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Probabilistic framework for evaluating droop control of photovoltaic inverters

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ABSTRACT

Active Power/Voltage (*P*/*V*) droop control is a method that is implemented in distributed photovoltaic (PV) units for the mitigation of overvoltage problems. This control does not require inter-unit communication and its benefit with respect to the on–off oscillations, the voltage level and the captured PV energy has already been demonstrated in previous studies. However, previous studies of *P*/*V* droop controllers only involved a deterministic “worst-case” approach on small networks and for restricted time periods, which often lead to oversized and costly technical solutions. In this paper, *P*/*V* droop control is for the first time evaluated with a probabilistic framework based on smart metering (SM) recordings in an existing Low Voltage (LV) network. Thanks to this approach, the uncertainty of PV energy injection, the randomness of the consumption loads and the fluctuations of voltage at the MV/LV transformer can be taken into consideration in the evaluation of the benefits related to the proposed control. The first objective of this paper is therefore to evaluate droop control in a model that is more faithful to the real operation of a LV network. Within this evaluation, the paper aims at doing a realistic parameter tuning of the control based on detailed probabilistic analysis. Practically, the evaluation model is based on a probabilistic framework previously developed by the authors but which up to now did not consider any voltage based droop (VBD) control. Thus, the second objective of this paper is to present a way for including time-based control strategies (here explained by means of droop control) in the probabilistic framework. The newly developed model is used to simulate an existing LV network and the results (EN50160 voltage requirements, curtailed PV generation, etc.) are compared to the scenario in which *P*/*V* droop control is not applied.

1. Introduction

Currently, the power that distributed PV units inject in the grid depends only on the Maximum Power Point Tracking (MPPT) of the panels and does not consider the current state of the grid. This passive operation of PV units combined with the trend to integrate more and more distributed generation (DG), leads the Distribution System Operator (DSO) to an impasse. Reinforcement of the grid by replacing existing lines does not longer appear to be a viable and sustainable solution as it is becoming very costly [1]. For this reason, the necessity of passing from grid-following DG units to DG units that act on the actual state of the network becomes more and more evident.

At present, hard curtailment is the traditional approach for coping with overvoltage caused by the high penetration of DG in LV networks [2,3], leading to on–off control of the DG units as soon as voltage violation occurs. This approach deteriorates the delivered power quality, due to significant voltage and current transients, and accelerates the degradation of the inverters; of course, it also leads to an important loss of generated renewable energy which affects the expected income of the PV producer. Hence, a more adequate voltage support by the PV inverters in LV networks is required. In order to provide voltage support, the conventional large power plants are equipped with reactive power/terminal voltage (*Q*/*V*) droop controllers. In LV grids, the grid-connected DG units can be equipped with analogous *Q*/*V* droop functions. However, voltage

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Nomenclature

VBD	voltage based droop
SM	smart smart metering
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 [kW h]
$E_{cons,i}$	total quarter-hourly (15-min) consumed energy at node i [kW h]
$P_{inj,i}$	peak injected active power at node i during a 15-min interval [W]
$P_{cons,i}$	peak consumed active power at node i during a 15-min interval [W]
f_i	time repartition factor of $E_{inj,i}$ or $E_{cons,i}$
P_{MPP}	injected active power at node i just before the action of P/V control [W]
k	droop coefficient of P/V controller
V_{nom}	nominal voltage [V]
V_{up}	upper reference of voltage in the P/V control [V]
f	network frequency (Hz)
P_{rated}	maximum (installed) active power of the PV unit [W]
b	constant-power band width in the P/V control (p.u.)
t	index of droop iteration
epsilon	error between two consecutive droop attempts [W]
E	droop convergence tolerance [W]
M	total number of Monte-Carlo iterations (=number of simulated typical days)
R	resistance (Ω/km)
X	reactance (Ω/km)
LF	load flow

support through reactive power is generally inefficient in LV grids as the grid voltage is linked with the active power, not the reactive power, due to the high R/X-value of the network lines [4,5]. Hence, large amounts of reactive power are required to influence the voltage. This is not the case for distribution grids with overhead lines, in which R/X-value is adequate for an efficient voltage control by means of reactive power. Nevertheless, reactive power control leads to increased losses in the distribution grid [6] that are not acceptable by the DSO. P/V droop controllers are more efficient and straightforward to provide voltage support in a LV grid [7–19], whereas inter-unit communication for the control support should be avoided because of the large number of small PV units.

In case of overvoltage, changing the injected active power of a PV unit in function of the local voltage would be preferable rather than imposing its total cut-off for certain minutes, which is generally the strategy in current PV inverters. This fact is justified by various arguments, which are thoroughly explained in [20]. The on–off control could be effective and sustainable in case of low PV penetration with a small impact on the voltage profile of the feeder. Besides, each cut-off of the PV unit means a loss of renewable energy during the specified cut-off period and thus a loss of income for the PV producer. Finally, decreasing the delivered power of PV units instead of cutting it off is also sustainable for increasing the network PV hosting capacity.

1.1. Droop control configuration

For the above reasons, the authors in [20] developed a soft curtailment methodology which involves a fast-acting primary control scheme based on voltage droops, without requiring communication infrastructure. The use of communication among PV units

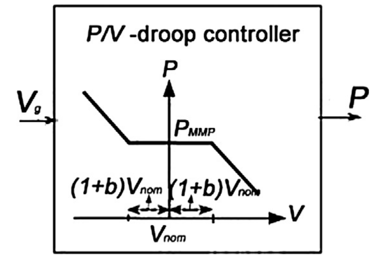

Fig. 1. VBD control; active power control; operation of the droop controller to determine the value of the active PV power that is injected towards the grid [20].

and centralised control [19,20] is not advisable for primary control schemes. Centralised control can lead to single point failure and inter-unit communication can harm the robustness and the rapid responsiveness of local droop control.

Reference [20] shows that voltage based droop (VBD) control is efficient in avoiding frequent power modifications while maintaining the voltage profile within the required limits. Along with this, it achieves a higher capture of renewable energy compared to hard curtailment while avoiding on–off oscillations. Moreover, it is highly flexible so that it can be applied in LV feeders with various kinds of DG sources and also for the control of storage elements. This strategy was initially designed for islanded microgrids [14,15] but it can also be implemented in grid-connected PV units in order to modify their delivered active power in function of the network state. In this primary control scheme, P/V droop controller modifies P according to the local voltage change as shown in Fig. 1 [20].

1.2. Need for probabilistic evaluation of droop control

Up to now, VBD control in specific and P/V droop controllers in general have only been analysed with a deterministic approach. That being so, their benefit was only proved for a restricted number of network states which are poorly representative of the time varying operation of real networks. Usually, these states represent “worst case” scenarios (highest expected PV injection simultaneously with lowest expected consumption). Although the “worst case” approach is safe for protection of the electrical system, it often discards multiple intermediate network states that may also lead to overvoltage events and frequent PV units cut-offs. The intermediate states also result in the degradation of network components along with significant PV power loss. Taking these states into account will refine the design of VBD control, in terms of efficiency and investment cost.

The deterministic approach considers therefore neither the time variance of PV energy injection nor the randomness of consumption loads in LV grids. These uncertain parameters undeniably influence the time-dependent behaviour and quality of the distributed power and thus the implementation of the control. For the above reasons, a doubt concerning the sufficiency of the deterministic models in evaluating voltage control strategies has lately arisen in literature and a set of probabilistic methods was presented [21–25]. However, the lack of real smart metering (SM) data restricted up to now the results of these probabilistic methods.

The novelty in this paper is that P/V droop control (implemented in VBD control) is for the first time integrated and evaluated within a probabilistic framework that uses real SM data. This last one is based on a probabilistic framework previously developed by the authors in [26–28] but which never considered the action of P/V controllers. The undeniable advantage of the probabilistic model is the consideration of multiple possible network states, represented by the Cumulative Distribution Functions (CDFs) of the variable parameters, in a fast optimised way. The probabilistic analysis can lead to refined solutions in techno-economic terms, compared to