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Ángel Molina-García
Rosa A. Mastromauro
Tania García-Sánchez
Sante Pugliese
Marco Liserre
Silvio Stasi

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Reactive Power Flow Control for PV Inverters Voltage Support in LV Distribution Networks

Ángel Molina-García, *Senior Member, IEEE*, Rosa A. Mastromauro, *Member, IEEE*, Tania García-Sánchez,
Sante Pugliese, Marco Liserre, *Fellow, IEEE*, and Silvio Stasi, *Member, IEEE*

***Abstract*—This paper proposes a reactive power flow control pursuing the active integration of photovoltaic systems in LV distribution networks. An alternative power flow analysis is performed according to the specific characteristics of LV networks, such as high resistance/reactance ratio and radial topologies. The proposed solution gives high performances, in terms of rms-voltage regulation, by estimating the reactive power reference on each node considering the influence of the rest of the nodes in terms of active and reactive power demanded/generated by them. The local control of each photovoltaic system is based on the power converter control, interfacing these units with the grid and the loads respectively. The local control is designed on the basis of locally measured feedback variables. Photovoltaic units thus guarantee universal operation, being able to change between islanding-mode and grid-connected mode without disrupting critical loads connected to them, and allowing smooth transitions. Exhaustive results are also included and discussed in this paper.**

***Index Terms*—LV radial networks, photovoltaic systems, reactive power control, voltage control.**

I. INTRODUCTION

THE INCREASED presence of Distributed Generation (DG) in LV networks has considerably modified the expected power flow patterns, being far from classical power system analysis. In this new scenario, where generation and consumption can simultaneously come from the demand-side, significant and undesirable voltage oscillations in LV networks may occur, leading to detrimental impacts on the network operation, mainly in remote feeder ends [1]. Several studies indicate that the voltage will rise when there is reverse power flow in the feeder due to DGs interconnection to the LV network [2], [3]. Notably, in some countries, the reverse power flow from the distribution network back to the transmission network is prohibited, e.g., Japan [4]. Hence, the integration of renewable energies such as DG in LV networks presents many significant challenges [5]. Among the possible renewable resources, some authors affirm that solutions based on PV systems (PVs) are the only viable option at small or distribution level [6]. Actually, most of the technical literature concentrates on distribution system studies, whereas the impact of solar PV in transmission systems has not been extensively studied [7]. According to [8], distribution systems have been designed as a passive network in a radial style and then the interconnection of PVs may cause some issues and impacts that need to be carefully considered and studied.

In parallel with the promotion of renewables, new requirements and rules have been issued during the last years. The main target has been focused on including LV customers as active elements of the grid, providing some ancillary services under normal operating conditions, basically by modulating their reactive power exchanged with the grid [9]. Examples of this can be found in Germany, Italy and Slovenia [10], [11], where the reactive power exchange should be maintained within a triangular/rectangular reactive power capability curve depending on the power rate converter. The extension to exploit the reactive power potential of the inverters more efficiently by expanding the capability area from a rectangular characteristic to a circular characteristic has been recently discussed in [12]. According to the specific literature, when large-scale applications of PV in the grid are considered, few references are found on PV in the individual customer line [13], with most of the work on large-scale PVs being reported either on large scale PV power generation or on central PV power schemes [14]. In [15], a statistical sampling approach is taken by the authors, fixing certain average ‘*macroscopic*’ parameters of the distribution circuit. Recently, some contributions can be found aiming to analyze the PVs inverter capacity to generate/demand reactive power as a potential solution to the voltage regulation problem [16], [17], including in some cases active power regulation [18], [19].

Á. Molina-García is with the Department of Electrical Engineering, Universidad Politécnica de Cartagena, 30202 Cartagena, Spain (e-mail: angel.molina@upct.es).

R. A. Mastromauro is with the Department of Information Engineering, University of Florence, 50139 Florence, Italy (e-mail: rosaaanna.mastromauro@unifi.it).

T. García-Sánchez is with the Renewable Energy Research Institute, Universidad de Castilla La-Mancha, 02071 Albacete, Spain (e-mail: tania.garcia@uclm.es).

S. Pugliese and S. Stasi are with the Department of Electrical and Information Engineering, Politecnico di Bari, 70125 Bari, Italy (e-mail: sante.pugliese@poliba.it; silvio.stasi@poliba.it).

M. Liserre is with the Christian-Albrechts-Universität zu Kiel, D-24143 Kiel, Germany (e-mail: ml@tf.uni-kiel.de).

Considering previous contributions and in line with current efforts to ensure reliable voltage regulation with alternative solutions to online tap changer, autotransformers, voltage regulators or switched capacitors, which are usually not justified due to low cost benefit ratios [20], a combined centralized-decentralized reactive power flow control strategy is presented in this paper for LV grid-interfaced PV inverters. The purpose of this paper is to control the bus voltage maintaining the rms-voltage level within a specific range on each node, including variations in active power demanded-supplied by the grid and improving the integration of renewable resources. The proposed method consists of a centralized-remote control performed by the Distribution System Operator (DSO) and a local/decentralized control performed by the power converter of each PV. The main contributions of the paper are: *(i)* a detailed extension of an alternative power flow based on the forward and backward voltage updating process is proposed. This solution avoids convergence problems and minimizes computational time costs for radial topologies, therefore, higher computational efficiency is expected than iterative methods. The cable resistance is explicitly considered in the LV line model, and an alternative Q-V relation is then proposed. *(ii)* a reactive power set-point estimation is carried out on each node by considering the influence of the rest of nodes, as well as the active/reactive power supplied/demanded by them, and not only local data corresponding to each node. Compared with traditional reactive power set-points adopted in the literature, the rms-voltage regulation is sharply improved, while preserving the desired control performance. *(iii)* a three-level control system based on power, voltage and current loops to ensure a universal operation for distribution power generation systems is described and assessed. This system allows us to operate not only under grid-connected conditions, but also in island-mode conditions thanks to the proposed hierarchical local control. An appropriate selection of controlled variables is one of the most important points in terms of measurement and communication requirements between the local system and the grid. Actually, most contributions in the field of DG system control design and grid management techniques present reduced practical applications.

The rest of the paper is structured as follows. Section II deals with the reactive power control algorithm based on a modified power flow methodology, Section III describes the PV inverter control and the decentralized/local solution proposed by the authors. Section IV outlines the main issues and open points related to the employment of the ICT infrastructure. The results and simulations are discussed in Section V. Finally, the conclusion is given in Section VI.

II. REACTIVE POWER FLOW CONTROL ALGORITHM

A. *Modeling of LV Network Topologies*

With regard to LV network modeling, and taking into account that LV distribution networks usually present a radial topology [21], a generalized LV network is modeled; including sub-branches (sB_j) connected to different nodes, see Fig. 1(a). Consequently, individual LV customers are explicitly considered, it is possible to demand/generate active or reactive power for each customer. Both global active and reactive power corresponding to a specific j-node (N_j) can then be defined as follows,

$$\left.\begin{array}{l} P_j = P_j^d + P_j^g + \sum_{k=1}^{m} P_j^k \\ Q_j = Q_j^d + Q_j^g + \sum_{k=1}^{m} Q_j^k \end{array}\right\}, \tag{1}$$

where m is the number of nodes depending on N_j, P_j and Q_j are the global active and reactive power viewed from j-node, P_j^d and Q_j^d are the active and reactive power demanded by the j-node, P_j^g and Q_j^g are the active and reactive power supplied by the j-node. In all cases the sign criteria for active power is P>0 (demanded) and for reactive power Q>0 (inductive). The uncertainty of solar radiation can also be considered as an oscillation or modification of P_j^g, the active power supplied by the j-node, and consequently a modification of the reactive power reference.

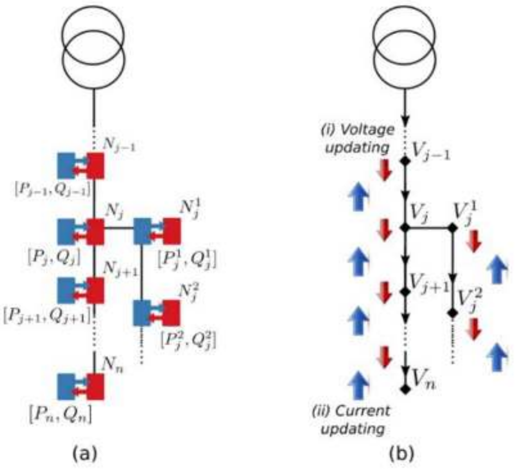


Fig. 1. (a) LV network modeling and (b) power-flow methodology.

Previous works focused on simplified circuits with only a main branch, neglecting sub-branches and the corresponding modifications on the global active and reactive power at the connection node [22]–[24]. However, our approach allows us to model more realistic LV topologies, where the global active and reactive power values on each node depend not only on the PVs and the loads, but also on the configuration of the rest of the LV distribution network. The alternative power flow is also suitable to solve unbalanced networks, provided that the topology of the grid remains radial, which is typical for distribution networks.

B. *Power-Flow Methodology*

The voltage regulation problem in distribution networks relies on Optimal Power Flow (OPF) solvers developed for transmission networks [25], [26]. However, traditional power-flow methods based on Gauss-Seidel, Newton-Raphson and fast decoupled load flow become ineffective for the analysis of distribution systems with high *R/X* ratios [26]. Moreover, [27] suggests that those algorithms were designed for transmission systems. Therefore, their application to distribution systems usually fails to provide good results and very often the solution diverges, despite contributions that focus on improving convergence problems and reducing computational time costs for distribution systems with high *R/X* ratios [28]. LV networks usually present radial topologies, an alternative power flow based on the forward and backward voltage updating by using a polynomial voltage equation for each branch as well as the Kirchhoff laws is proposed and applied [29], [30], see Fig. 1(b). This methodology involves a recursive process to update voltage and current values in reverse and forward direction, considering that

$$V_{j-1} - V_j \approx \frac{RP_{j_{eq}} + XQ_{j_{eq}}}{V_{j-1}}, \tag{2}$$

being $P_{j_{eq}} = \sum_{k=j}^{n} P_j$ and $Q_{j_{eq}} = \sum_{k=j}^{n} Q_j$.

According to the LV network modeling depicted in Fig. 1(a), the voltage drop between nodes, N_j and N_{j-1}, not only depends on the partial P_j and Q_j values corresponding to *j*-Node (N_j), but also on the equivalent LV network from this point.

On the other hand, and due to the *R/X* ratios in LV, some contributions suggest that the method of reactive power compensation device may not be sufficient for voltage regulation at LV grid with PV, especially with relative high penetration of PV at LV grid during a typical sunny day [31]. In this proposal, we focus on solutions based on reactive power control for voltage regulation, while active power curtailment techniques, reducing the amount of active power injected by the PV inverters, has recently been proposed to prevent overvoltage and to increase the installed PV capacity [32], [33]. An iterative process is proposed to be repeated until the convergence tolerance on each voltage node is reached. The proposed power flow algorithm can be extended to a π-circuit model including capacitances for radial distribution networks, [34], [35]. In line with [36], an orthogonal linear transformation matrix is proposed to transform from the active and reactive power to the modified active and reactive power values on each node,

$$\begin{pmatrix} P'_{j_{eq}} \\ Q'_{j_{eq}} \end{pmatrix} = \begin{pmatrix} X/Z & -R/Z \\ R/Z & X/Z \end{pmatrix} \begin{pmatrix} P_{j_{eq}} \\ Q_{j_{eq}} \end{pmatrix}. \tag{3}$$

For a small power angle δ, see Fig. 2(b), which is a typical value in most studies, combining (2) and (3) it can be assumed that the power angle only depends on the equivalent active power, and that the voltage only depends on the equivalent reactive power [37],

$$\begin{aligned} V_j \sin\delta &= \frac{XP_{j_{eq}} - RQ_{j_{eq}}}{V_{j-1}} \\ &= \frac{Z}{V_{j-1}} P'_{j_{eq}} \quad \Rightarrow \quad \delta \approx \frac{Z}{V_j V_{j-1}} P'_{j_{eq}} \qquad (4) \\ V_{j-1} - V_j \cos\delta &= \frac{RP_{j_{eq}} + XQ_{j_{eq}}}{V_{j-1}} \\ &= \frac{Z}{V_{j-1}} Q'_{j_{eq}} \Rightarrow \Delta V \approx \frac{Z}{V_{j-1}} Q'_{j_{eq}}, \qquad (5) \end{aligned}$$

being possible to independently analyze the influence on the grid frequency and the voltage amplitude respectively by means of introducing these modified active and reactive power values.

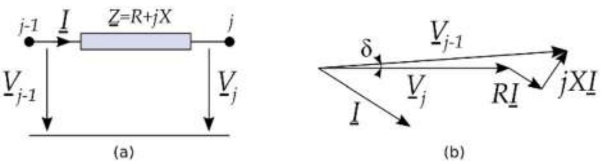


Fig. 2. (a) Power flow through a line and (b) phasor diagram.

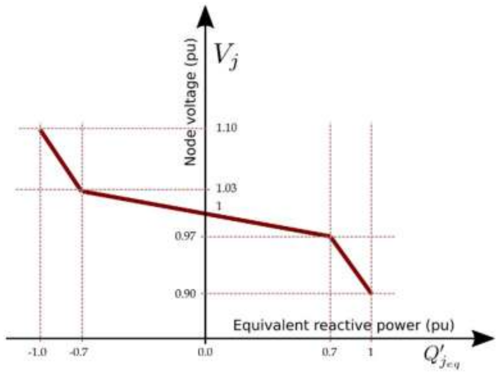


Fig. 3. Proposed *V-Q* characteristic for voltage control.

C. Reactive Power Control Strategy

A variety of strategies can be found in the specific literature to adjust the DG reactive power injection in response to either local or global variations of the feeder bus voltages. Some contributions propose alternatives to minimize the total power dissipation in the network by controlling the DG reactive power injection [38]. Others directly control the injected reactive power to prevent bus voltage rise under the presence of distributed generation [39], [40]. Power curtailment is an alternative solution to reactive power control, where the active power generation is constrained to prevent voltage rise along the feeder [41]. Other approaches are based on setting the reactive power injection levels of the PV inverters according to a predefined relationship between the inverter power factor and the LV bus voltage, even considering an electronic tap changer into the primary distribution transformer for the feeder. Nevertheless, and according to [42], while reactive power management is designed to enable PV inverters to inject/absorb reactive power, its objective is not to control bus voltages, but rather to attempt to ensure that PV real power injection does not cause a high voltage rise on the LV feeder.

The proposed voltage-reactive power characteristic is shown in Fig. 3, where the equivalent reactive power is obtained taking into account the voltage level required on each node. From this equivalent reactive power, and according to Section II-B, the required reactive power on each node is then determined to reduce the voltage drop to the rated level on each node. In our proposal, this reactive power value corresponds with the global reactive power on each node. Consequently, the PV inverter reactive power has to be deduced from the power flow solution and the rest of the active and reactive power values.

III. PV INVERTER CONTROL DECENTRALIZED/ LOCAL SOLUTION

The local control of small and medium power DG systems integrated into the distribution network can be distributed or centralized. Since the availability of high computing facilities or dedicated operators in LV grids has been highly unlikely up to now, decentralized solutions were imposed to the overall problem of DG and microgrids. Decentralized control is inertly optimal due to the lack of full network information, but it leads to uncoordinated operation of the different DGs, which is in contrast with the aim of the paper: to optimize the voltage profile of the overall grid or one of its portions. Among the distributed control methods, the droop control technique provides frequency and amplitude regulation of the DG converter's voltage and, at the same time, a non-communication-based power sharing strategy among the different units inside the microgrid [43]. However, in order to limit the communication lines, the droop control method is also an optimum candidate for combined centralized-decentralized control strategies. Actually, this solution is able to regulate the power exchange between each DG system and the grid, while the DSO gives set-points to the local control. In this scenario, DG systems can provide a service to the grid during grid-connected operation.

The management of each single DPGS with one-level of control is not attainable, since it just allows us to inject the power available from the sources into the grid without possibility of full-control (current control). A cascade control based on two loops (power and current loops) guarantees full-control of the injected power. A three-level control system (power, voltage and current loops) extends the previous solution giving a "universal operation" of the single DPGS, and being able to operate under grid-connected conditions and also under island mode situations thanks to the voltage profile regulation. For these reasons, and with the aim of providing a "standard" and "universal" configuration, the proposed local control is based on a hierarchical solution. The hierarchical control for PVs integrated into LV distribution networks is proposed as an attempt to emulate the transmission-distribution network management. For this proposal, the central dispatcher periodically updates the set-points of the local/decentralized controller of each PV inverter, on the basis of the power flow for the radial networks according to Section II. The local control system is comprehensively responsible to operate the local voltage control at the PCC of the PVs, as well as to manage the active/reactive power exchange with the loads and the main power system by means of *three-level* cascade loops. The primary control needs a fast dynamics. It is based on a current controller, controlling the current at the PV converter output and a voltage controller, controlling the voltage on the capacitor of the *LCL* filter that interfaces the converter with the grid and with the local loads. The secondary control operates on a slower time frame and it deals with the power exchange among the LV distribution network, the PV system and the local loads, whilst at the same time providing the reference for the capacitor voltage control. With the proposed control structure, the regulation of the local voltage profile at the PCC of each PV system is then fixed. The local control scheme of each PVs is shown in Fig. 4, where C denotes the capacitance of the *LCL* filter and C_{DC} denotes the capacitance of the DC-link. If all equations are expressed in dq-frame, the instantaneous active and reactive powers can be then determined from the corresponding voltage and current variables as follows:

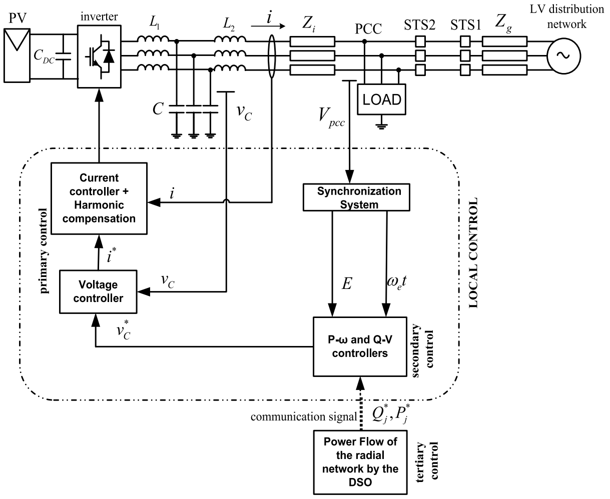


Fig. 4. Local control of a PV system.

$$p = \frac{3}{2}\left(v_d i_d + v_q i_q\right)$$
$$q = \frac{3}{2}\left(v_d i_q - v_q i_d\right) \tag{6}$$

The reference voltage of the primary control can be determined by its operating point on the *Q-V* droop curve shown in Fig. 5, where a possible *V/Q* characteristic is depicted and where P_n is the rated active power. Under normal mode of operation, each PV system is connected to the grid at the PCC, usually through a static transfer switch (STS), see Fig. 4. When a fault is detected, the PV system can move to island operation and the loads are supplied by the DG system. The total active/reactive power should be shared according to the respective loads. Ratings and DG systems may adapt their generated power in order to fulfill the balance with the power demand. During island operation, the active/reactive control can be regulated by means of the following equations:

$$\omega = \omega_b - m_{island}(P - P_{MAX})$$
$$\hat{V}_d = \hat{V}_{Cb} - n_{island}(Q - Q_{MAX}) \tag{7}$$
$$\hat{V}_q = 0 \tag{8}$$

where $\hat{V}_{Cb}$ and ω_b are the phase and amplitude voltage references set to their nominal values; P_{MAX} and Q_{MAX} are the maximum active and reactive power for the PV systems; m_{island} and n_{island} are the droop gains for the island mode operation. These droop coefficients are moved from grid-connected to island operation conditions, then with the integrator block of the reactive power control being deactivated. Apart from these adjustments, the local control structure is the same in both operation modes, guaranteeing universal operation for the PV converters. Subsequently, when a fault is cleared, the system has to be resynchronized with the utility grid by means of a Phase Locked Loop (PLL), before the STS can be reclosed to return the system smoothly back to the grid-connected operation mode.

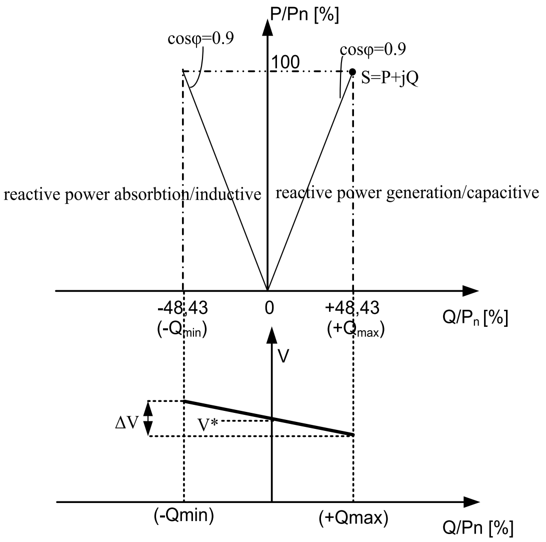


Fig. 5. Triangular/rectangular reactive power capability curves for power converters over 6 kW [10].

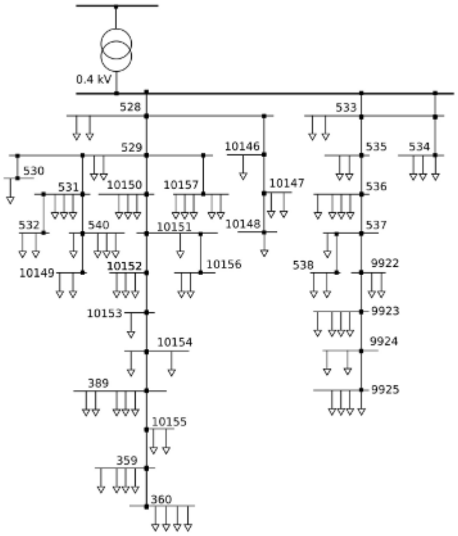


Fig. 6. Radial LV network test system (Bornholm, Denmark).

IV. Role of the Communication Systems: Issues and Open-Points

One of the main drawback towards the employment of communication systems in smart grids and DG systems is that different functions set different requirements for the communications. Among other functionalities, especially grid protection and monitoring set requirements for latency and jitter. The latency requirement for grid protection is 10 ms and for monitoring between 100ms and 1s, respectively. Smart metering applications, in turn, set demands for throughput, especially in large grids with many customers, where the total amount of transmitted data can be up to gigabytes. Thus, broadband data rate (> 1Mbps) is one of the requirements. Other requirements for communication besides sufficient latency and data rate are the reliability and the range of the communication [44]. The use of communications for protection purposes can be reduced to the minimum considering that the DG systems can actually be equipped with islanding detection techniques and that the local control of each PVs can be designed using only feedback variables that can be measured locally. In particular, in the proposed application, each PVs is able to switch between island and grid-connected modes without disrupting critical loads connected to it and allowing a smooth transition. However, for the grid voltage profile optimization, the communication system cannot be removed, since the estimation of the reactive power to be injected by each individual inverter is dependent on the influence of the rest of nodes. As a consequence, at least information about the active and reactive powers has to be exchanged between the PVs and the central controller in order to perform the power flow of the radial network. By considering different communication methods, the local area network (LAN/Ethernet) and optical fiber trans-mission can be used for the implementation of High Bandwidth Communication (HBC). However additional cost is entailed to achieve the infrastructure for this communication method. In this scenario the DNP3 protocol has also been proposed in the past [44]. Meanwhile, among the Low Bandwidth Communication (LBC) methods, Power Line Communication (PLC) can be used. The advantage of the LBC-based methods lays in the reduced amount of data flowing in the communication network. Denoting the sampling frequency as f_s, the communication frequency of the HBN is f_s. Meanwhile the communication frequency of the LBC network can be selected to f_s/N. Hence for an HBC-based control method the data transfer is accomplished every control period, while for a LBC-based method the data transfer is accomplished every N control period. Hence, during the same length of time the amount of data is reduced to $1/N$ [45], [46].

In the proposed strategy, it is assumed that the control set-points are provided by a supporting communication infrastructure. Among the considered solutions, the selection of the most appropriate communication system depends on the extension of the grid portion managed by the same central controller. Nevertheless, there are still uncertainties associated with the communications systems, namely the delay or the loss of control information that needs to be accounted for to ensure the resilience of the overall system. In [47], the importance of a communication infrastructure for demanding applications such as frequency control and the need to ensure the necessary coordination between local and central control to overcome potential uncertainties in the communication systems is highlighted. It is also shown how high data losses can likely lead the system to collapse. This represents the main challenge in the presented scenario and for this reason an approach that limits the amount of data transfer is essential.

V. Results

The proposed methodology has been evaluated by using a real LV network from Bornholm (Denmark) available in the specific literature. This is a radial LV topology shown in Fig. 6 with 71 users and a 100 kVA distribution transformer used for simulation purposes, being assumed as representative for LV networks. In line with [48], loads are considered

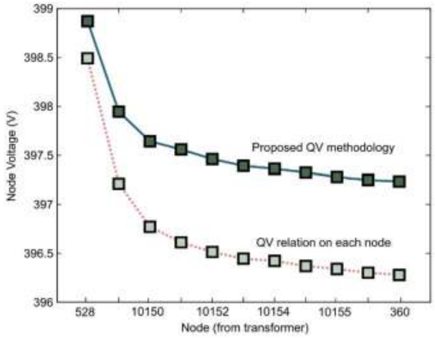


Fig. 7. Comparison of node voltage profiles with PV installations at rate active power.

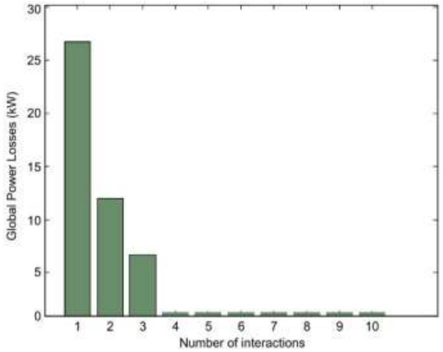


Fig. 8. Power flow convergence with PV installations at rate active power.

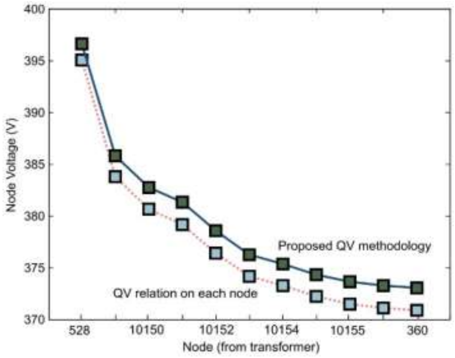


Fig. 9. Comparison of node voltage profiles with PV installations at 50% rate active power.

three-phase and balanced, and connected to a set of nodes labeled according to the different branches identified in the LV network. In the case study, ± 48% of the rate active power is assumed as reactive power range for PV inverters, according to the Italian Standard CEI 0-21. All consumers are equipped with solar PV systems of a size similar to the power they demand. The power consumption demanded by the consumers for each hour is based on time-series containing 8760 hourly values for a year of generic consumption, according to yearly consumption provided in [48]. In a similar way, the solar PV generation is based on synthesized hourly irradiance, taking both clear sky and covered sky into consideration. All loads are assumed as being with a constant power factor at 0.95 inductive.

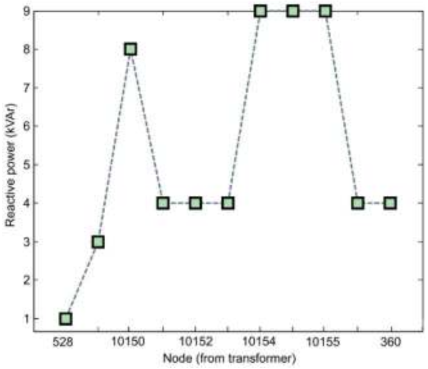
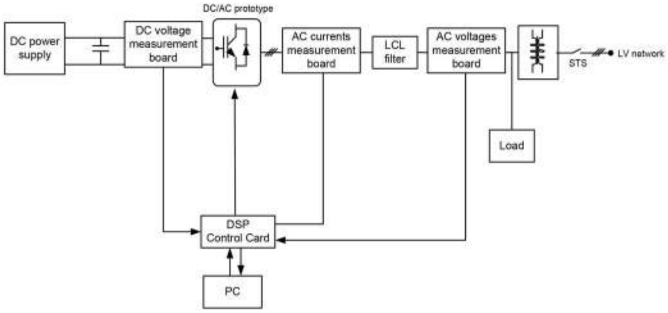


Fig. 10. Reactive power references for PV inverters at 50% rate active power.

(a). 30 kW prototype converter used to test the PVs local control.



(b). Laboratory setup details

Fig. 11. Experimental system configuration.

According to the *QV* strategy proposed by the authors, the reactive power references for each inverter are estimated not only by considering explicitly the cable resistance, but also the influence of both active and reactive power values of the rest of nodes. The estimation of the reactive power to be injected by each individual inverter thus depends on the influence of the rest of nodes, which implies a centralized solution providing innovative characteristics in terms of voltage control for LV networks. As previously discussed, most contributions are currently based on applying on each node a *QV* relation directly related with values of each node, neglecting the rest of the nodes. To point out the differences in terms of voltage values on each node and reactive power set-points, Fig. 7 compares the results when the influence of the rest of the nodes are considered and neglected, both under steady-state conditions and assuming that PV installations are supplied their rate active power. The proposed solution allows maintaining significantly fewer node voltage drops, and the power flow algorithm

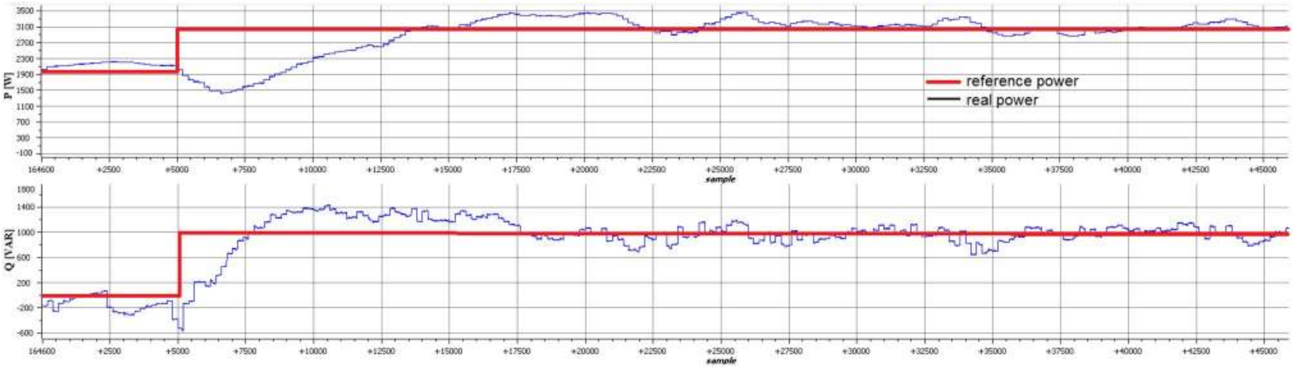
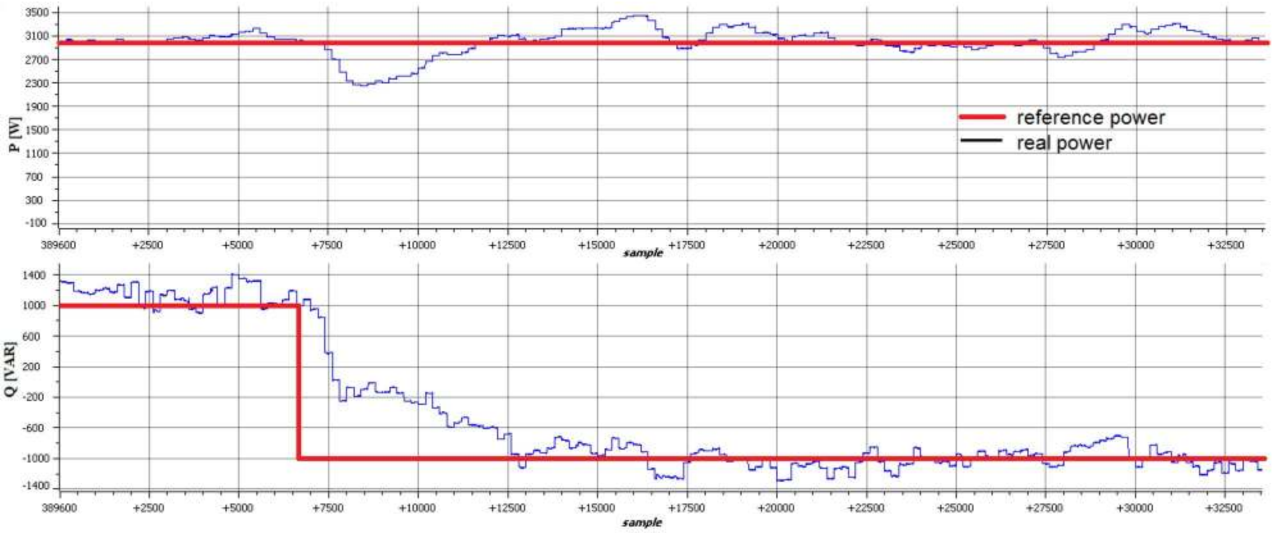
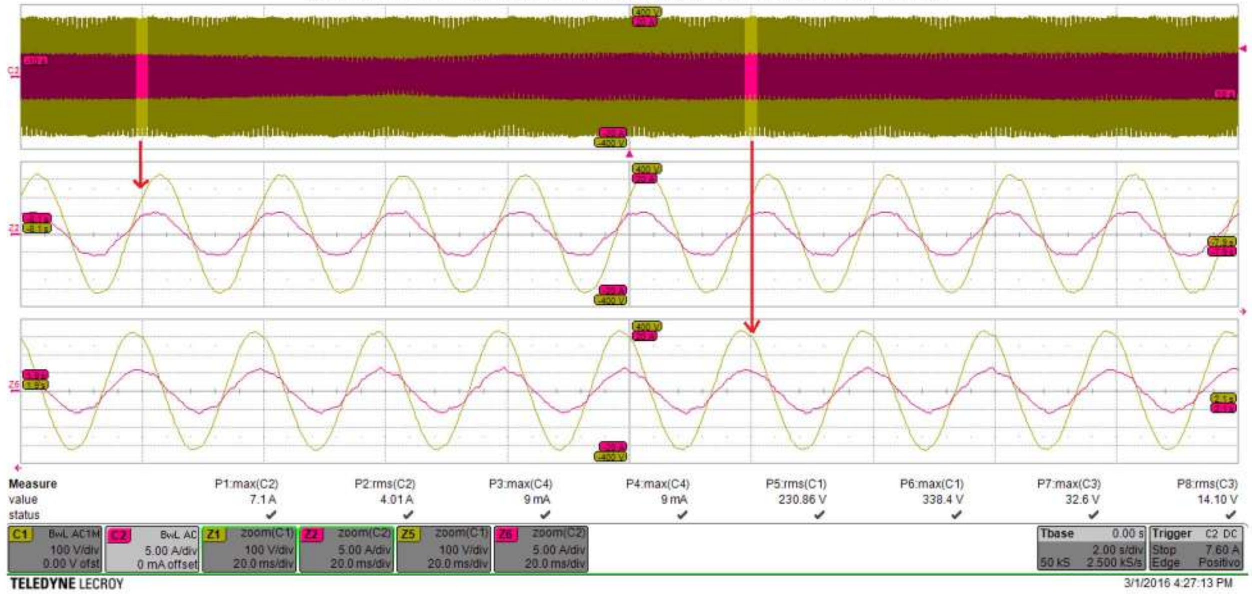


Fig. 12. Experimental results for the converter control algorithm. Active and reactive power evolution (references and collected values).



(a). Active and reactive power evolution (references and collected values).



Measure	P1:max(C2)	P2:rms(C2)	P3:max(C4)	P4:max(C4)	P5:rms(C1)	P6:max(C1)	P7:max(C3)	P8:rms(C3)
value	7.1 A	4.01 A	9 mA	9 mA	230.86 V	338.4 V	32.6 V	14.10 V
status	✓	✓	✓	✓	✓	✓	✓	✓

(b) Transient and steady state waveforms of the capacitor voltage (C1) and of the injected current (C2). Collected values

Fig. 13. Experimental results for the inverter control algorithm.

avoids convergence problems giving negligible computational time costs. Fig. 8 shows the results for power losses and the fast convergence of the methodology.

With regard to the solar irradiance variation during the day and the direct influence on the active power supplied by the PV installations, Fig. 9 compares the voltage profile values

TABLE I
POWER STAGE AND LOCAL CONTROL PARAMETERS

Power stage parameters			
Grid voltage	230 V	L_1	4 mH
Grid frequency	50 Hz	C	3 μF
V_{DC}	700 V	L_2	1 mH
Transformer inductance		3mH	
Active and reactive power controllers parameters in grid-connected operation mode			
m		$2\cdot10^{-7}$	
n		$1\cdot10^{-6}$	
T_{iQ}		2	
Voltage controllers parameters			
k_{p_v}	0.07	T_{i_v}	0.12
Current controllers parameters			
k_{p_c}	27	T_{i_c}	0.01

when PV installations supply 50% of their rate active power. Fig. 10 shows an example of the reactive power references according to the proposed methodology. In this case, power losses are reduced from 61.54 kW to 27.53 kW. Power losses are significantly different depending on both reactive power regulation ranges and active power demanded/supplied by the customers. Additional results are related to the local control of a 30 kW grid-connected PV converter. Experimental tests have been carried out in a laboratory setup based on a 30 kW back-to-back converter prototype, where just one of the two full-bridges has been considered, see Fig. 11(a). The converter involves three SEMiX202GB12E4s SEMIKRON IGBT modules, Skyper32ProRSEMIKRON IGBT drivers, a voltage measurement board and a control card. The developed control board is equipped with a Texas Instruments DSP TMS320F28335. This is a 32bit floating point DSP (up to 150MHz). The measurement and interface board consists of 8-analog channels collecting 3 AC-currents, 3-AC voltages, 1-DC voltage and temperature. Over-current and over-temperature protection are included. The DC link of the converter is supplied by a 30 kW DC-power source emulating the PV panel strings. The AC side of the converter is connected to the PCC by means of an *LCL* filter and an isolation transformer. On laboratory tests, the PV converter feeds a 1 kW resistive load. The tests have been carried out by means of a reduced active power respect to the converter rate power, due to the isolation transformer nominal power available in the laboratory (7.5 kVA). Control and physical parameters for the PV converter control system are defined in Table I. The laboratory setup configuration is shown in Fig. 11(b), being the control system discussed in Section III assessed experimentally. Fig. 12 depicts the active and the reactive power evolution provided by the converter when an active power reference step from 2 to 3 kW and a reactive power reference step from 0 to 1 kVAr (capacitive) are simultaneously set. These modifications can model solar radiation oscillations and a range of the uncertainty of the solar radiation. Fig. 13(a) shows the results when a constant active power reference is considered (3 kW) and a reactive power step from 1kVAr (capacitive) to -1 kVAr (inductive) is set. A current phase shift can be observed in Fig. 13(b), moving from capacitive to inductive reactive power. In both cases, high power quality performances are obtained, with 3.6% for the injected current Total Harmonic Distortion.

VI. CONCLUSION

A centralized/decentralized strategy to determine reactive power references for PV inverters connected to a LV radial network is discussed and evaluated in this paper. The proposed solution allows us to provide voltage regulations considering not only local power values on each node, but also the influence of active and reactive power data from all the nodes of the network. Both a high *R/X* ratio typical of LV feeders and constraints for reactive power references of the PV converters, in compliance with the most recent national standards, are considered by the proposed methodology.

An alternative power flow solution suitable for radial topologies is described and implemented, avoiding convergence problems and minimizing computational time costs. The proposed power flow is performed by the DSO and the results are communicated as power set-points to the local control of each PV converter. The paper is supported by exhaustive results both related to the centralized controller and to the PV local controller. The feasibility of the overall control strategy has been verified and it has been demonstrated that better LV voltage regulation is achieved in comparison with traditional approaches.

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