Joint Optimization of Control Performance and Network Resource Utilization in Homogeneous Power Networks

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***Abstract*—A framework that jointly optimizes the control and communication networks of network-controlled interactive power electronics networks is described in this paper. The joint optimization framework includes two coupled blocks, one whose focus is to ensure optimal performance of the power network within its stability bounds and the other whose thrust is on optimizing the information flow in a communication network. These two networks have contrasting requirements because, on the one hand, time delays are detrimental to the stability and performance of the control system, while on the other hand, allowing higher time delays leads to efficient utilization of the communication network's resources. The proposed framework leads to an optimal compromise between these two noncooperative networks. Three different implementation approaches for the integrated control–communication framework are investigated, namely, centralized, distributed, and clustered. A case illustration of a homogeneous power network is provided to demonstrate the efficacy of the joint control–communication framework and compare the performance of the three implementation approaches.**

***Index Terms*—Interactive power electronic networks (IPNs), joint optimization, Lyapunov stability, network control systems, network resource utilization.**

I. Introduction

NEXT-GENERATION power systems applications, such as distributed generation, active power filters, and flexible ac transmission systems for grid power-flow control, all-electric ships, and aircraft are expected to rely heavily on interactive power electronic networks (IPNs) [1]–[4]. In addition, because of their high reliability, reduced harmonic distortion, and better dynamic performance, IPNs are also used for applications, such as uninterruptible power supplies [5] and dc distributed power systems for telecommunication applications [6], among others.

Because of intermodule interactions, the control design of IPNs is more involved than that for stand-alone converters. An approach for controlling interconnected networks, such as IPNs, is based on model-predictive control, where the control inputs over a given time horizon are determined based on the overall model of the system [7], [8]. The application of such a control scheme to interconnected power converters, while guaranteeing the IPN's global stability, has been demonstrated [9]. Distributed implementations of model predictive control, which achieve a compromise between redundancy and control performance, rely on the coordination of the local controllers using intermodule information exchange [10]–[13]. A fundamental feature of these architectures is the need for a communication infrastructure for information exchange among the modules in case of distributed implementation and between the master and the slave modules for centralized implementation. The communication network introduces time delays. However, in the aforementioned references, impacts of time delays on the stability and performance of the system have been ignored.

Although impacts of time delay on the stability and performance of networked control systems have been well researched in the control and systems community [14]–[16], one key observation from recent research works [17]–[22] is that the control and the communication networks do not always operate cooperatively if the communication protocol does not yield channel interference. For instance, in [18] and [22], the authors demonstrated that, to increase the stability margin of the power networks and attain high control performance, fast information exchange is desired. However, from the point of view of the communication network, progressively higher data rates cannot be sustained due to network resource limitations [23]. This problem is further aggravated as the number of nodes of the overall network increases because a progressively higher volume of information flow typically cannot be sustained at the same data rate without enhancing the probabilities of failed (end-to-end) transmissions.

To address this issue, a joint control–communication optimization strategy is desired, which ensures an optimal compromise between the performance of the control system and the resource utilization of the wireless communication network under constraints of the power network stability and communication network capacity bounds. In this paper, such a joint control–communication optimization strategy for interconnected power networks is outlined in Section II, as shown in Fig. 1. In Section III, a case illustration of a homogeneous inverter network is used to evaluate the efficacy of the optimization strategy.

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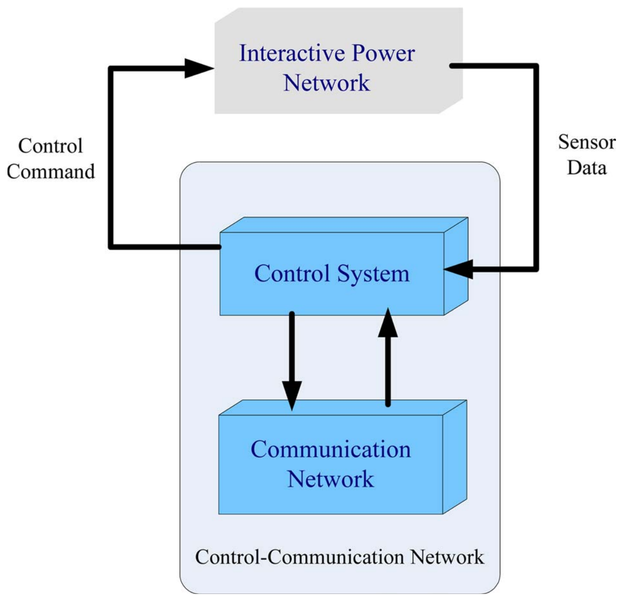

Fig. 1. Block diagram of the overall control–communication framework.

II. Joint Control–Communication Framework

In this section, the joint control–communication optimization framework is described. The goal of the optimization problem is to determine the set of feasible switching sequences [16] and the time spent in each switching state of the sequence [9] for all the modules (n), and the transmitter power levels $(\mathbf{P}_k)$ and the transmission rates $(r^{(l_{nj})})$ for all the communication links. The models of the power network and the maximum values that each state can attain $(\mathbf{x}_{\max}^{(n)})$ constitute the constraints of the control network.

The communication network is modeled as a directed graph $G(N, L)$ where N is the set of modules and L is the set of communication links. Each link $l_{nj} \in L$ between a transmitting module j and a receiving module n has an associated transmission capacity $c_{l_{nj}}$, actual transmission rate $r^{(l_{nj})}$, and delay $\tau^{(l_{nj})}$. The link delay is obtained using the M/M/1 queuing model [24] and is given by $\tau^{(l_{nj})} \geq \mu_{l_{nj}}(c_{l_{nj}}(\mathbf{P}) - r^{(l_{nj})})^{-1}$.

For the control system, a positive-definite quadratic cost function is chosen, while for the communication network, utility functions for the rate and delay (to account for the communication resource allocation) constitute the cost function. Constraints for the optimization problem include the system model, maximum values that each state can attain, and the time-delay bound to ensure stable operation. Overall, the integrated control–communication optimization problem can be expressed as follows:

$$\text{minimize } J = \left\{ \sum_{n\in N} \left(\left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right)' Z^{(n)} \left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right) \right) + \sum_{l_{nj}\in L} WU_\tau\left(\tau_k^{(l_{nj})}\right) - \sum_{l_{nj}\in L} U_r\left(r_k^{(l_{nj})}\right) \right\}$$

$$\text{s.t.} \quad \mathbf{x}_{k+1}^{(n)} = f_n\left(\mathbf{A}_{0i}^{(n)}, \mathbf{A}_{1i}^{(n)}, \mathbf{B}_i^{(n)}, \mathbf{x}_k^{(n)}, \mathbf{x}_k^{(j)}\left(-\tau_k^{(l_{nj})}\right)\right) \tag{1a}$$

$$j \neq n \quad j \in N \qquad \forall n \tag{1b}$$

$$\mathbf{x}_{k+1}^{(n)} - \mathbf{x}_{\max}^{(n)} \leq 0 \qquad \forall n \tag{1c}$$

$$\tau_k^{(l_{nj})} \leq D_{\max} \qquad \forall l_{nj} \tag{1d}$$

$$\left(c_{l_{nj}}(\mathbf{P}_k) - r_k^{(l_{nj})}\right)\tau_k^{(l_{nj})} \geq \mu_{l_{nj}} \qquad \forall l_{nj} \tag{1e}$$

$$\mathbf{x}_{k+1}^{(n)} \geq 0 \qquad \forall n$$

$$R_{\min}(l_{nj}) \leq r_k^{(l_{nj})} \quad \mathbf{1}P_{\max} \succeq \mathbf{P}_k \succeq \mathbf{0} \qquad \forall l_{nj} \tag{1f}$$

where $\mathbf{x}_k^{(n)}$ represents the states of the nth module, $\mathbf{x}_k^{(j)}(-\tau_k^{(l_{nj})})$ represents the delayed states of the other modules, i represents its switching states, $\mathbf{x}_{\text{ref}}^{(n)}$ are the references, $Z\ (> \mathbf{0})$ is a positive-definite diagonal weighting matrix, $\mathbf{A}_{0i}^{(n)}$, $\mathbf{A}_{1i}^{(n)}$, and $\mathbf{B}_i^{(n)}$ are switching-state-dependent matrices of appropriate dimensions and are described in [16] and [18], and f_n is a map of the states of the nth module at time instant $(k+1)$, given the states of the module at time instant (k) and the delayed states of the other modules. Also, $\mathbf{1}$ is the vector with all its entries equal to unity, and $D_{\max}$ is the time-delay bound. In (1f), $\succeq$ represents componentwise inequality.

Next, dual variables φ_n, ψ_n, $\forall n$, and $\lambda_{l_{nj}}$, $\pi_{l_{nj}}$, $\forall l_{nj}$, for the constraint sets (1b), (1c) and (1d), (1e), respectively, are introduced. Using the dual representation, the Lagrangian for the optimization problem in (1) is given in (2), as shown at the bottom of the page. After rearranging the terms in (2), the problem can be rewritten as (3), shown at the bottom of the next page. The elements of (3) constitute the distributed control and communication subproblems.

$$\begin{aligned} &L(\mathbf{x}, \mathbf{u}, \mathbf{d}, \mathbf{r}, \mathbf{P}, \boldsymbol{\psi}, \boldsymbol{\varphi}, \boldsymbol{\pi}) \\ &= \Bigg\{ \Bigg(\sum_{n\in N} \left(\left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right)' Z^{(n)} \left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right) \right) + \sum_{n\in N} \varphi_n \left\{ f_n\left(\mathbf{A}_{0i}^{(n)}, \mathbf{A}_{1i}^{(n)}, \mathbf{B}_i^{(n)}, \mathbf{x}_k^{(n)}, \mathbf{x}_k^{(j)}\left(-\tau_k^{(l_{nj})}\right)\right) - \mathbf{x}_{k+1}^{(n)} \right\} \\ &\quad + \sum_{n\in N} \psi_n \left(\mathbf{x}_{k+1}^{(n)} - \mathbf{x}_{\max}^{(n)} \right) + \sum_{l_{nj}\in L} WU_\tau\left(\tau_k^{(l_{nj})}\right) - \sum_{l_{nj}\in L} U_r\left(r_k^{(l_{nj})}\right) + \sum_{l_{nj}\in L} \lambda_{l_{nj}} \left(r_k^{(l_{nj})} - c_{l_{nj}}(\mathbf{P}_k) + \mu_{l_{nj}} \Big/ \tau_k^{(l_{nj})} \right) \\ &\quad + \sum_{l_{nj}\in L} \pi_{l_{nj}} \left(\tau_k^{(l_{nj})} - D_{\max} \right) \Bigg) \Bigg| R_{\min}(l_{nj}) \leq r_k^{(l_{nj})}, \mathbf{x}_{k+1}^{(n)} \geq 0, \mathbf{1}P_{\max} \succeq \mathbf{P}_k \succeq \mathbf{0} \Bigg\} \end{aligned} \tag{2}$$

A. Distributed Control Subproblem

The goal of the control subproblem is to determine the set of feasible switching sequences [16] and the time spent in each switching state of the sequence [9] for all the modules, which minimizes the control cost function

$$J_{\text{control}} = \sum_{n \in N} \left(\left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right)' \mathrm{Z}^{(n)} \left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right) \right).$$

From (3), the following distributed control subproblem can be obtained:

$$\begin{aligned} &\text{minimize} \\ &\sum_{n \in N} \Bigg(\left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right)' \mathrm{Z}^{(n)} \left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right) \\ &\qquad + (\psi_n - \varphi_n)\mathbf{x}_{k+1}^{(n)} - \psi_n \mathbf{x}_{\max}^{(n)} \\ &\qquad + \varphi_{n_i} f_n \left(\mathbf{A}_{0i}^{(n)}, \mathbf{A}_{1i}^{(n)}, \mathbf{B}_i^{(n)}, \mathbf{x}_k^{(n)}, \mathbf{x}_k^{(j)} \left(-\tau_k^{(l_{nj})} \right) \right) \Bigg) \\ &\text{s.t.} \qquad \mathbf{x}_{k+1}^{(n)} \geq 0 \qquad \forall n. \end{aligned} \tag{4}$$

For the distributed implementation of (4), each module requires information from other modules of the network because of the presence of the coupling terms in the control problem of each module. Contributions of the states $\mathbf{x}_k^{(n)}(-\tau_k^{(l_{nj})})$ from the other modules are assumed to be a lumped disturbance, which is updated using the information exchange through the communication network. Each of the distributed subproblems in (5) can be solved using quadratic programming.

B. Distributed Communication Subproblem

The communication subproblem has three components: rate, power, and delay optimization problems. Each of these problems is solved independently as discussed in the following.

1) Rate Allocation Problem:

$$\begin{aligned} &\text{minimize} \qquad \sum_{l_{nj} \in L} \left(\lambda_{l_{nj}} r_k^{(l_{nj})} - U_r \left(r_k^{(l_{nj})} \right) \right) \\ &\text{s.t.} \qquad R_{\min}(l_{nj}) \leq r_k^{(l_{nj})} \qquad \forall l_{nj}. \end{aligned} \tag{5}$$

The aforementioned problem is separable and can be solved in closed form using Karush–Kuhn–Tucker conditions [25]. The solution for the objective function

$$U_r \left(r_k^{(l_{nj})} \right) = \log \left(r_k^{(l_{nj})} \right) \qquad \forall r_k^{(l_{nj})}$$

is given by

$$r_k^{(l_{nj})*} = \begin{cases} R_{\min}(l_{nj}), & \text{if } R_{\min}(l_{nj}) \geq \frac{1}{\lambda_{l_{nj}}} \\ \left(\lambda_{l_{nj}} \right)^{-1}, & \text{otherwise.} \end{cases} \tag{6}$$

The choice of the optimal rate reduces to the selection of the minimum rate required or the inverse of the link prices (in the form of dual variables), depending on whichever is larger.

2) Power Allocation Problem: The power allocation problem for each link is a coupled and nonconvex geometric program and is expressed as

$$\begin{aligned} &\text{minimize} \qquad -\sum_{l_{nj} \in L} \lambda_{l_{nj}} \left(c_{l_{nj}}(\mathbf{P}_k) \right) \\ &\text{s.t.} \qquad \mathbf{1} P_{\max} \succeq \mathbf{P}_k \succeq \mathbf{0}. \end{aligned} \tag{7}$$

By using the "log" transformation and change of variables, the problem is converted into a convex program [26]. The iterative link power update is given by (8), as shown at the bottom of the page, where β_P is the step size and $\gamma_{l_{nj}}$ is the channel gain from the transmitter of node j to the receiver of node n.

$$\begin{aligned} &L(\mathbf{x}, \mathbf{u}, \mathbf{d}, \mathbf{r}, \mathbf{P}, \boldsymbol{\psi}, \boldsymbol{\varphi}, \boldsymbol{\pi}) \\ &= \sum_{n_i \in N} \Bigg\{ \Bigg(\left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right)' \mathrm{Z}^{(n)} \left(\mathbf{x}_{\text{ref}}^{(n)} - \mathbf{x}_{k+1}^{(n)} \right) \Bigg) + (\psi_n - \varphi_n)\mathbf{x}_{k+1}^{(n)} - \psi_n \mathbf{x}_{\max}^{(n)} + \varphi_{n_i} f_n \left(\mathbf{A}_{0i}^{(n)}, \mathbf{A}_{1i}^{(n)}, \mathbf{B}_i^{(n)}, \mathbf{x}_k^{(n)}, \mathbf{x}_k^{(j)} \left(-\tau_k^{(l_{nj})} \right) \right) \\ &\qquad \Big| \mathbf{x}_{k+1}^{(n)} \geq 0 \Bigg\} + \left\{ \sum_{l_{nj} \in L} \left(\lambda_{l_{nj}} r_k^{(l_{nj})} - U_r \left(r_k^{(l_{nj})} \right) \right) \Big| R_{\min}(l_{nj}) \leq r_k^{(l_{nj})} \right\} \\ &\quad + \left\{ \sum_{l_{nj} \in L} \left(W U_\tau \left(\tau_k^{(l_{nj})} \right) + \pi_{l_{nj}} \left(\tau_k^{(l_{nj})} - D_{\max} \right) + \lambda_{l_{nj}} \mu_{l_{nj}} \Big/ \tau_k^{(l_{nj})} \right) \right\} - \left\{ \sum_{l_{nj} \in L} \lambda_{l_{nj}} \left(c_{l_{nj}}(\mathbf{P}_k) \right) \Big| \mathbf{1} P_{\max} \succeq \mathbf{P}_k \succeq \mathbf{0} \right\} \end{aligned} \tag{3}$$

$$P_{k+1}(l_{nj}) = P_k(l_{nj}) - \beta_P \left(\frac{\lambda_{l_{nj}}}{P_k(l_{nj})} - \sum_{l_{km} \neq l_{nj}} \frac{\gamma_{l_{km} l_{nj}} \lambda_{l_{km}}}{\sum_{l_{pq} \neq l_{km}} \gamma_{l_{km} l_{pq}} \gamma_{jm} P_k(l_{pq}) + \sigma_{l_{km}}} \right) \tag{8}$$

3) Delay Minimization Problem: The delay minimization problem given by

$$\text{minimize} \sum_{l_{nj}\in L}\left(WU_\tau\left(\tau_k^{(l_{nj})}\right) + \pi_{l_{nj}}\left(\tau_k^{(l_{nj})} - D_{\max}\right) + \lambda_{l_{nj}}\frac{\mu_{l_{nj}}}{\tau_k^{(l_{nj})}}\right) \quad (9)$$

is decomposable into individual link delay problems. The problem in (9) is a convex program for $U_\tau(\tau_k^{(l_{nj})}) = (\tau_k^{(l_{nj})})^\kappa$, $\kappa > 1$. It should be mentioned here that the decomposability of the aforementioned problem is due to the availability of direct communication between the sender and the intended receiver. The more general case of a multihop network is not decomposable due to the presence of linear coupling constraints, and a gradient projection algorithm can be used.

C. Dual Problem

The dual problem associated with the primal optimization problem in (1) [27] is given by

$$\begin{aligned} &\text{maximize} && g(\boldsymbol{\psi},\boldsymbol{\varphi},\boldsymbol{\pi},\boldsymbol{\lambda})\\ &\text{s.t.} && \boldsymbol{\psi},\boldsymbol{\varphi},\boldsymbol{\pi},\boldsymbol{\lambda} \succeq 0 \end{aligned} \quad (10)$$

where $g(\boldsymbol{\psi},\boldsymbol{\varphi},\boldsymbol{\pi},\boldsymbol{\lambda}) = L(\mathbf{x}^*,\mathbf{u}^*,\mathbf{d}^*,\mathbf{r}^*,\mathbf{P}^*,\boldsymbol{\psi},\boldsymbol{\varphi},\boldsymbol{\pi},\boldsymbol{\lambda})$. The updates for the dual variables $\boldsymbol{\psi}$, $\boldsymbol{\varphi}$, $\boldsymbol{\pi}$, and $\boldsymbol{\lambda}$ are obtained by evaluating the subgradients of $\mathbf{g}(\boldsymbol{\psi},\boldsymbol{\varphi},\boldsymbol{\pi},\boldsymbol{\lambda})$ with respect to each of the dual variables and are given by (11a)–(11d), shown at the bottom of the page.

III. Case Illustration: Parallel Inverter Network

In this section, the application of the integrated control–communication optimization framework to a homogeneous parallel inverter network, as shown in Fig. 2, is evaluated. Nominal parameters of one of the modules are provided in Table I. The piecewise linear model of each module in the synchronous reference frame, which is used to derive the map (1b), is described as

$$\dot{\mathbf{x}}^{(n)} = \mathbf{A}_{0i}^{(n)}\mathbf{x}^{(n)} + \mathbf{A}_{1i}^{(n)}\mathbf{x}^{(j)}\left(-\tau^{(l_{nj})}\right) + \mathbf{B}_i^{(n)} \quad (12)$$

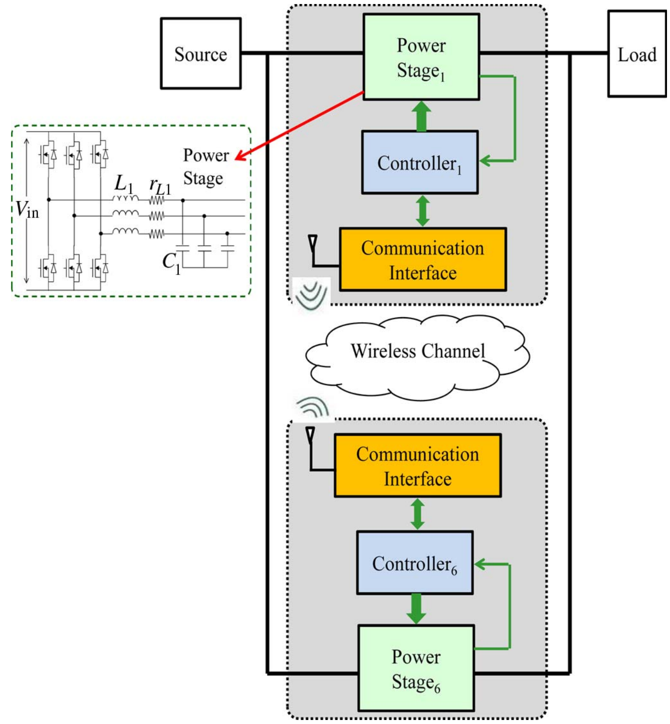

Fig. 2. Block diagram of a six-module parallel inverter network with the communication interface and wireless network for exchanging control information.

TABLE I
Parameters of a Single Module of the Three-Phase Inverter Network

Parameter	Nominal Values
Input voltage, V_{in}	400 V
Output line-line voltage	208 Vrms
Output line frequency	60 Hz
Power	2.5 kVA
Switching frequency, f_{sw}	20 kHz
Inverter line inductors, L_1	1.5 mH
Output filter capacitors, C_1	10 µF

where

$$\mathbf{x}^{(n)} = \left[\, i_d^{(n)} \quad i_q^{(n)} \quad i_z^{(n)} \quad v_d^{(n)} \quad v_q^{(n)} \quad v_z^{(n)} \,\right]^{\mathrm{T}}$$

represents the states of the nth inverter module in the synchronous reference frame and $\mathbf{A}_{0i}^{(n)}$, $\mathbf{A}_{1i}^{(n)}$, and $\mathbf{B}_i^{(n)}$ are switching-state-dependent matrices of appropriate dimensions. Detailed descriptions of these matrices are given in [16] and [18]. For the results provided in this section, $n = 1-6$. The map (1b)

$$\varphi_n(k+1) = \max\left\{0, \varphi_n + \beta_\varphi\left(f_n\left(\mathbf{A}_{0i}^{(n)}, \mathbf{A}_{1i}^{(n)}, \mathbf{B}_i^{(n)}, \mathbf{x}_k^{(n)}, \mathbf{x}_k^{(j)}\left(-\tau_k^{(l_{nj})}\right)\right) - \mathbf{x}_{k+1}^{(n)}\right)\right\} \quad \forall n \quad (11a)$$

$$\psi_n(k+1) = \max\left\{0, \psi_n + \beta_\psi\left(\mathbf{x}_{k+1}^{(n)} - \mathbf{x}_{\max}^{(n)}\right)\right\} \quad \forall n \quad (11b)$$

$$\lambda_{l_{nj}}(k+1) = \max\left\{0, \lambda_{l_{nj}}(k) + \beta_\lambda\left(r_k^{(l_{nj})} - c_{l_{nj}}(\mathbf{P}_k) + \mu_{l_{nj}}\Big/\tau_k^{(l_{nj})}\right)\right\} \quad \forall l_{nj} \quad (11c)$$

$$\pi_{l_{nj}}(k+1) = \max\left\{0, \pi_{l_{nj}}(k) + \beta_\lambda\left(\tau_k^{(l_{nj})} - D_{\max}\right)\right\} \quad \forall l_{nj} \quad (11d)$$

can be derived by patching together the solutions of (12) for all the switching states (i).

Control objectives of the parallel inverter include voltage regulation and load sharing among the inverter modules. The reference vector for the nth inverter module is given by $\mathbf{x}_{\mathrm{ref}}^{(n)} = \lfloor I_d^{\mathrm{ref}} \quad I_q^{\mathrm{ref}} \quad I_z^{\mathrm{ref}} \quad V_d^{\mathrm{ref}} \quad V_q^{\mathrm{ref}} \quad V_z^{\mathrm{ref}} \rfloor$. Here, symbol V_d^{ref} is the d-axis reference voltage, $I_d^{\mathrm{ref}} = (1/N)\sum_{n=1}^{N} i_d^{(n)}$ and $I_q^{\mathrm{ref}} = (1/N)\sum_{n=1}^{N} i_q^{(n)}$ are the averaged d- and q-axis currents of N inverter modules, and I_z^{ref}, V_q^{ref}, and V_z^{ref} are all equal to zero. The current reference for each module is determined using information exchange among all of the inverter modules. The weighting function $\mathrm{Z}^{(n)}$ for the nth module is a 6×6 diagonal matrix, whose diagonal elements are $z_1^{(n)} = 10$, $z_2^{(n)} = 10$, $z_4^{(n)} = 5$, and $z_3^{(n)} = z_5^{(n)} = z_6^{(n)} = 0$. Variations of the weights on the performance of the parallel inverter will be investigated later in Section III-A.

In this section, three scenarios are investigated, as shown in Fig. 3. The transmission schedules for these three cases (corresponding to $N = 6$) are shown in Fig. 4. Fig. 3(a) shows a centralized scheme, where a master module receives state-feedback information from all the modules of the network, computes the optimal switching sequences, and transmits them to each module. Because information exchange with the master module takes place via broadcast-based time-division multiple access, as shown in Fig. 4(a), this scheme is referred to as centralized-broadcast TDMA (CBTDMA). Here, M denotes the master module. On the other hand, Fig. 3(b) shows a distributed control scheme, where all of the modules exchange information with each other via broadcast-based TDMA, as shown in Fig. 4(b). This scheme is referred to as the distributed-broadcast TDMA (DBTDMA). Finally, Fig. 3(c) shows a case where the distributed control is implemented over a network, where many-to-many communication can take place. Fig. 4(c) shows a spatial TDMA-based transmission schedule [28], [29] for information exchange among the modules. Here, the channels marked with the same colors can communicate simultaneously and therefore interfere with each other's communication. Averaged information of the states (represented as $\langle\cdot\rangle$ in Fig. 4) is exchanged across the clusters. This scheme is referred to as distributed spatial TDMA (DSTDMA) in the rest of this paper. Note that, in Fig. 4, the additional time required to synchronize the modules for the DSTDMA case has not been shown.

First, in Section III-A, using simulation results, the need for an integrated control–communication strategy is established for the DSTDMA case. Subsequently, in Section III-B, experimental results demonstrating the application of the integrated control–communication optimization scheme are presented and compared with the performances for the CBTDMA and DBTDMA cases.

A. Simulation Results

Fig. 5 shows the variations of the load-sharing error and the network throughput with variations of the number of modules for the case of DSTDMA. Note that these results are obtained using dynamic simulations in the SimPowerSystems

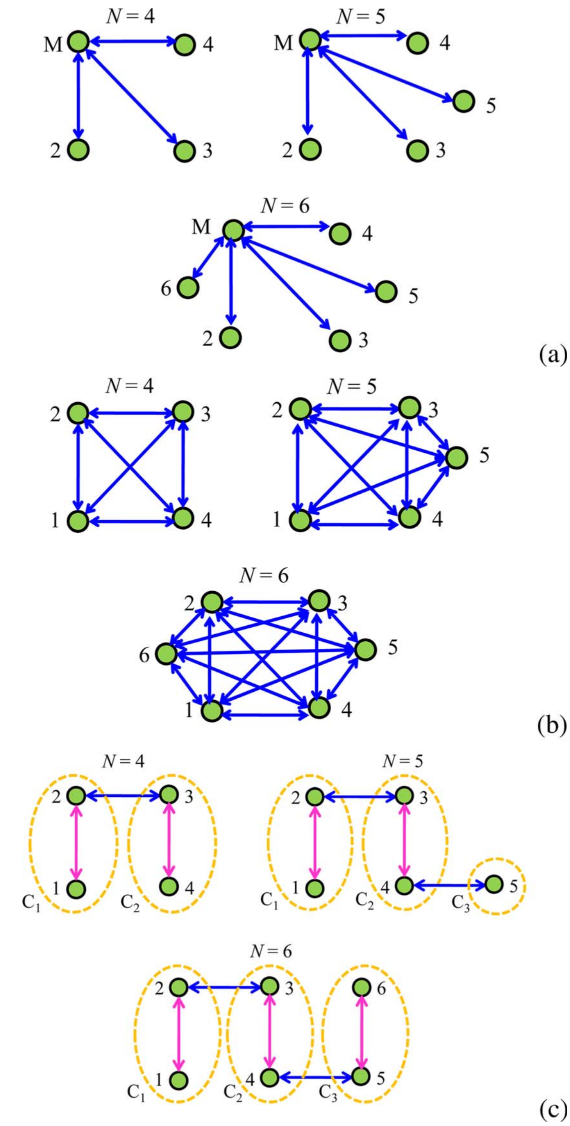

Fig. 3. Schematics illustrating the connectivity of the communication networks (for $N = 6$) under investigation. (a) CBTDMA. (b) DBTDMA. (c) Distributed many-to-many spatial TDMA [29] schemes. Note that the links marked with the same colors can communicate simultaneously.

Version 4.0 toolbox of Simulink. Fig. 5 shows that the control system performance deteriorates with an increase in the number of modules for the three cases shown in Figs. 3 and 4. In this figure, the load-sharing error is calculated with respect to the overall load. The increase in the load-sharing error can be attributed to the parametric differences among the modules and increase in the time delay to sustain more communication overhead. However, for the DSTDMA case [Fig. 5(c)], the effective throughput of the communication network increases with an increase in the number of modules, which means that the network operates closer to its capacity. Note that, here, the network throughput is defined as the sum of the rates that can be sustained by each communication session and is given by $\sum_{l_{nj}} r_k^{(l_{nj})*}$. An increased network throughput might be desirable for applications where network size scalability is required. Because the two problems are noncooperative, the results illustrate the need for an integrated control–communication optimization scheme.

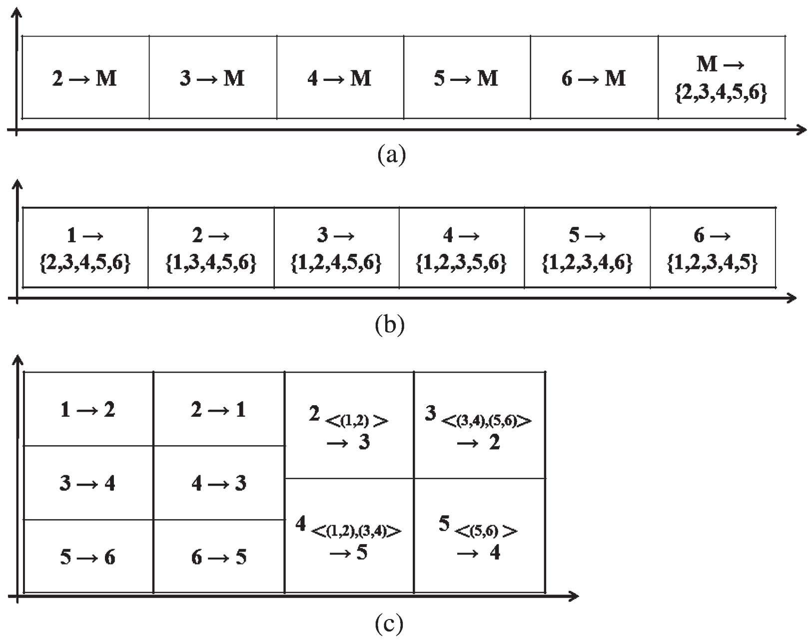

Fig. 4. Comparison of the transmission schedules (for $N = 6$) of (a) CBTDMA, (b) DBTDMA [Fig. 3(a)], and (c) distributed many-to-many spatial TDMA [Fig. 3(b)] schemes.

Furthermore, Fig. 6 shows the variations of the load-sharing error and convergence times with variations of one of the parameters of the weighting function $Z^{(n)}$. The values of the other parameters are as follows:

$$z_2^{(n)} = 10 \qquad z_4^{(n)} = 5 \qquad z_3^{(n)} = z_5^{(n)} = z_6^{(n)} = 0.$$

While increasing $z_1^{(n)}$ results in improved convergence times, the normalized overshoot increases. However, note here that, because of constraint (1c) in the control scheme, this overshoot does not increase beyond the maximum ratings of the components. These results illustrate that a tradeoff study would be helpful to determine the different weights. Similar tradeoff studies were performed to select the other values of the weighting function as well.

Next, the variation of the communication-network resource utilization for different values of the delay weighting factor W is evaluated. Fig. 7 shows that, for small values of the weighting factor W, the end-to-end delay and $D_{\max}$ (the maximum end-to-end delay threshold) are close. As W increases, higher delay margins are obtained at smaller values of $D_{\max}$, as shown in Fig. 8. The optimal end-to-end-delay performance in Fig. 7 also shows that, for a $D_{\max}$ higher than a specific value (e.g., 0.005 s for $W = 100$), a further increase in $D_{\max}$ does not increase the network throughput. The desired network throughput performance can be obtained by adjusting the weight factor W.

B. Experimental Results

Next, using experimental results, the performance of the parallel inverter network with the three schemes shown in Fig. 3 is evaluated. The experimental setup for evaluating the performance of the parallel inverter network is shown in Fig. 9. A digital control platform is used, which contains a DSP (TI TMS320C6713) and a field-programmable gate array (Altera Flex10K Series). The set of feasible switching sequences [16] is computed offline and is used subsequently for solving the distributed control subproblem described in Section II-A. A MicroLinear ML 2722 1.5-Mb/s transceiver that operates in the unlicensed 900-MHz industrial, scientific, and medical frequency band is used and allows half-duplex communication. The algorithm for the communication network subproblem is solved beforehand using some dummy data packets.

Fig. 10 shows a small degradation in the performance of the power network for the DSTDMA case compared to the DBTDMA case. This can be attributed to higher time delays because of interference among the channels during simultaneous communications. The results follow the simulation results presented in Section III-A. Because the network throughput for the interference-limited case is significantly higher than for the broadcast-based communication case (Fig. 5), the integrated control–communication scheme might be more suitable from the point-of-view of network scalability. The significant increase in the convergence times for the CBTDMA case can be attributed to the increased computation times, as shown in Fig. 11. Note that, for these results, the centralized integrated control–communication optimization problem is implemented on the same platform as the distributed case. If a computationally more powerful processor is used, the performance obtained with the centralized architecture is expected to improve.

IV. Summary and Conclusion

In this paper, it is demonstrated that, for a networked control scheme implemented over an interference-limited communication network, the optimal operating points of the control

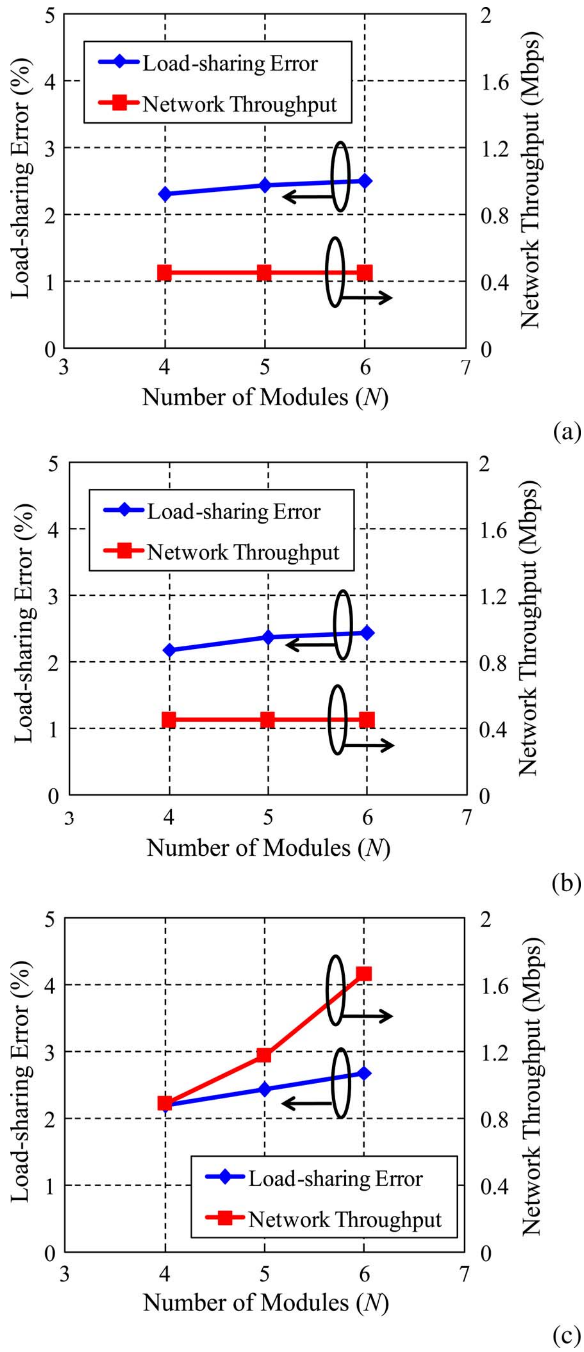

Fig. 5. Simulation results illustrating the variation of the load-sharing error and the network throughput with the number of inverter modules for (a) CBTDMA, (b) DBTDMA, and (c) DSTDMA cases.

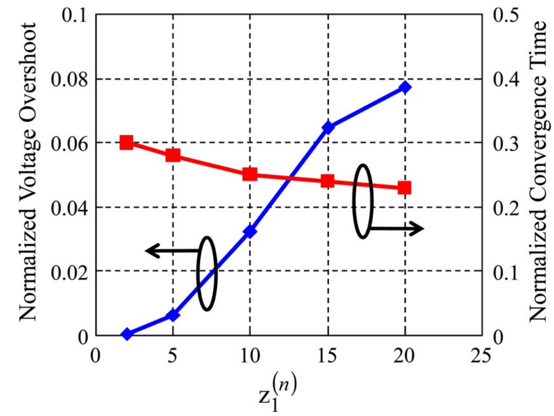

Fig. 6. Simulation results for $N = 6$ illustrating the variations of the load-sharing error and convergence times with variation of $z_1^{(n)}$, which is one of the parameters of the weighting function $Z^{(n)}$.

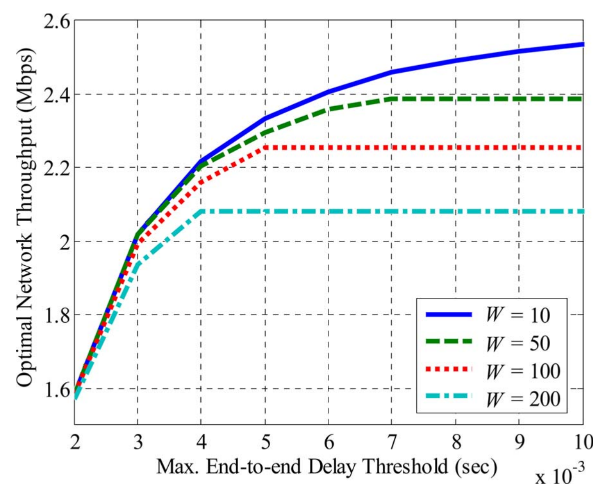

Fig. 7. Throughput performance of the delay-throughput tradeoff for varying weights W.

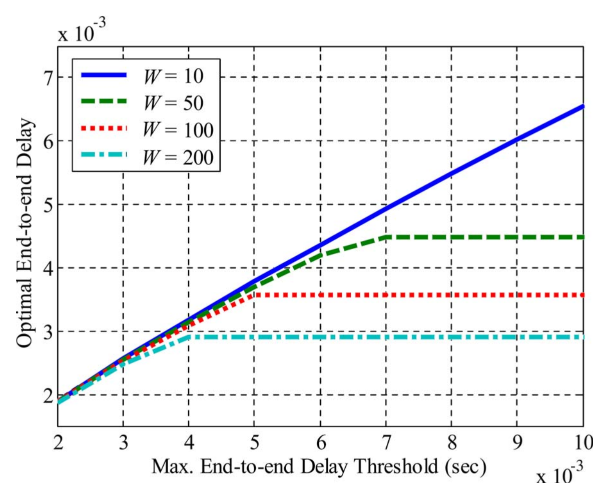

Fig. 8. Optimal end-to-end delay performance of the framework providing delay-throughput tradeoff for varying weights W.

system and the communication network do not necessarily coincide. For such noncooperative systems, an integrated control–communication optimization framework is described that achieves an optimal compromise between the conflicting requirements of the control and communication networks while operating within the stability bounds of the power network and the capacity bounds of the communication network. A case illustration of a homogeneous parallel inverter network is presented in this paper. The performance of the distributed control scheme with many-to-many communications using spatial TDMA and the integrated control–communication framework is compared with centralized- and distributed-broadcast-based TDMA schemes.

The results indicate that joint optimization may not be necessary if the communication protocol does not yield channel

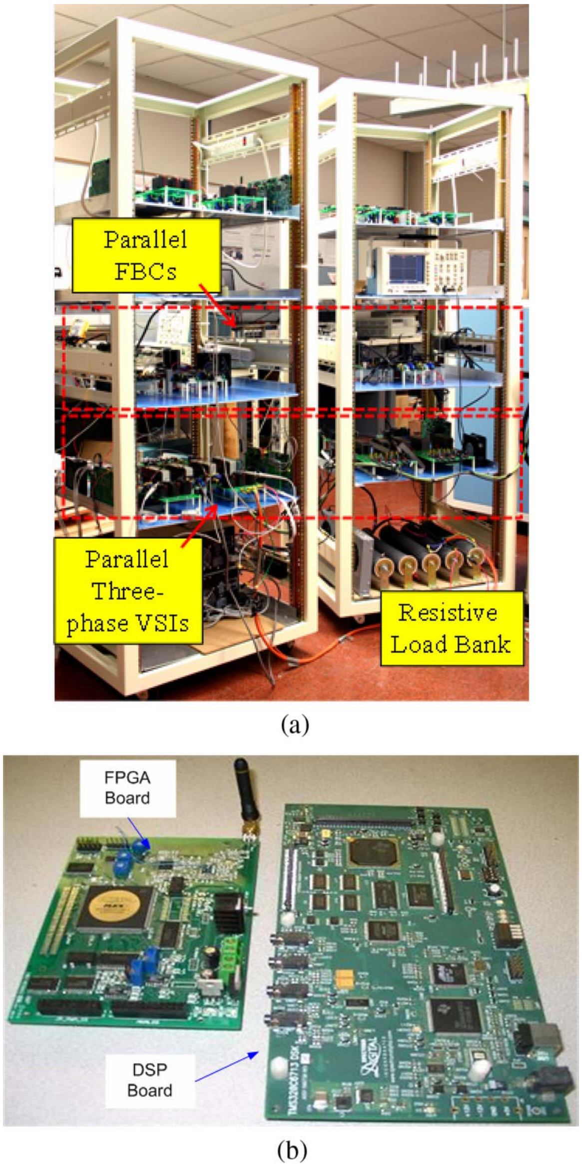

Fig. 9. (a) Experimental setup consisting of six inverter modules connected in parallel. (b) Digital controller interface for implementing the integrated control–communication optimization problem.

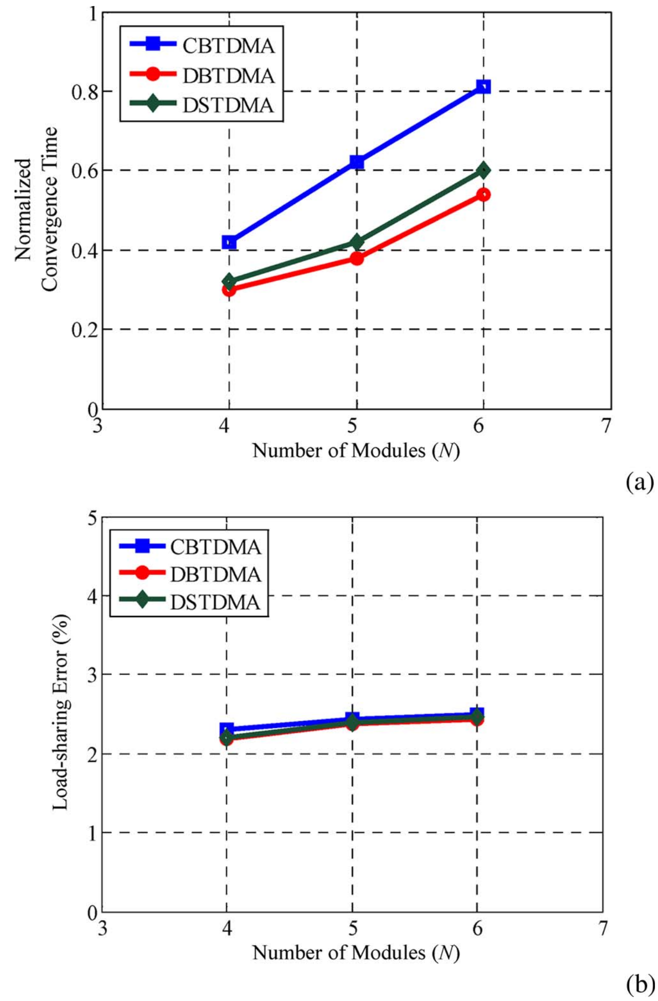

Fig. 10. Experimental results illustrating the variations of (a) the normalized convergence time and (b) load-sharing errors of the homogeneous inverter network.

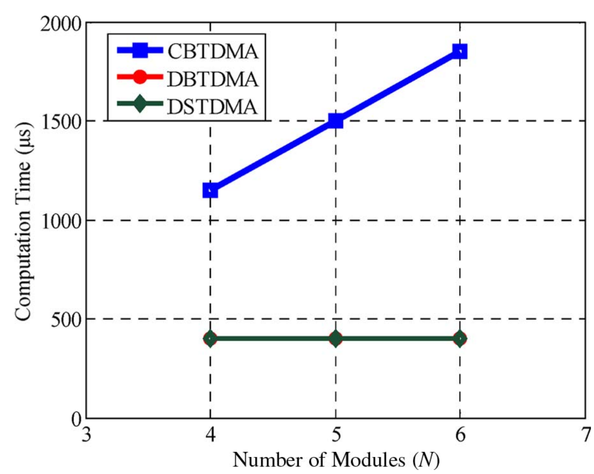

Fig. 11. Comparison of the computation time required to experimentally solve the optimization problem at each module for the centralized and distributed implementations. Note that the entire centralized problem is solved at a single master module.

interference. For instance, in the one-to-many transmission schemes (i.e., CBTDMA and DBTDMA), one can increase network throughput by enhancing the rate of data transmission. However, since each nodal packet is transmitted one at a time, there is no interference, and hence, delay can be simultaneously reduced. On the other hand, for the interference-limited many-to-many scheme (DSTDMA), a joint optimization issue arises because increasing the network throughput (due to simultaneous transmission) comes at the price of the end-to-end delay due to channel interference leading to a direct effect on the control stability and performance.

The distributed control methodology outlined in this paper can be potentially applied to both homogeneous and heterogeneous power networks. Compared to the centralized scheme, the computational complexity of the distributed scheme is lower; however, for the latter, the amount of information exchange may be the limiting factor. As outlined in this paper, clustering can be a way around this problem. While the basic mechanism of the distributed control for the heterogeneous and homogeneous power networks is similar, the issue of scalability may have to be addressed differently. For instance, while in a homogeneous network, commonality of functionality can be exploited for the geographical clustering of the control–communication network, in a heterogeneous network, one may need to focus on the existence of spatial correlation as a possible means for clustering.

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REFERENCES

[1] R. H. Lasseter, "Microgrids and distributed generation," *J. Energy Eng.*, vol. 133, no. 3, pp. 144–149, Sep. 2007. [Online]. Available: http://www.pserc.wisc.edu/ecow/get/publication/2007public/lasseter_asceg2-colum_2007.pdf

[2] M. Prodanovic and T. C. Green, "High-quality power generation through distributed control of a power park microgrid," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1471–1482, Oct. 2006.

[3] S. Chakraborty, M. D. Weiss, and M. G. Simoes, "Distributed intelligent energy management system for a single-phase high-frequency ac microgrid," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 97–109, Feb. 2007.

[4] E. Zivi and T. McCoy, "Control of a shipboard integrated power system," in *Proc. 33rd Annu. Conf. Inf. Sci. Syst.*, 1999. [Online]. Available: www.usna.edu/EPNES/Zivi_McCoy_CISS99.pdf

[5] G. Escobar, P. Mattavelli, A. M. Stankovic, A. A. Valdez, and J. Leyva-Ramos, "An adaptive control for UPS to compensate unbalance and harmonic distortion using a combined capacitor/load current sensing," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 839–847, Apr. 2007.

[6] B. Mammano, "Distributed power systems," *TI Application Note*. [Online]. Available: http://focus.ti.com/lit/ml/slup099/slup099.pdf

[7] E. F. Camacho and C. Bordons, *Model Predictive Control in the Process Industry*. New York: Springer-Verlag, 1995.

[8] K.-S. Low and R. Cao, "Model predictive control of parallel-connected inverters for uninterruptible power supplies," *IEEE Trans. Ind. Electron.*, vol. 55, no. 8, pp. 2884–2893, Aug. 2008.

[9] K. Acharya and S. K. Mazumder, "Optimal sequence-based control of switching power converters with periodic disturbances," in *Proc. IEEE Power Electron. Spec. Conf.*, 2008, pp. 3880–3886.

[10] E. Camponogara, D. Jia, B. H. Krogh, and S. Talukdar, "Distributed model predictive control," *IEEE Control Syst. Mag.*, vol. 22, no. 1, pp. 44–52, Feb. 2002.

[11] S. Talukdar, D. Jia, P. Hines, and B. H. Krogh, "Distributed model predictive control for the mitigation of cascading failures," in *Proc. IEEE Conf. Decision Control*, 2005, pp. 4440–4445.

[12] D. Q. Mayne, J. B. Rawlings, C. V. Rao, and P. O. M. Scokaert, "Constrained model predictive control: Stability and optimality," *Automatica*, vol. 36, no. 6, pp. 789–814, Jun. 2000.

[13] A. Bemporad, S. di Cairano, E. Henriksson, and K. H. Johansson, "Hybrid model predictive control based on wireless sensor feedback: An experimental study," in *Proc. IEEE Conf. Decision Control*, 2007, pp. 5062–5067.

[14] G. Walsh and H. Ye, "Scheduling of networked control systems," *IEEE Control Syst. Mag.*, vol. 21, no. 1, pp. 57–65, Feb. 2001.

[15] J. Nilsson, "Real time control systems with delays," Ph.D. dissertation, Dept. Autom. Control, Lund Inst. Technol., Lund, Sweden, 1998.

[16] S. K. Mazumder and K. Acharya, "Multiple Lyapunov function based reaching condition for orbital existence of switching power converters," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1449–1471, May 2008.

[17] S. K. Mazumder, M. Tahir, and K. Acharya, "Master-slave current-sharing control of a parallel dc–dc converter system over and RF communication interface," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 59–66, Jan. 2008.

[18] K. Acharya, S. K. Mazumder, and M. Tahir, "Fault-tolerant wireless network control of load-sharing multiphase interactive power network," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2006, pp. 1167–1174.

[19] L. Xiao, M. Johansson, H. Hindi, S. Boyd, and A. Goldsmith, "Joint optimization of communication rates and linear systems," *IEEE Trans. Autom. Control*, vol. 48, no. 1, pp. 148–153, Jan. 2003.

[20] X. Liu and A. Goldsmith, "Wireless communication tradeoffs in distributed control," in *Proc. IEEE Conf. Decision Control*, Dec. 2003, pp. 688–694.

[21] M. M. Ben Gaid, A. Cela, and Y. Hamam, "Optimal integrated control and scheduling of networked control systems with communication constraints: Application to a car suspension system," *IEEE Trans. Control Syst. Technol.*, vol. 14, no. 4, pp. 776–787, Jul. 2006.

[22] S. K. Mazumder, M. Tahir, and K. Acharya, "Pseudo-decentralized control–communication optimization framework for microgrids: A case illustration," in *Proc. IEEE Power Energy Soc. Transmiss. Distrib. Conf.*, 2008, pp. 1–8.

[23] M. Tahir and S. K. Mazumder, "Delay constrained optimal resource utilization of wireless networks for distributed control systems," *IEEE Commun. Lett.*, vol. 12, no. 4, pp. 289–291, Apr. 2008.

[24] D. Bertsekas and R. G. Gallager, *Data Networks*. Englewood Cliffs, NJ: Prentice-Hall, 1991.

[25] S. Boyd and L. Vandenberghe, *Convex Optimization*. New York: Cambridge Univ. Press, 2004.

[26] M. Chiang, "Balancing transport and physical layers in wireless multihop networks: Jointly optimal congestion control and power control," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 104–116, Jan. 2005.

[27] D. P. Palomar and M. Chiang, "A tutorial on decomposition methods for network utility maximization," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 8, pp. 1439–1451, Aug. 2006.

[28] P. Bjorklund, P. Varbrand, and D. Yuan, "Resource optimization of spatial TDMA in ad hoc radio networks: A column generation approach," in *Proc. IEEE INFOCOM*, 2003, vol. 2, pp. 818–824.

[29] R. Nelson and L. Kleinrock, "Spatial TDMA: A collision-free multihop channel access protocol," *IEEE Trans. Commun.*, vol. COM-33, no. 9, pp. 934–944, Sep. 1985.

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