Small Inverter-Interfaced Distributed Energy Resources for Reactive Power Support

Alejandro D. Domínguez-García[†], Christoforos N. Hadjicostis[‡†], Philip T. Krein[†], and Stanton T. Cady[†]
[†]Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[‡]Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, Cyprus
E-mail: {aledan, krein, chadjic, scady2}@ILLINOIS.EDU

***Abstract*—The use of small inverter-interfaced distributed energy resources for reactive power support is discussed. While the primary function of these resources is to deliver active power, they can also be used to provide reactive power, often identified as an ancillary service by a utility. Given the large and increasing number of small grid-connected inverters, the total reactive power that can be collectively provided under proper control is substantial. The paper discusses inverter configurations for reactive power production, and presents distributed control strategies that enable these resources to provide reactive power support.**

I. Introduction

Electrical generators connected to ac power grids must deliver both active (real) power—the average energy flow—and reactive power. In a properly functioning electric power grid, reactive power must be delivered to meet energy storage requirements of inductances and capacitances in transmission lines, motors, and other devices. Reactive power impacts grid bus voltages, so its control is important for voltage stability and regulation [1]. Reactive power control is usually managed by the utility, and can be achieved by controlling generator excitation, with banks of capacitors, or with FACTS devices [1]. A challenge is that reactive power does not "flow" in the same sense as energy—reactive power production at central generating stations is necessary but not sufficient for proper system balance.

Many distributed energy resources can produce and control reactive power [2], [3]. Examples include inverters for photovoltaic (PV) systems, motor drives with active rectifier inputs, and wind turbine power converters. However, most devices today seek to operate at unity power factor, equivalent to zero reactive power flow. Power supplies with active power factor correction also seek to operate at unity power factor. This operating choice makes sense as small-scale generators are compensated for the energy they produce. At the smallest sizes, a few hundred watts or so, lack of reactive power has little impact. As these systems become widespread, the situation is a concern. Imagine a scenario where 30% of generation is from resources that do not produce reactive produce. Grid reactive power requirements remain, thus utilities will need to greatly expand reactive power generation.

The obvious solution is to ensure that distributed generation resources produce reactive power. There are, however, two major barriers. First, fee structures and interconnection requirements discourage reactive power production; the developer would have to take on additional costs without additional revenue. Second is the emphasis on unity power factor in small inverters. Examples involve "unfolding bridge" topologies in which an output bridge switching at line frequency is synchronized with voltage zero crossings and is not capable of delivering reactive power.

The need for reactive power makes it likely that, in the long run, distributed generators will be required to produce it. Forward-looking developers may anticipate such a requirement and design accordingly, but they could put themselves at a short-term disadvantage if there are extra costs involved. Additional challenges relate to control. Even if a distributed generation resource can deliver reactive power, how should it be controlled? Should the utility company provide this function? Should control be based on local voltage regulation? In summary, two major technical challenges need to be addressed: i) development of appropriate controls for individual power converters so they can provide reactive power, and ii) development of system-level control strategies to coordinate these dispersed resources for the grid. This paper discusses inverter configurations for reactive power generation and proposes system-level control strategies that enable the utilization of these resures for reactive power support. A testbed has been developed to experimentally verify the feasibility of the control strategies.

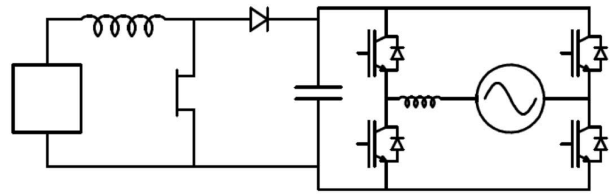
The remainder of this paper is organized as follows. Section II discusses inverter-level control issues for enabling existing topologies to provide reactive power, and shows the capability of commercial inverters to provide reactive power. Section III presents an overview of the proposed system-level control architecture for providing voltage control through reactive power support provided by inverter-interfaced distributed energy resources (DERs) . Section V illustrates the implementation of the system-level control strategies in an experimental setup. Concluding remarks are discussed in Section VI.

II. INVERTER-LEVEL CONTROL

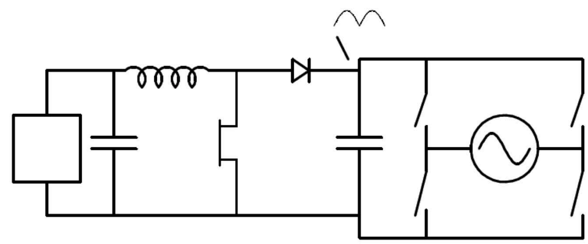
A typical dc link inverter for PV generation is shown in Fig. 1(a). Generally, there are two ways to operate the inverter in an ac grid-connected application. The first is to interface the inverter to the grid with a substantial inductor and control the inverter voltage. It is well known in power systems that the voltage phase shift across the inductor has a primary role in setting the real power flow, while the voltage magnitude difference influences reactive power flow. A practical system synchronizes the voltage reference signal to the grid, then sets the magnitude and phase of the inverter output voltage to deliver a desired real power P and reactive power Q. In three-phase inverters of this type, $d-q$ control methods are often employed to adjust P and Q [4]. The second approach is to control the inverter current, and interface to the grid through a suitable filter that will reduce switching frequency ripple. Here, current magnitude influences real power, while current phase has primary influence on reactive power. The current control method can be represented as a "reverse power factor correction" technique [5], and nonzero phase shifts will produce reactive power. In practice, voltage control methods tend to be associated with relatively large inverters—10 kW or more—as the currents involved can be high enough to distort local grid voltage. Current control methods are well-matched to small units, such as microinverters, in which the grid current is low and the local grid voltage may be used as the basis for the current command waveform. This paper treats the inverter as current-controlled, following from [5]. Any conventional control approach, such as pulse width modulation (PWM) based on a reference current waveform or current hysteresis control, should be able to deliver a desired current magnitude and phase. A particularly useful approach is based on admittance control, in which the current is commanded to be an admittance function, $G(s)$, times the measured grid voltage, $V(s)$. The function $G(s)$ can have an assigned magnitude and phase to control P and Q.

Fig. 1(b) shows an inverter with an unfolding bridge and variable dc link [6]. This design seeks to reduce power losses. As the output bridge switches at line frequency, and since the output switches at current and voltage zero crossings, switching losses are nearly zero and conduction losses dominate in the output. At unity power factor, an unfolding bridge is useful and straightforward to design. With current and voltage tracking each other, each switch sees only one operating quadrant. In [7], SCRs are used in the unfolding bridge. In [6], MOSFETs are employed.

Now consider a situation in Fig. 1(b) in which a current phase shift is desired to produce nonzero reactive power flow. This requires four-quadrant switches, as generally



(a) Basic dc link inverter with input boost converter.



(b) Inverter with variable link to support output unfolding bridge.

Fig. 1. Inverter topologies with reactive power capabilities.

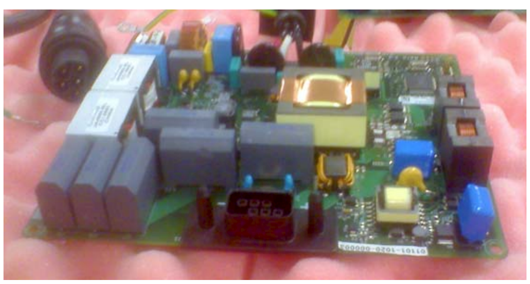
any given current and voltage polarity can be encountered. Since four-quadrant devices are implemented with multiple series semiconductors, conduction losses will double, negating the advantage of low switching loss. In practice, this means that unfolding bridge structures as in [6], [7] do not offer advantages when reactive power is to be produced. The dc link arrangement in Fig. 1(a) does not have this disadvantage. One reported alternative for an unfolding bridge structure has been to provide an alternative power path that manages reactive power [8]. Disadvantages are the extra complexity and effort for an independent converter dedicated to reactive power control. Control of conventional inverters for reactive power flow provides a more direct solution.

A. Inverter Advantages

Given a dc link inverter with current-based real and reactive power capability, a crucial advantage from the power system perspective is speed and flexibility of reactive power control. Reactive power can be varied on the same time scale as the line frequency. The amount of reactive power is also substantial, based on the inverter volt-amp rating. For unity power factor, the full rating can be used for real power. At zero power factor, the rating can be used entirely for reactive power. This flexibility is comparable to a conventional large synchronous machine, but faster. In a PV application, the power varies over time, peaking at local solar noon. At all other times of the day, the inverter has extra capacity. Even at noon, there is nearly always extra volt-amp capacity. At night, when real power is zero, a PV inverter can be used entirely to produce reactive power. In some systems, light nighttime loads can reduce reactive power requirements, causing overvoltage problems. Hence, PV inverters can potentially supply or consume reactive power.

The dichotomy between magnitude and phase settings means that reactive and real power can be controlled independently, subject only to the volt-amp rating of the inverter. An inverter rated at 2 A and 240 V ac 60 Hz single phase, for example, can deliver 480 W and 0 VAR at zero phase shift. It can deliver 384 W and 288 VAR at 80% leading power factor, or 456 W and 150 VAR at 95% leading power factor. Clearly, substantial reactive power delivery can be achieved with only a small percentage of real power derating. In this example inverter, a power rating of 400 W would provide enough headroom to produce or sink reactive power between 0 and 265 VAR, as determined by the choice of phase shift. Given the wide range and fast dynamic control, small inverters in distributed generation offer important opportunities for reactive power supply.

Fig. 2(a) shows a commercial inverter with reactive power capability. Its internal control commands can respond to phase-angle requests from an external system-level controller. Figure 2(b) shows an experimental grid voltage and phase-shifted current delivered by the inverter from Fig. 2(a). Its current control has been commanded to produce the phase shift. Notice that the current is smooth (other than ripple), with no abrupt transitions as the operating quadrants change.



(a) Inverter layout.

(b) Grid voltage and injected current for inverter delivering active and reactive power.

Fig. 2. Commercial inverter with reactive power capability. (Images courtesy of SolarBridge Technologies, Inc.).

III. System-Level Control Architecture

One solution to the system-level control problem can be achieved through a centralized controller located, for example, at a substation. The controller issues a command to each distributed resource so that collectively they provide a requested reactive power. To accomplish this, it is necessary to overlay a communication network. Such a centralized control strategy was adopted in [9] for PV systems mounted on utility poles.

A second approach, which should be more economical and does not require complete knowledge of DERs, relies on a decentralized control strategy. Here, each power converter exchanges information with its neighbors and makes a local control decision. Collectively, local control decisions should have the same effect as the centralized control strategy. Such a solution could rely on inexpensive communication protocols, e.g., ZigBee [10]. In this work, decentralized strategies for inverter reactive power production are proposed.

A. Decentralized Control Architecture

The control architecture of Fig. 3 illustrates how DERs can be used to control voltage. In this example, the voltage at bus s is to be maintained at a reference value through reactive power control. The total reactive power demand at bus s is $Q_s - Q_s^d$, where Q_s is provided from the grid and Q_s^d is provided by DERs connected there.

In order to adjust Q_s^d so the reference voltage V_s^{ref} is maintained, a *coordination controller* will take the difference between V_s, the actual voltage at node s, and the reference voltage V_s^{ref} and will issue a command demanding an amount of reactive power denoted by ρ_d. This command is relayed to a communication node called *leader* and labeled as 0. The leader subsequently relays evenly split demands for reactive power to DERs located in *neighboring* nodes (i.e., nodes that the leader can communicate to and which in Fig. 3 are denoted by q_1 and q_2) so that the total amount ρ_d remains constant. Thus, in Fig. 3, node q_1 gets $\rho_d/2$ and node q_2 gets $\rho_d/2$. More generally, each neighboring node of the leader will receive ρ_d/l, where l is the number of nodes neighboring the leader.

After the nodes neighboring the leader receive the command ρ_d/l, an iterative exchange of information begins: each node in the network exchanges information with its neighboring nodes, captured in Fig. 3 by the arrows connecting nodes with DERs. The objective of this information exchange is to distribute the required amount ρ_d of reactive power among all the nodes such that after several rounds of exchanges, each node j keeps a fraction of ρ_d, which we denote by q_j, such that the sum of all q_j's amounts to the total ρ_d, and thus, collectively the nodes provide the total amount of reactive power Q_s^d demanded by the leader, i.e., $Q_s^d = \rho_d = \sum_j q_j$.

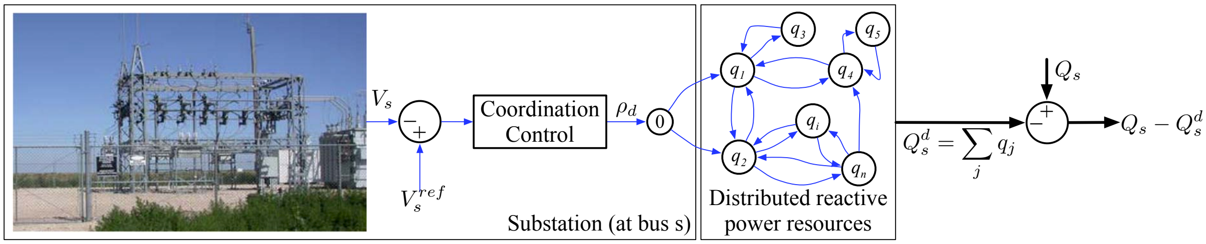


Fig. 3. Overall control architecture. Photo credit: DOE/NREL.

IV. Decentralized Control of DERs

The objective is to design a distributed iterative algorithm that, at step k, updates the reactive power demand from node j based on: i) its current reactive power demand $q_j[k]$, and ii) the current reactive power demanded from neighbors of j (nodes that can transmit information to j), such that after m steps the collective reactive power generated by the DERs equals the reactive power demanded by the leader: $\sum_{j=1}^{n} q_j[m] = \rho_d$. To address the problem, we adopt distributed algorithms proposed in [11].

A. Distributed Coordination Algorithm

The exchange of information between nodes where reactive power resources are located can be described by a directed graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, where $\mathcal{V} = \{1, 2, \ldots, n\}$ is the vertex set (each vertex corresponds to a node), and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the set of directed edges, where $(j, i) \in \mathcal{E}$ if node j can receive information from node i. All nodes that can transmit information to node j are said to be neighbors of node j and are represented by the set $\mathcal{N}_j = \{i \in \mathcal{V} : (j, i) \in \mathcal{E}\}$.

We assume there is a leading node that knows the total amount of reactive power ρ_d that needs to be collectively provided by the remaining n nodes. This leader can communicate with $l \geq 1$ nodes, and initially sends a command demanding ρ_d/l units of reactive power from each of them. Unless ρ_d changes, the leader will not subsequently communicate with the nodes.

Let $q_j[k]$ be the reactive power demanded from node j at step k. Define the collective reactive power demand as $\rho[k] = \sum_{j=1}^{n} q_j[k]$, and let ρ_d be the collective reactive power demanded from the leader. As shown in [11], the simplest solution is for each node i to equally split its current value among itself and the nodes that have i as neighbor, i.e., the nodes that i can transmit information to [12]. Thus, the update for node j depends on the values that it receives from each neighbor as follows:

$$q_j[k+1] = \frac{1}{1 + \mathcal{D}_j^+} q_j[k] + \sum_{i \in \mathcal{N}_j} \frac{1}{1 + \mathcal{D}_i^+} q_i[k] \quad (1)$$

where $\mathcal{D}_j^+$ ($\mathcal{D}_i^+$) the number of nodes that j (i) can transmit information to. Note that iteration (1) does not necessarily split the total reactive power demand ρ_d evenly among all the nodes, but it ensures that $\sum_{j=1}^{N} q_j[k] = \rho_d, \ \forall k \geq 0$. Furthermore, provided the directed graph describing the exchanges between nodes has a single recurrent class, which necessarily makes it aperiodic by construction (due to the fact that $\frac{1}{1+\mathcal{D}_j^+} \neq 0$), the steady state solution provided by (1) is unique. For a convergence proof, the reader is referred to [11].

1) Convergence speed: This is important as it will determine how fast the feedback control in Fig. 3 can react and compensate for changes in the voltage V_s. Define the corresponding reactive power demand vector as $q[k] = [q_1[k], \ q_2[k], \ldots, qi_j[k], \ldots, q_n[k]]'$. Then, convergence speed can be easily analyzed by rewriting (1) in matrix form as follows:

$$\begin{aligned} q[k+1] &= P_c q[k], \\ q[0] &= \pi_0, \end{aligned} \quad (2)$$

where $q_0 = [q_1[0], \ q_2[0], \ldots, q_j[0], \ldots, q_n[0]]'$ with $q_i[0] = \rho_d/l$ if i is a neighbor of the leader node and $q_i[0] = 0$ otherwise. By construction, matrix P_c is *column stochastic*, i.e., the sum of the entries of each column adds up to one, and also primitive [13]. In fact, the transition system in (2) is mathematically equivalent to a Markov chain, and it is well-known (see, e.g., [14]), that the convergence speed in a Markov chain is governed by the second largest eigenvalue λ_2 of P_c, i.e., the smaller the λ_2, the faster (2) converges to steady-state. Thus, the convergence speed of (1) is determine by $\mathcal{D}_j^+, \ \forall j$. However the choice of weights multiplying the $q_j[k]'s$ in (1) is not constrained to have the form described there (the only hard constraint is that weights associated with values of non-neighboring nodes are set to zero). Thus, in practice, if there is global knowledge of the graph describing the exchange of information between nodes, it is possible to choose the weights in (1) so as to achieve the fastest convergence speed [15].

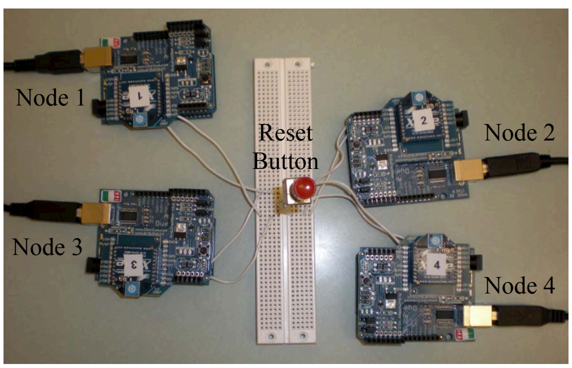
2) Constraints on node capacity: The algorithm in (1) does not take into account the case when the amount of reactive power that each node must provide is constrained. As shown in [11], the algorithm in (1) can be easily tailored to address the more realistic case when there are constraints on the maximum amount of reactive power that each DER can provide.

V. Experimental Setup

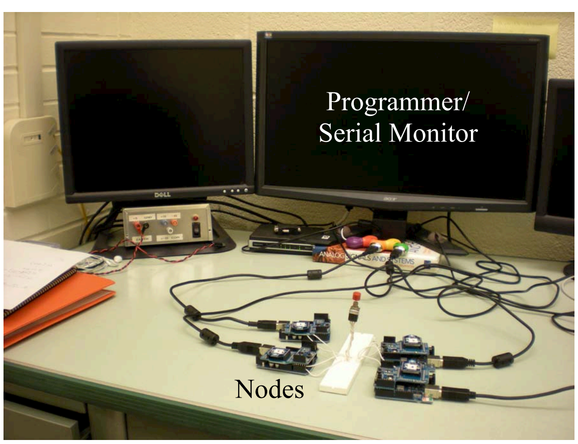
In order to verify the feasibility of the proposed coordination algorithm to control a network of power-electronics interfaced DERs, we implement the 4-node network illustrated in Fig. 5(a) using commercial hardware. The implementation details and experimental results are discussed next.

A. Implementation Details

The hardware implementation is illustrated in Fig. 4(a) and Fig. 4(b). Each node consists of an Arduino Duemilanove prototype board with AVR ATmega328P 8-bit microcontroller, an Xbee shield and a MaxStream XB24-DMCIT-250 revB Xbee module. Software was written and uploaded to the nodes using the Arduino environment. To ensure the nodes were synchronized, a single momentary push button switch was connected to the (active low) reset pin of all of the nodes. Power was supplied to the nodes over USB via a 4-port hub thus enabling all of the microcontrollers to share a ground reference. The output of each node was observed using the serial monitor built into the Arduino environment.



(a) Communication/processing nodes.



(b) Programmer/serial monitor.

Fig. 4. Experimental setup hardware implementation.

The communication protocol used to achieve coordination among nodes is based on a simple broadcast algorithm in which each iteration is performed in a 1.5-s time interval. At every iteration, each node must perform 3 functions: i) receive the weighted reactive power commands from all neighboring nodes, ii) broadcast its weighted reactive power command, and iii) compute its next reactive power command.

To avoid collisions, every node generates a random number during initialization that is used as a broadcast time. Thus, within each iteration, each node is always in listening mode awaiting for values broadcasted by its neighbors except for the time when it is broadcasting its own value.

To make the algorithm more robust against possible synchronization problems, the nodes are only allowed to broadcast during the interval [0.5 s, 1 s] during each 1.5-second time interval. The 1.5-second time interval chosen is not due to hardware constraints, and it would be possible to make it smaller. The choice of time interval is constrained by the time it takes for each node to receive values from other nodes, send out its own value, and update its value.

Each node was programmed to ignore messages received from some of its neighbors to create a partially connected network while all weights were specified beforehand. In a more realistic setup, the exchange of information between nodes will be determined by the distance between the DERs and the strength of their transmitter/receiver.

B. Experimental Results

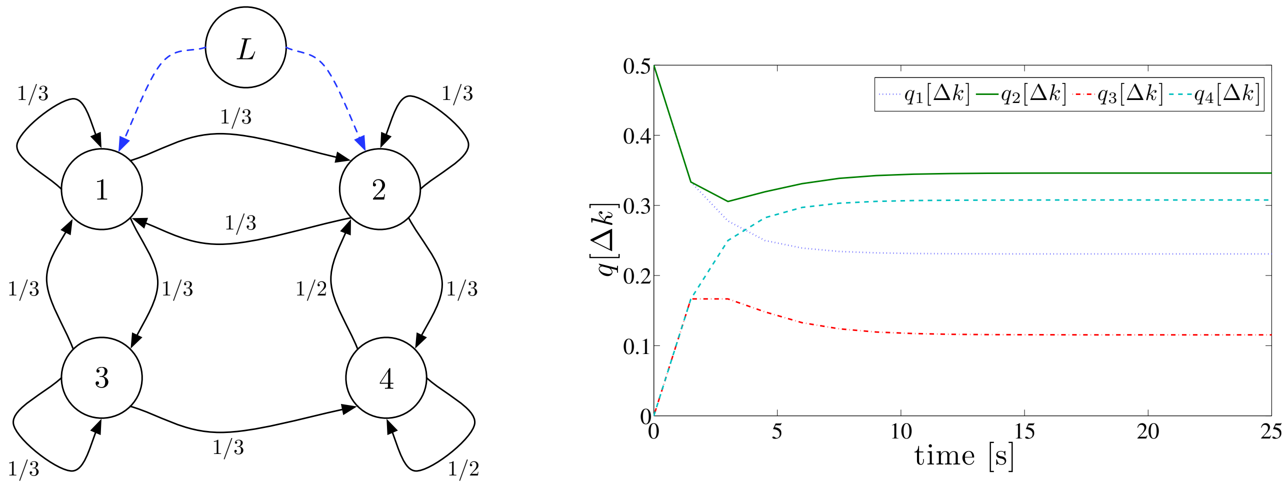
The exchange of information between the nodes in Fig. 4(a) is described by the weighted graph in Fig. 5(a). Following the matrix notation in (2), the nodes will update their values every $\Delta = 1.5s$ according to

$$q[k+1] = P_c q[k], \forall k = 0, 1, ..., n, \tag{3}$$

where the vector of initial reactive power demands is $q[0] = [0.5,\ 0.5,\ 0,\ 0]'$, and where the transition matrix is

$$P_c = \begin{bmatrix} 1/3 & 1/3 & 1/3 & 0 \\ 1/3 & 1/3 & 0 & 1/2 \\ 1/3 & 0 & 1/3 & 0 \\ 0 & 1/3 & 1/3 & 1/2 \end{bmatrix}.$$

The time evolution for each node is shown in Fig. 5(b) where it can be seen that the nodes converge to their steady state values, $q^{ss} = [0.231,\ 0.345,\ 0.117,\ 0.307]'$, in approximately 12 seconds, or 8 iterations. This is an example where the nodes do not equally split the total requested amount among themselves due to the directed edge between nodes 3 and 4.



(a) Graph.

(b) Time Evolution of π.

Fig. 5. Graph describing the exchange of information in the hardware setup and algorithm evolution.

VI. Concluding Remarks

Distributed control of properly designed small-scale inverters and other power converters can support system-level reactive power management. The new functionality has vital implications for the growth of alternative and renewable energy resources. This paper introduces a distributed control configuration and strategy that can make microinverters designed with reactive-power capabilities serve as system-level reactive power resources. Small-scale power electronics designed to be reactive-power capable is vital to long-term aspects of grid operation. Extensions of the concepts can be employed to control real power, or direct ancillary services, such as voltage, demand, or frequency regulation.

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