DISTRIBUTED MODEL-FREE CONTROL OF PHOTOVOLTAIC UNITS FOR MITIGATING OVERVOLTAGES IN LOW-VOLTAGE NETWORKS

Petros Aristidou
University of Liège, Belgium,
p.aristidou@ieee.org

Frédéric Olivier
University of Liège, Belgium,
frederic.olivier@ulg.ac.be

Maria Emilia Hervas
GreenWatch SA, Belgium,
mehervas@greenwatch.be

Damien Ernst
University of Liège,
Belgium,
dernst@ulg.ac.be

Thierry Van Cutsem
FNRS and the
University of Liège, Belgium
t.vancutsem@ulg.ac.be

ABSTRACT

In this paper, a distributed model-free control scheme to mitigate overvoltage problems caused by high photovoltaic generation in low-voltage feeders is proposed. The distributed controllers are implemented on the photovoltaic inverters and modulate the active and reactive power injected into the network. In particular, they direct photovoltaic units first to consume reactive power and, if necessary, curtail active power generation to reduce high voltages in the feeder.

INTRODUCTION

The increasing number of PhotoVoltaic (PV) panels connected to the Low Voltage (LV) Distribution Networks (DNs) are challenging the way these systems are managed and protected. LV DNs were not initially designed to accommodate power generation and this increased amount of renewables can endanger their security. For example, their intermittent nature may cause voltage fluctuations and flicker. Furthermore, they can cause reverse power flow, leading to unacceptable voltage rises in LV DNs. Finally, the massive installation of power electronics interfaced PV panels changes the behavior of the system on all voltage levels.

Modern PV invertersimplement Maximum Power Point Tracking (MPPT) algorithms to inject the maximum possible active power in the network. Thevariation of PV power output can in turn lead to voltage fluctuations. Some basic protection schemes are utilized to protect the devices from over/under-voltages, such as automatically switching off the PV units when the voltage at the terminal is too high [1]. Thus, in networks with high penetration of PV units can be repeatedly switched off during a sunny day leading to a financial loss for the producer and calling into question their profitability. A solution is needed to minimize the loss while guaranteeing the security, reliability and voltage quality of the network.

Rather than relying on costly investments to upgrade and reinforce the DNs, the current trend is to design and develop flexible, inexpensive control schemes for dealing with voltage problems. Several schemes have been suggested in the literature, acting on the PV active and reactive power outputs, to control the voltage profile of the system [2].

The proposed control schemes can be classified as centralized and *distributed*. In a distributed scheme, the algorithm is implemented over several controlling units, with no central entity and with limited or no communication. Such a scheme can be implemented at the inverter level, modulating its local generation.

In this paper, a distributed control scheme that modulates the active and reactive power injected by the PV units is proposed. The objective of the algorithm is to mitigate overvoltage problems by directing PV units to consume reactive power and, if necessary, curtail active power. The distributed controllers would be implemented on the PV inverters with three modes of operation. First, if there are no overvoltage problems in the LV DN, the controllers act preventively, modulating the PVs' reactive power, to avert their occurrence [3]. In this mode of operation, only local measurements are used and no communication among the controllers is needed. Second, if overvoltage problems occur, the controllers make use of limited communication for coordinating their reactive power modulation, within each DN LV feeder. Finally, if the overvoltage persists, even after all PVs have utilized their maximum reactive capabilities, the controllers switch to coordinated active power curtailment, again with limited communication.

The proposed scheme is model-free, as the topology, the parameters or even the PVs' relative position in the LV feeder is not required by the controllers. Moreover, it is robust and fault-tolerant, as the lack of centralized controller allows for the algorithm to work even if a number of PV units is malfunctioning or not participating.

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The paper is organized as follows. First, the dynamic model of the PV units, used in this study, will be presented. Following, the proposed control algorithm will be detailed. Then, the test-system and the simulation results will be presented followed by the concluding remarks.

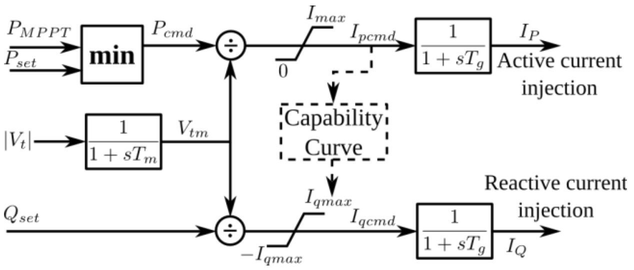

Figure 1 PV Dynamic Model

PV DYNAMIC MODEL

The dynamic PV model selected for this study is detailed in Figure 1. The closed-loop voltage regulator and the DC dynamics have been neglected to simplify the model [4].

The modelreflects active power priority withthe active current command (I_{pcmd}) limited by the maximum rating of the PV inverter (I_{max}). P_{set} and Q_{set} are the active and reactive power setpoints computed by the controller. When $P_{set} > P_{MPPT}$, the unit tracks the available solar power (MPPT).

T_g(~20ms) and T_m(~50ms) are the inverter current and the voltage measurement time constants, respectively. Finally, the limits on the reactive current command (I_{qcmd}) are calculated from the PV's reactive power capability curve using I_{pcmd}.

The reactive power capability of the PV unit is limited by the rating of the inverter and the current Total Harmonic Distortion (THD) [5] and is shown in the shaded area below the green dashed curve of Figure 2. The red lines define the minimum Power Factor (PF). Lower PF values would result in high current distortion and unacceptable THD values [5].

These limitations impose the upper and lower bounds on reactive powermodulation with respect to active power and rating of the inverter. It is technically possible to design PV inverters to provide reactive support at smaller PF values or even if solar input is zero, much like a STATCOM. However, this functionality is not standard in the industry and would significantly increase the cost.

Finally, PV inverters can be oversized to relax the upper limit and allow for some amount of reactive power even at full active power generation (purple dashed curve). Thus, the reactive current limit is computed as:

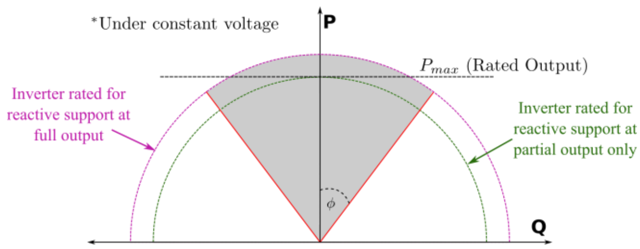

Figure 2 PV capability curve

$$I_{qmax} = \min\{I_{pcmd}\tan(\cos^{-1}PF), \sqrt{I_{max}^{\ 2} - I_{pcmd}^{\ 2}}\}$$

CONTROL ALGORITHM

The distributed scheme control logic is implemented at the inverter level, taking as input the locally measured terminal voltage (V_{tm}) and setting the active and reactive power set-points (P_{set},Q_{set}). Each controller is implemented as a *discrete* device, updating the control actions with an interval T_{upd}, that is the n-th action takes place at time $t = nT_{upd}$. This discrete nature is justified by the use of embedded microcontrollers and the communication, measuring and computing delays involved in the procedure.

As summarized in the introduction, the controllers have three modes of operation shown in Figure 3.

Mode A: Normal operating conditions

During normal operating conditions, when all PV terminal voltages in the LV feeder are below a predefined maximum the PV units follow an MPPT logic for active power setpoint and modulate the reactive power as a function of their terminal voltage [3], as shown in Figure 4. The reactive power modulation is designed to act preemptively to the

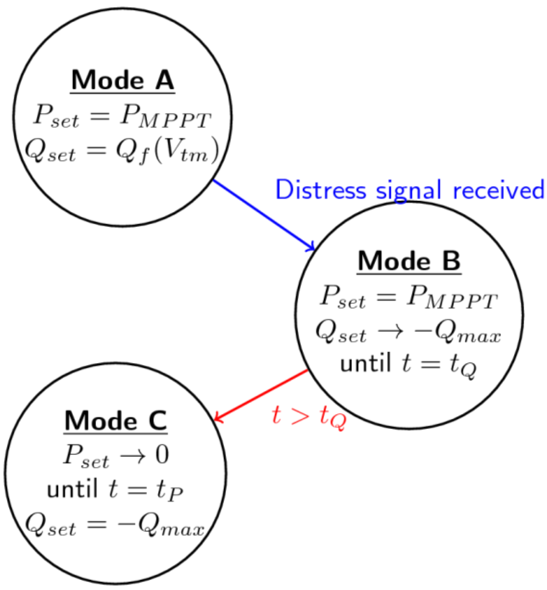

Figure 3 Controller state transitions

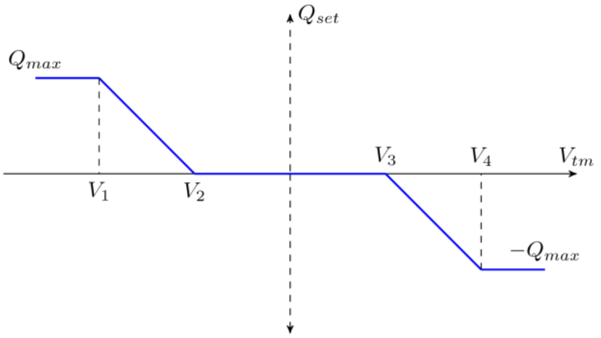

Figure 4 Q(V_{tm}) function

overvoltage when V_{tm} exceeds V_3. V_4 is the predefined maximum voltage so that if the terminal voltage reaches this value, the corresponding PV unit has already utilized its own reactive power capabilities trying to solve the problem. The symmetrical part of the reference figure is used in undervoltage situations, which are not considered in this study.

When all the PV units in a feeder are in this mode of operation, only local measurements are used and no communication among the controllers is needed.

Mode B: Coordinated reactive power modulation

A PV unit whose terminal voltage has reached V_4, has already made full use of its reactive power adjustment capability and cannot mitigate the overvoltage by itself without proceeding to active power curtailment. At this moment and for as long as the overvoltage persists, a repeating distress signal is sent to all PV controllers in the same feeder.

Upon receiving this signal, all PV controllers in the same feeder start reactive power modulation to decrease the terminal voltage of the distressed PV(s). During this mode of operation, the PV units follow an MPPT logic for active power setpoint and modulate their reactive power, increasingly consuming more reactive power, until they reach their Q_{max} at $t = t_Q$.More specifically, the dynamics of Q_{set} is chosen as follow:

$$Q_{set}[t_n] = Q_{set}[t_{n-1}] + (-Q_{max}[t_n] - Q_{set}[t_{n-1}])\frac{t_n - t_{n-1}}{t_Q - t_{n-1}}$$

where the value of Q_{max} is updated at each step based on the capability curve (Figure 2) and the terminal voltage. An example can be seen in Figure 5.

This mode of operation has two possible outcomes. First, if the overvoltage problem is resolved by the coordinated reactive power modulation and if the distress signal disappears, the PV controllers freeze their reactive power setpoints while continuing to follow the MPPT logic for active power. In this case, no active power is curtailed and the overvoltages are mitigated only with reactive power modulation. Otherwise, if the problem persists after a period t_Q, the PV controllers proceed to coordinated active power curtailment (Mode C).

Mode C: Coordinated active power curtailment

In this mode, the PV controllers stop applying MPPT and start curtailing active power according to:

$$P_{set}[t_n] = P_{out}\left(1 - \frac{t_n - t_{n-1}}{t_P - t_{n-1}}\right)$$

where P_{out} is the PV unit's active power output *at the moment of entering Mode C* and t_P is the time horizon by which all PVs would have curtailed all their active power outputs.

At the same time, the reactive power setpoint is fixed to $-Q_{max}[t_n]$, with the latter continuously being updated due to the modulation of the active power and the change of terminal voltage, as dictated by the capability curve (Figure 2).

Finally, if the overvoltage problem is resolved, the PV controllers freeze their power set-points and timers. Otherwise, all the PV units in the distressed feeder will reach zero power output, almost simultaneously, at $t = t_P$.

General considerations

The presented distributed scheme makes no use of the network model or parameters. Moreover, it does not need information on the position of each PV inside the LV feeder. During normal operating conditions, there is no exchange of information amongst the PV controllers, while limited communication, in the form of a distress signal, is needed for Modes B and C.

It is noteworthy that at the end of Mode C, all PV units in the distressed feeder have approximately curtailed the same percentage of active power, thus the financial loss is shared evenly amongst them. Minor differences between them will exist due to the discrete nature of the controllers. If continuous controllers were used, they would be synchronized and the final output would exactly the same.

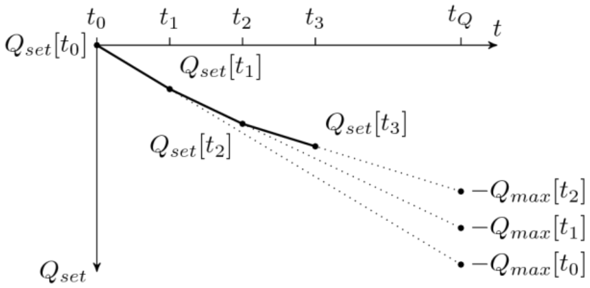

Figure 5 Q_{set} modulation in Mode B

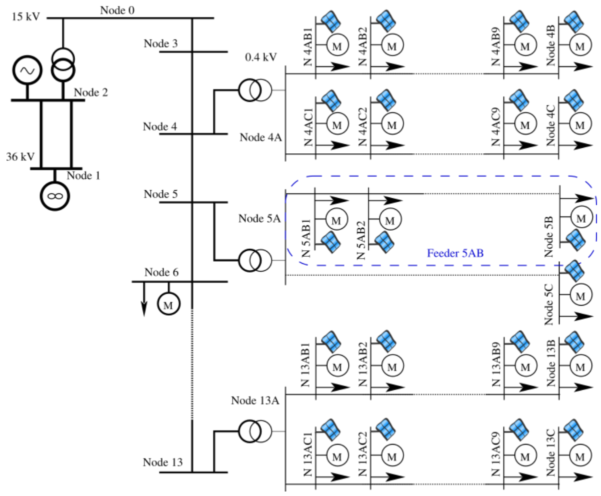

Figure 6 MV/LV test-system

Finally, while in Modes B or C, if the distress signal disappears before depleting the reactive (resp. active) reserves, then the timers are frozen until a new signal is received.

SIMULATION AND RESULTS

The proposed scheme has been tested on the MV/LV distribution system presented in [6], which was modified for the purpose of demonstrating the performance of the method in a demanding situation. Its one-line diagram is partially sketched in Figure 6. The system includes 14 LV feeders, each of them supplying 10 loads and including 10 PV units equipped with a discrete controller implementing the proposed control method.

Each of the 140 loads includes an equivalent motor and a non-motor, voltage dependent load. For the sake of simplicity, the same fraction of motor load is considered for all loads, namely 30%. The feeders are connected in pairs to the MV buses 4, 5, 7, 8, 10, 11 and 13. Larger motors are connected to the MV buses 6, 9 and 12. Furthermore, a synchronous machine with detailed

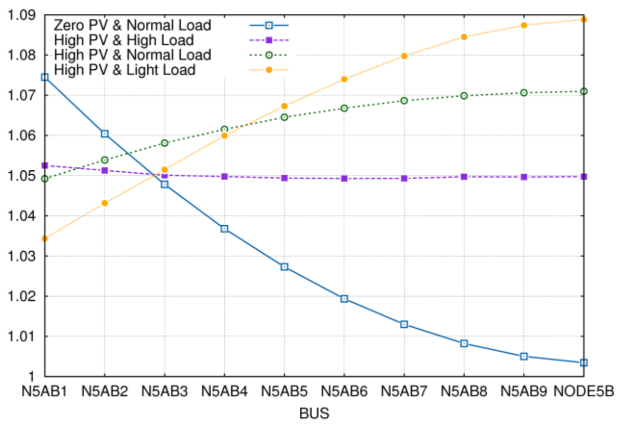

Figure 7 Voltage profile at various levels of load consumption and PV generation

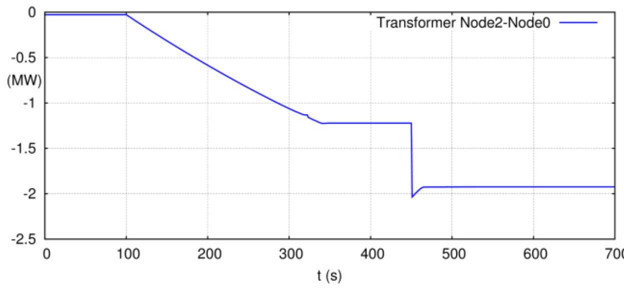

Figure 8 Active power flow in transformer

model is connected to Node 2. Each equivalent induction motor has a 6-kVA rated apparent power and its model accounts for the presence of a double-cage rotor.

The PV units were rated between 20 and 30 kW and their initial generation is set from 90 to 100% of their rating. The inverters were not oversized, so they do not provide reactive power at full output. The discrete action interval of each controller was randomly drawn between 0.8 and 1.2 second. The coordination and the distress signals, as explained previously, are limited within each feeder as shown in the figure for Feeder 5AB. However, all feeders are equipped with the same control scheme and operate independently and concurrently. The parameters for the Q(V_{tm}) of Figure 4 were set to $V_1 = 0.90$, $V_2 = 0.95$, $V_3 = 1.04$ and $V_4 = 1.09$. Finally, the time to deplete reactive power was set to $t_Q = 60\ s$ and for active power $t_P = 180\ s$.

The dynamic simulations in phasor mode have been performed using the RAMSES software [7] developed at the University of Liège.

The test case considers the network with high PV generation and high loading with all controllers in Mode A. Thus, initially the voltage profile inside the feeders has the shape shown in purple in Figure 7. From $t = 100$ to $340\ s$, the loads in the feeders are gradually decreased to "light load" while the PV generation is kept high. Following, at $t = 450\ s$ a comparatively larger MV load, attached to Node 6 is disconnected.

The load decrease causes a significant reverse power flow, which can be seen in Figure 8 from the active power flow in the transformer "Node 2-Node 0". As a consequence, overvoltage problems are observed in several feeders and are successfully mitigated by entering Mode B.

Figure 9 shows the voltages inside Feeder 5AB. As the loads decrease, the voltages increase. At $t = 290\ s$, the PV unit the furthest away from the transformer (NODE5B) crosses the upper voltage limit V_4. At this moment, the PV has depleted its own reactive power capabilities and sends a repeating distress signal in the feeder. Hence, all PV controllers enter Mode B and help mitigate the problem using their reactive power

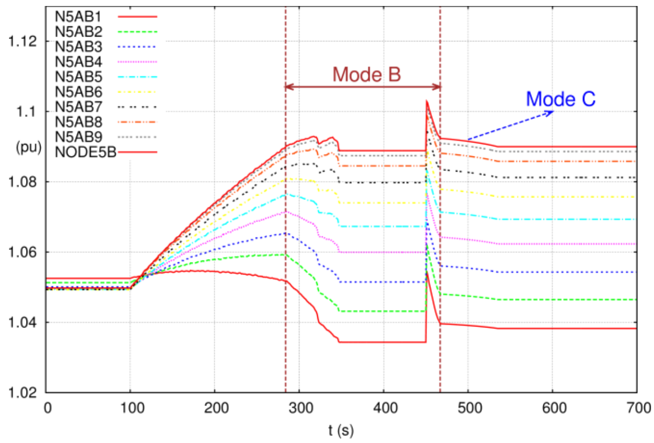

Figure 9 Voltage evolution in Feeder 5AB

reserves. The problem is solved at $t = 345\ s$, with all voltages within limits, and the distress signal disappears. At this point, no active power curtailment was needed.

Next, the whole load of Node 6 is disconnected at $t = 450\ s$ causing an overvoltage spike and new distress signals. First, the PVs (which are still in Mode B) try to mitigate the problem utilizing their remaining reactive power capabilities. At $t = 470\ s$, all the PVs in the feeder have reached their maximum reactive power and they enter Mode C with active power curtailment until the overvoltage problems are solved at $t = 540\ s$.

Figure 10 shows the percentage of energy lost over the entire simulation for each PV unit because of the operation in Mode C. It can be observed that due to the discrete and asynchronous nature of the controllers, some small deviations (~0.4%) are observed.

CONCLUSION

The distributed control scheme presented in this paper, modulates the active and reactive power injected by the PV units in a LV feeder to mitigate overvoltage problems. It has been shown that the controllers can alleviate problems arising from high PV generation as well as problems due to disturbances in the MV network. Thus, they can help improve the security and voltage quality of LV networks.

Moreover, the proposed control scheme does not need information on the parameters of the feeders and makes little use of communication.

A significant aspect of the control algorithm, that has not been discussed in this paper due to space limitations, is the restoration of the PV controllers to normal operating conditions (Mode A) when the conditions causing the overvoltages change. In brief, this can be done by introducing a reset timer, which will lead the controllers into a restoring mode after a certain time

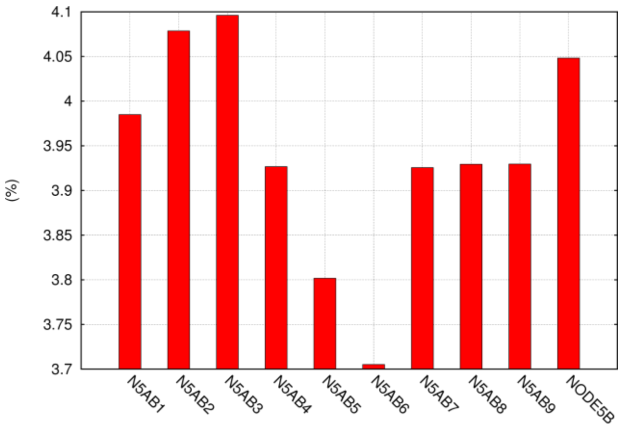

Figure 10 Percentage of energy lost by each PV

without any distress signals. In this mode, the controllers need to first increase the generated power to P_{MPPT} and then modulate their reactive power to match $Q(V_{tm})$ before switching back to Mode A.

REFERENCES

[1] "IEEE 1547 standard for interconnecting distributed resources with electric power systems", IEEE Std 1547-2003.

[2] A.R. Malekpour, A. Pahwa, S. Das, "Inverter-based VAR control in low voltage distribution systems with rooftop solar PV", *Proceedings* 2013 *North American Power Symposium*.

[3] R. Dugan,W. Sunderman, B. Seal, "Advanced inverter controls for distributed resources", *Proceedings 2013 22nd International Conference and Exhibition on Electricity Distribution(CIRED)*

[4] WECC REMTF, WECC "Generic solar photovoltaic system dynamic simulation model specification", September 2012, Available: http://www.wecc.biz/ [Accessed January 2014].

[5] T.F. Wu, C.L. Kuo, K.H. Sun, H.C. Hsieh, 2014, "Combined unipolar and bipolar PWM for current distortion improvement during power compensation", *IEEE Transactions on Power Electronics*, vol.29, no.4, pp.1702-1709.

[6] B. Otomega and T. Van Cutsem, "Distributed load interruption and shedding against voltage delayed recovery or instability", *Proceedings 2013 IEEE PES PowerTech Conference*.

[7] P. Aristidou, D. Fabozzi, T. Van Cutsem, 2013, "Dynamic simulation of large-scale power systems using a parallel Schur-complement-based decomposition method", *IEEE Transactions on Parallel and Distributed Systems (early access).*