mathrm{MV/LV}}$ is the voltage at the MV/LV transformer node. Therefore, the injected peak power P_{MPP} for the studied network state is:

$$P_{MPP,i} = {E_{\mathrm{inj,i}}}/{f_{\mathrm{i}}} \text{ for nodes i} = 2{:}\mathrm{N} \tag{2}$$

These nodal values are introduced in the power-flow algorithm which calculates the voltage profile along the feeder for the studied 15-min interval. As thoroughly explained in [8], in case the rms voltage V at the connection point of a PV unit exceeds the reference band ($V > (1{+}b){\cdot}V_{\mathrm{nom}}$), the P/V controller which is integrated in the PV inverter turns on in order to modify the P that is injected by the PV unit in the network. This modification of P can be applied with various strategies for instance load increasing, dump loads, storage charging or deviation from MPP for lowering the generated power. In every case, the modification of P is determined by the next relations [3]:

$$P = P_{MPP} - k \cdot (\mathrm{V} - V_{up}) \tag{3}$$

$$V_{up} = V_{nom} \cdot (1 + b), b < 0.1 \tag{4}$$

where the droop coefficient k is generally determined according to the ratings of the PV units, P_{MPP} is the instantaneous maximum power point (MPP), V_{up} is the upper adjustment network voltage, and namely the reference voltage for enabling the P/V control and V is the calculated by the load flow algorithm rms voltage at the respective node. The upper adjustment voltage V_{up} enables a dead-band in which the P/V droop controllers are not active. Therefore, the P/V droop control strategy changes the power P_{MMP} delivered by the PV panel to a different value equal to P, under the following conditions:

- power is injected into the grid,

- $V_{up}=V_{nom}\cdot(1+b)< V < V_{nom}\cdot(1+0,1)$, with b <0.1

where V is the calculated rms voltage at the respective node by the load flow algorithm. It is worth to clarify that if on/off control is the only control available in the feeder (therefore no droop control) and the mean rms voltage at a node is higher than the $V_{nom}\cdot(1+0,1)$ limit during ten minutes, the PV unit at this node turns off for the next ten minutes [1-2]. This cut-off is instantaneously applied if the node rms voltage instantaneously exceeds the $V_{nom}\cdot(1+0,15)$ limit.

In the present case where P/V controllers are available, as soon as $V > V_{nom}\cdot(1+0,10)$, the PV unit instantaneously turns off but only for some instants until the value of V is stabilized, thanks to the action of the P/V controller, at a value lower than $V_{nom}\cdot(1+0,10)$ and the unit can step by step re-inject its initial P_{MPP}. If the node rms voltage instantaneously exceeds the $V_{nom}\cdot(1+0,15)$ limit, the unit is also in this case (P/V control available) instantaneously cut off. In case a PV node lies under the conditions for the application of the P/V droop function, the P/V control is activated and the unit's P is calculated according to (3). Once these actions are done for all PV nodes, a new power flow computation is done in order to determine the new voltage profile along the feeder, which is now modified thanks to the action of the droop control [8].

At this point, a new iteration of the droop control starts and in case some nodes lie again under the conditions for the application of the control, a new modification of P takes place followed by a new power flow analysis. This series of actions goes on until the values of P for two consecutive iterations of the droop control converge at every node and there are no more nodes that lie under the conditions for the application of the droop control. As soon as this is achieved, a final power flow takes place which calculates the final voltage values V along the feeder for this 15-min interval.

In this way the P/V control eliminates the overvoltage risk and lowers the voltage profile along the feeder in a gradual and controllable manner such that the minimum PV energy curtailment is achieved and voltage and current transients are avoided.

2 SIMULATION OF AN EXISTING LV FEEDER

The probabilistic framework complemented with the P/V controllers is used for the simulation of an existing LV feeder in Belgium in the purpose of techno-economically evaluating the benefit of the presented control.

The simulated LV feeder is illustrated in figure 2 and technically described in [6-7]. In total, 16 clients are connected to the feeder and in reality 3 out of them are equipped with a PV unit (5kVA at node 4, 2.65 at node 12 and 5kVA at node 3). In order to clearly demonstrate the influence of the PV integration on the voltage variation, 6 more PV clients have been considered at nodes 5, 6, 8, 10, 11 and 14 for this simulation. For these units, the same PV injection SM data as for the PV unit at node 13 were considered. In this simulation, correlation among clients is not taken into account and therefore the 15-min network states are independently sampled for each one of them. The system is simulated as a perfectly balanced three-phase system and therefore the existing phase unbalance is not taken into account.

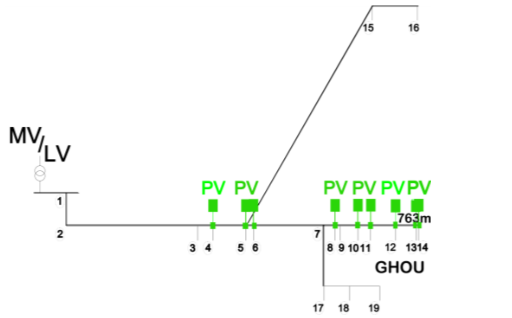

Figure 2: The simulated LV feeder (3φ/balanced configuration)

As far as the P/V control is concerned, all PV nodes have been considered equipped with P/V controllers. The system parameters "k" and "b" for the application of the control were based on a trial procedure that was initiated with the values applied in [3]. These values were afterwards adapted in respect of the voltage profile results obtained by the simulations of the base scenario (on-off control currently implemented by the DSO) and the droop control scenario. As a matter of fact, in reality, such actions can be locally determined based on the needs or the background history of the specific PV unit. In case of centralized control, the droop coefficients can be dynamically adapted in real time, in function of the current state of the network. In the present simulation the droop parameters were considered as follows:

- $k2= P_{rated}/500$ and $V_{up}=V1=1.06V_{nom}$

The LV feeder was therefore simulated with the probabilistic framework for $96\cdot M$ $(M=1000)$ possible network states for the month of July, complemented with the P/V control. Previous simulations of the same feeder considering only the on-off control, namely the strategy that is currently applied by the DSO, demonstrated that the overvoltage risk is higher during this month, at all nodes. The current simulation proved that the P/V control is efficient in eliminating the overvoltage risk at all PV nodes.

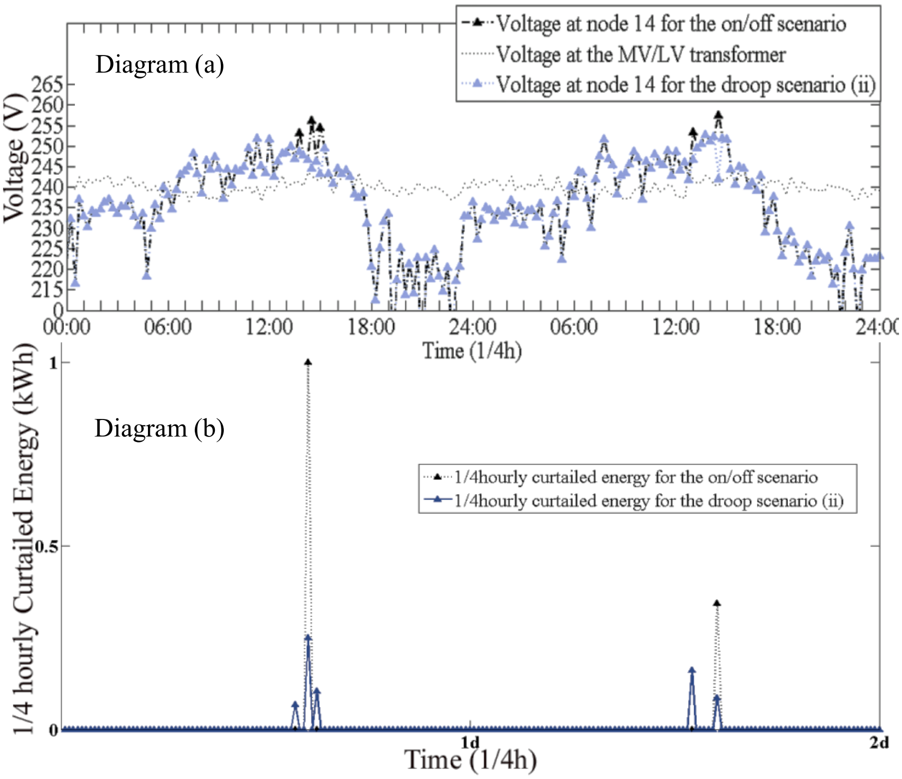

Figure 3: The 15-min voltage profile (diagram (a)) and the respective 15-min curtailed energy (diagram (b)) at node 14 for the on/off control and the droop scenario for two consecutive typical days of the month of July

The action of the P/V controller at node 14 during certain 15-min intervals of two typical days of July is indicatively shown in figure (3a). In this figure the voltage profile a node 14 for the droop control and for the on-off control scenario are presented for a period of two typical days of July. Generally the voltage profile of the P/V control scenario coincides with the one of the on-off scenario apart from the three 15-min intervals of the first day and two 15-min intervals of the second day (all of them between 13:00PM and 15:00PM) during which the P/V control was activated. Indeed during these periods the rms voltage at node 14 exceeded the reference value of the droop control V_{up} and therefore the control was activated in order to modify the injected P of the unit. As a result the nodal voltage during these intervals was gradually smoothed in order to avoid an eventual cut-off of the unit.

However, in order to achieve this gradual smoothing of the voltage profile an amount of generated PV power is obviously curtailed. For instance, the amount of PV energy that was curtailed due to the P/V control, during these two typical days of July, is shown in figure (3b). In the same figure, the amount of PV energy that would have been curtailed in case no P/V control was available (therefore only the conventional on-off control is available) is also illustrated. In this case, the curtailed PV energy is prompted by the cut-off of the PV unit during ten minutes, imposed by the on-off control. It is clear that the PV curtailment due to the droop control is more gradual and optimized taking account of the current state of the network.

In order to evaluate the economic benefit of the droop control, the average daily injected PV energy per node $E_{tot,mean}$ (calculated with the sampled SM recordings of total 15-min PV injection) and the average daily curtailed energy per node $E_{curt,mean}$ (both for the on/off and the droop control scenario) are computed as follows [8]:

$$E_{tot,mean} = \frac{1}{M}\sum_{m=1}^{M}\left(\sum_{i=1}^{96} E_{\mathrm{inj,i,m}}\right) \tag{5}$$

$$E_{\mathrm{curt,mean}} = \frac{1}{M}\cdot\sum_{m=1}^{M}\left(\sum_{i=1}^{96} f_{\mathrm{i,m}}(P_{\mathrm{MPP,i,m}}-P_{\mathrm{i,m}})\right) \tag{6}$$

where M is the number of simulated days, E_{inj} is the 15-min amount of energy that is injected in the grid (in case no droop control would be applied), f_i is the time repartition factor of the 15-min energy flow defined in [7], P is defined in (3) and P_{MPP} is defined in (2). In the case of the on-off control, relation (6) is applied with the value of $f_{i,m}$ that corresponds to a temporary cut-off of ten minutes, as suggested in the regulation, and with P=0.

The obtained values of $E_{curt,mean}$ and $E_{tot,\,mean}$ for the month of July are presented in Table 1. The $E_{curt,mean}$ values both for the droop and the on-off control result quite low for the specific network during the studied period.

The average values for the droop control for a period of a month are higher than the ones for the on-off control. This increase can be compensated by the fact that the P/V control allows a much more gradual PV energy curtailment.

Table 1: Average daily injected and curtailed PV energy (kWh)

Nodes	4	5	6	8	10	11	12	13	14
$E_{curt,mean}$ (P/V control)	0.01	0.01	0.01	0.06	0.09	0.11	0.1	0.18	0.18
$E_{curt,mean}$ (on-off control)	0.09	0.07	0.07	0.08	0.08	0.08	0.06	0.09	0.08
$E_{tot,mean}$	14.29	11.55	11.53	11.52	11.57	11.53	10.32	13.01	11.56

Indeed as already discussed before (figure 3a) the instantaneous curtailed PV energy can often be much more direct and higher for the on-off control. This argument can play an important role in respect of the acceptance of a certain overvoltage mitigation strategy, such as the P/V control, by the concerned PV customers. Indeed, the challenge in this case is to accurately evaluate the long-term impact of this result on the income of the PV producer and on the operation and maintenance cost of the network which is currently assigned to the DSO.

4 CONCLUSIONS

In this study, a probabilistic framework, developed for the analysis of LV networks based on SM data, is used to evaluate the benefit of a P/V control on overvoltage mitigation and PV energy curtailment in a LV feeder with distributed PV generation. This control is for the first time analysed within an accurate probabilistic model which considers the high uncertainty of PV injection and consumption over time. It was proved that the VBD control has indeed a lowering effect on the voltage profile while ensuring a gradual and network state aware PV energy curtailment along the feeder. The probabilistic framework could be used for the further refinement of the P/V control, concerning the droop parameters of each PV inverter in function of the position of the PV node in the feeder. This optimisation study would eventually allow a more fair distribution of the curtailed PV energy among PV nodes of the feeder.

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