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Congestion Avoidance in Low-Voltage Networks by using the Advanced Metering Infrastructure

Extended Abstract

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ABSTRACT

Large-scale decentralized photovoltaic (PV) generators are currently being installed in many low-voltage distribution networks. Without grid reinforcements or production curtailment, they might create current and/or voltage issues. In this paper, we consider the use the advanced metering infrastructure (AMI) as the basis for PV generation control. We show that the advanced metering infrastructure may be used to infer some knowledge about the underlying network, and we show how this knowledge can be used by a simple feed-forward controller to curtail the solar production efficiently. By means of numerical simulations, we compare our proposed controller with two other controller structures: open-loop, and feed-back $P(U)$ and $Q(U)$. We demonstrate that our feed-forward controller — that requires no prior knowledge of the underlying electrical network — brings significant performance improvements as it can effectively suppress over-voltage and over-current while requiring low energy curtailment. This method can be implemented at low cost and require no specific information about the network on which it is deployed.

1. INTRODUCTION

Advanced metering infrastructures are currently deployed in many countries [4]. In addition to streamlining the billing process, the rationale is that these infrastructures will help mitigating the grid congestion caused by the rise of distributed generation, improve grid observability, and allow for new customer services. For example when local generation is high and demand is low, distribution grids may experience overloads in transformers and possibly in lines, and voltage excursions outside of the allowed voltage range. Among these issues, voltage excursions and in particular over-voltages are the major problem of embedded generation on low-voltage distribution networks [6].

The most standard solution to solve this kind of issues is grid reinforcement, which involves replacing or adding lines and/or transformers. Grid reinforcement comes at a relatively high cost, and is not always the best option [1]. As a consequence, many alternate solutions have been suggested by the industry and the research community, emphasizing the need for more *active* distribution networks. Another solution is to use the so-called flexibility of loads and generators – their ability to modify their (active or reactive) power consumption or output. One of the most notorious of these numerous options is probably to locally control the reactive power output of PV inverters based on local measurements — *a.k.a.* $Q(U)$ controller — in order to flatten the voltage profile of the feeder [2, 7]. In this paper, we focus on controlling the *active* power output of PV inverters.

We consider the problem of controlling the output of PV generators in a low-voltage network with two important constraints:

1. We do not assume any knowledge of the details of the underlying electrical network (topology, characteristics of the lines, etc), but we *infer* from AMI data what we need for control.
2. We assume the use of an *advanced metering infrastructure* (AMI) as a measurement and communication platform on which a centralized controller is deployed.

This leads us to formulate the problem of optimal energy curtailment as an optimization problem in which the constraints are learned from past historic AMI data. We use it to send to each generator a maximal generation “quota”.

We evaluate the performance of our controller by means of numerical simulations. These experiments use network data from the “Low Voltage Network Solutions” project [3] and simulate the exact three-phased load-flow equations. We compare our proposed feed-forward controller with popular alternatives such as open-loop controllers and pure local feed-back controllers $P(U)$ or $Q(U)$.

Our main conclusion is that using the PV generators can be controlled using the AMI despite of its inherent limitations (lateness, inaccuracy and the long duration of control time-steps). The centralized feed-forward controller performs better, overall, than local controllers (that do not use the AMI and are thus oblivious to communication problems). Indeed, it is the only controller that is able to suppress most of the over-voltage or over-power constraints, and appears as an appealing method to mitigate congestion created by PV generators without reinforcement and with limited solar energy curtailment.

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2. PROBLEM SETTING

2.1 Network Model and Objectives

We consider a three-phase (AC) low voltage network connected to an upstream medium voltage (MV) network. The voltage at the point of coupling with the MV network is fixed, and the loads are all modeled as constant (complex) power, single-phase loads (the load consumed by a consumer ℓ at time t is $p_\ell(t)$). We assume that PV generators are controllable (with an active production $p_g(t) \in [0, p_g^{\max}(t)]$, where $p_g^{\max}(t)$ depends on the irradiance received at time t and the characteristics of the panel). Time is slotted and each time step corresponds to a 15min interval.

Active and reactive power consumption (or generation) at all customer nodes determine the complex voltages everywhere in the network through the (three-phase, unbalanced) load flow equations. These equations are standard [5] and are omitted here for the sake of concision. The only important thing is that, given the characteristics of the network, there exists two functions $U(.)$ and $T(.)$ such that the voltage at a bus b is equal to $U_b(\mathbf{p})$ whereas $T(\mathbf{p})$ is the power flow that goes trough the MV/LV transformer. The notation $\mathbf{p}$ denotes the vector of production and consumption at all buses.

Given this definition, the problem of minimizing the PV curtailment is naturally cast as the following optimization problem :

$$\begin{aligned} \max \sum_{g \in \text{Generators}} & p_g(t) & (1) \\ \text{such that } & \forall g : p_g(t) \in [0, p_g^{\max}(t)] \\ & \mathbf{p}(t) = \mathbf{p}_g(t) + \mathbf{p}_\ell(t) \\ & \forall b : U_b(\mathbf{p}) = 230V \pm 8.5\% \\ & T(\mathbf{p}) \in [0, \text{Transformer capacity}]. \end{aligned}$$

This problem is a classical optimal power flow (OPF) problem. What makes the problem interesting in our case is to take into account the constraints posed by the AMI which are essentially that the functions V and T are not known; only $p_\ell(t-1)$ and $p_g(t-1)$ are known but not the values at time t, where $t-1$ represents the previous 15min time-slot.

2.2 Possible Controllers

To solve the above problems, various control policy have been proposed in the literature. We now describe two classical policy (open-loop and pure feedback) as well as our controller that uses a feed-forward controller.

2.2.1 *Open-loop policy*

The open-loop controller is the simplest of all. It is parameterized by a value that indicates how much of its nominal power a generator is allowed to produced. The “open-loop 75%” strategy means that the PV are allowed to produce up to 75% of their nominal power. Note that on our data, it curtails less than 5% *energy* because PV generators rarely produce at their maximal power.

2.2.2 *Pure feedback controllers (P(U) and Q(U))*

The pure feed-back methods that we consider are the well-known $P(U)$ and $Q(U)$ controls. The $P(U)$ control for the generators adapts the generated power as $\beta(U_g(t))p_g^{\max}$, where $U_g(t)$ is the voltage at the bus of generator g. The function β is a sigmoïd function that decreases from 1 to 0 as $U_g(t)$ reaches its admissible upper limit. The $Q(U)$ control is similar and adjust the reactive power produced similarly. We refer to [8] for more details.

2.2.3 *Feed-forward controller*

The main ideas of the feed-forward controller is to

- Replace the non-linear constraints of Equation (1) by linear constraints with parameters that have been learned using past data.
- Use a learning algorithm to estimate $p_g^{\max}(t)$ and $p_\ell(t)$ based on $p_g(t-1)$ and $p_\ell(t-1)$.

In our simulations, we implement two of the simplest solutions to these problems : a linear regression for the first step; an auto-regressive model to predict the production $p_g(t)$ and a persistence forecast to predict the consumption of the load p_ℓ. We agree that there are probably better choices. Yet, our observation is that these simplest choices already give very good results.

This leads us to replace the original optimization problem (1) by the following approximation:

$$\begin{aligned} \max \sum_{g \in \text{Generators}} & p_g(t) & (2) \\ \text{such that } & \forall g : p_g(t) \in [0, \tilde{p}_g^{\max}(t)] \\ & \mathbf{p} = \mathbf{p}_g(t) + \mathbf{p}_\ell(t-1) \\ & \forall b : A\mathbf{p} + b = 230V \pm 8.5\% \\ & C\mathbf{p} + d \in [0, \text{Transformer capacity}], \end{aligned}$$

where the matrices A and C and the vectors b and d have been learned using past measurement and where $\tilde{p}_g^{\max}(t)$ is an estimation of the maximal output of a PV generator.

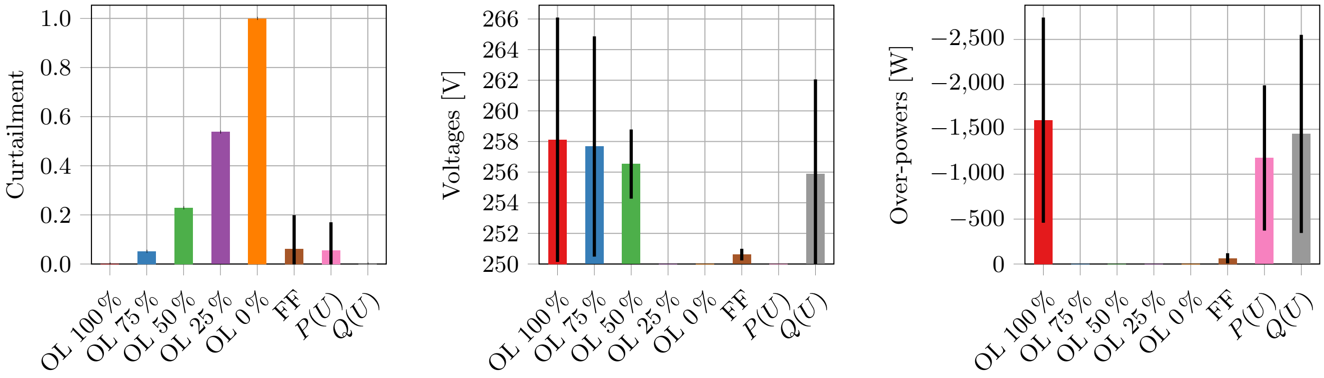
3. NUMERICAL EVALUATION

We experimented the above control policies on a data extracted from the database of the “Low Voltage Network Solutions” [3]. It contains the topology of 25 electrical distribution networks of various sizes (from ten to hundreds of clients) and provides load and generation profiles. We choose to equip 50% of the consumer with PV generators. Load profiles peak roughly at 6kW while generation peaks at 3kW to 6kW. We implemented a simulator that simulate the three phase load flow equations and allows us to compare the different scenarios. We compare the various algorithms on summer data. For the last algorithm that needs a learning phase, we choose to learn with winter data in order to have very distinct profiles.

3.1 Optimal trade-offs

In Figure 1, we report the fraction of the total solar energy that was curtailed, the average over-voltage and the average over-powers that was observed at the transformer. From this figure, we observe that:

- Open-loop – The open-loop 75 curtails about 5% of the energy and is sufficient to curtail all over-power at the transformer. However, to prevent over-voltage, one must adopt the open-loop 25, that curtails about 50% of the total energy which is not admissible in practice.
- By applying a local control, the $P(U)$ policy can prevent all the over-voltage (for which it has been designed for) and at relatively low cost (less than 5% of



(a) Energy curtailed (b) Over-voltage (c) Over-powers

Figure 1: Performance of the various controllers. The black line shows standard deviation.

energy curtailed). The $Q(U)$ control is less efficient; this is because voltage violations are here relatively strong, the reactive capacity of generators is limited, and the R/X factor in our data-set.

- Despite is relative simplicity in its design choice, the feed-forward controller appears to provide the best of both world : it can effectively suppress over-voltage and over-powers while having a limited impact of the PV production.

4. CONCLUSION

In this paper, we studied different control methods to eliminate congestion (over-voltage and over-power) caused by distributed PV generation: some local, and some centralized and based on the advanced metering infrastructure (AMI). We discussed how the AMI could be used for control purpose on two levels: firstly to infer knowledge of the underlying network structure, and secondly to populate the values of the parameters that enter the optimization problem that is solved inside the centralized controller. These arguments led us to the design of a feed-forward controller, that we prove numerically to be more efficient than classical strategies like open-loop or local feedback policies. From the implementation perspective, this policy can be implemented with limited communication and limited infrastructure deployment. Also, the method does not require any parameter tuning, nor prior detailed model ling of the underlying electric network.

This paper also suggests some directions for future research. First, one might improve on the learning side. Our numerical results suggest that simple learning algorithms are already sufficient to suppress most problems in our case study. Yet, there might be better choices. Second, we did not study in detail the fairness between clients of the same network but our preliminary results suggest that this is an issue. Third, the problem of adequately combining the feed-forward and local feed-back control seems both promising while maintaining a relative simplicity.

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