Integrating Control and Scheduling of Distributed Energy Resources Over Networks ⋆

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Abstract: This paper presents an integrated approach for the control and scheduling of Distributed Energy Resources (DERs) that are managed by a central supervisor over a resource-constrained communication network. The objective is to enhance the performance and disturbance-handling capabilities of the DERs while keeping the communication requirements with the supervisor to a minimum in order to reduce the susceptibility of the DERs to communication outages. To this end, the rate of data transfer from the DERs to the supervisor is initially minimized by embedding in the supervisor a set of models that are used to generate the necessary control action when measurements are not transmitted over the network, and then updating the models' states at discrete time instances. Only a subset of the DERs are allowed to transmit their data at any given time to provide updates to their target models according to a certain scheduling strategy. By formulating the networked closed-loop system as a hybrid system, an explicit characterization of the interdependence between the performance of the DERs, the communication rate, the transmission schedule and times, and the plant-models' mismatch is obtained. It is shown that by judicious selection of the transmission schedule and models, it is possible to optimize the performance of the DERs while simultaneously reducing network utilization beyond what is possible with concurrent transmission configurations. The results are demonstrated through an application to a collection of solid oxide fuel cells in a distributed power network.

Keywords: Networked control, model-based control, scheduling algorithms, distributed energy resources, solid oxide fuel cells.

1. INTRODUCTION

Distributed Energy Resources (DERs) are a suite of on-site, grid-connected or stand-alone technology systems that can be integrated into residential, commercial, or institutional buildings and/or industrial facilities. These energy systems include distributed generation, renewable energy sources, and hybrid generation technologies; energy storage; thermally activated technologies that use recoverable heat for cooling, heating, or power. Such distributed resources offer advantages over conventional grid electricity by offering end users a diversified fuel supply; higher power reliability, quality, and efficiency; lower emissions and greater flexibility to respond to changing energy needs. As the number and diversity of DERs on the grid increases, dispatching these resources at the right time and accounting for the flow of energy correctly become complex problems that require reliable monitoring and telemetering equipment, as well as reliable communication and control technologies to enable the integration and inter-operability functions of a broad range of DERs. Some estimates (Lovins et al (2002)) place the market potential for advanced control and communications technologies in DERs at \$3.75-\$7.5 billion domestically, and at \$15-\$30 billion worldwide .

While managing DERs over a communication network offers an appealing modern solution to the control of distributed energy generation, it poses a number of challenges that must be addressed before the full economic and environmental potential of DERs can be realized. These challenges stem in part from the inherent limitations on the information transmission and processing capabilities of communication networks, such as bandwidth limitations, network-induced delays, data losses, signal quantization and real-time scheduling constraints, which can interrupt the connection between the central control authority (the supervisor), the generation units and the loads, and consequently degrade the overall control quality if not properly accounted for in the control system design (see, for example, Zhang et al. (2001); Walsh et al. (2002); Hokayem and Abdallah (2004); Xu and Hespanha (2004); Munoz de la Pena and Christofides (2008) and the references therein for discussions and results on control over communication networks). Despite the availability of fast and reliable communication networks, the fact that the distributed power market is primarily driven by the need for super-reliable, high-quality power implies that the impact of even a brief communication disruption (e.g., due to local network congestion or server outage) can be substantial.

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In sites such as hospitals, police stations, data centers and high-tech plants which cannot afford blackouts, millisecond outages that merely cause lights to flicker will cause costly computer crashes. Such high-stake risks provide a strong incentive for the development of robust control and communication strategies that ensure the desired levels and quality of power supply from the DERs while minimizing their reliance on the communication medium, which in turn minimizes the impact of communication disruptions on power supply.

Over the past decade, several efforts have been made towards the development and implementation of control strategies for DERs (e.g., Wang (2001); Barsali et al. (2002); Ro and Rahman (2003); Marei et al. (2004); Lasseter (2007)). While the focus of these studies has been mainly on demonstrating the feasibility of the developed control algorithms, the explicit characterization and management of communication constraints in the formulation and solution of the DER control problem have not yet been addressed. An effort to address this problem was initiated in Sun et al. (2009) where a model-based networked control approach was developed for a DER that communicates with the central controller over a bandwidth-constrained communication network that is shared by several other DERs. The minimum allowable communication frequency was characterized for the case when all DER sensor suites communicate their measurements over the network concurrently and are given simultaneous access to the network. In addition to controlling the transmission frequencies of individual DERs in the network, another important way of reducing network utilization is to select and dispatch only a subset of the deployed DERs at any given time to communicate with the supervisor. Under this restriction, the stability and performance properties of each DER become dependent not only on the controller design but also on the selection of the scheduling strategy that determines the order and times in which the sensor suites of the DERs transmit their data to the supervisor.

Motivated by these considerations, we focus in this work on the problem of integrating control and scheduling of DERs over resource-constrained communication networks. The objective is to find an optimal strategy for establishing and terminating communication between the DERs and the central controller that minimizes the rate at which each DER must collect and disseminate data to the supervisor without jeopardizing the stability and performance properties of the DERs. The rest of the paper is organized as follows. Following some preliminaries in Section 2, the problem of DER scheduling over the network is formulated and an overview of its solution is presented. Section 3 then presents the networked control structure and describes its implementation under scheduling. The closed-loop system is then formulated and analyzed in Section 4 where a precise characterization of the interdependence between the networked closed-loop performance, the communication rate between the DERs and the supervisor, the scheduling strategy, as well as the accuracy of the models and the choice of the control laws, is provided. This characterization is shown to allow a systematic search for the sensor transmission schedules that enhance the overall performance while simultaneously reducing the unnecessary utilization of the communication medium. The implementation of the networked control and scheduling strategy are demonstrated in Section 5 through an application to a network of solid oxide fuel cell (SOFC) plants managed by a supervisor over a communication network.

2. PRELIMINARIES

2.1 Structure of distributed generation units

We consider an array of n DERs managed by a higher-level supervisor over a shared bandwidth-limited communication network. Each DER is modeled by a continuous–time system with the following state–space description:

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i + B_{i_1} w_i + B_{i_2} u_i \\ z_i(t) &= C_i x_i + D_i u_i, \ \ i = 1, \cdots, n \end{aligned} \tag{1}$$

where $x_i \in \mathbb{R}^{n_i}$ denotes the vector of state variables associated with the i–th DER (e.g., exhaust temperatures and rotation speed in turbines and internal combustion engines, operating temperature and pressures in fuel cells), $u_i \in \mathbb{R}^{m_i}$ denotes the vector of manipulated inputs associated with the i–th DER (e.g., inlet fuel flow rate in fuel cells, shaft speed in turbines), $w_i \in \mathbb{R}^{q_i}$ denotes the vector of disturbance inputs, $z_i \in \mathbb{R}^{p_i}$ is the vector of DER performance output signals of interest (e.g., power, voltage and frequency), and A_i, B_{i_1}, B_{i_2}, C_i, and D_i are constant matrices. Each DER has local (on-board) sensors and actuators with some limited built-in intelligence that gives the DER the ability to run autonomously for periods of time when no communication exists with the remote software controller (the supervisor). The local sensors in each DER transmit their data over a shared communication network to the supervisor where the necessary control calculations are carried out and the control commands are sent back to each DER over the communication network. Based on load changes, changes in utility grid power prices and the state and capacity of each DER, the supervisor regulates and coordinates local power generation in the DERs.

2.2 Problem formulation and methodological framework

One of the main problems to be addressed when managing a large number of DERs over a communication network is the large amount of bandwidth required by the different subsystems sharing the communication medium. A tradeoff typically exists between the control performance and the extent of network utilization. On the one hand, optimal control of each DER to deliver the required power quality in the presence of process variations and disturbances is best achieved when information (e.g., measurements, control commands) are exchanged continuously between each DER and the supervisor. Minimal network utilization necessary to save on communication costs, on the other hand, favors only limited communication. Proper characterization and management of this tradeoff is an essential first step to the design of resource-aware networked control systems that ensure the desired performance while respecting inherent constraints on the resources of the communication medium. To address this problem, we will focus in this work on minimizing the sensor-controller communication costs under the assumption that the actuators and supervisor are collocated (i.e., the network exists between the sensors and the controller; generalizations to account for actuator-controller communication constraints are possible and the subject of other research work). To this end, we will consider the following approach:

- Initially design for each DER an appropriate feedback control law that regulates its output (in the absence of communication constraints) at the desired set-point decided by the supervisor.
- Reduce the collection and transfer of information from each DER to the supervisor as much as possible to limit the bandwidth required from the network without sacrificing the desired stability and performance properties by using models of the DERs in the supervisor to calculate the control action when measurements are not available.
- Limit the number of DERs that, at any time, transmit their data to update the corresponding target models.
- Find a scheduling strategy for establishing and terminating communications between the DERs and the supervisor that optimizes a certain performance metric for the closed-loop system while simultaneously keeping the communication rate to a minimum.

3. NETWORKED CONTROLLER DESIGN AND SCHEDULING

3.1 Model-based networked control of DERs

In order to reduce network usage, we embed a dynamic model of each DER in the supervisor to provide it with an estimate of the evolution of the states of the DER when measurements are not available. The use of a model at the controller/actuator side to recreate the dynamics of each DER allows the on-board sensors to transmit their data at discrete time instances and not continuously (since the model can provide an approximation of the DER dynamics) thus allowing conservation of network resources. The computational load associated with this step (e.g., model forecasting and control calculations) is justified and supported by the increasing capabilities of modern computing systems used by the central control authority. Feedback from the DER is then performed by updating the state of the model state using the actual state that is provided by its sensors at discrete time instances. The model-based controller is implemented as follows:

$$\begin{aligned} u_i(t) &= K_i \widehat{x}_i(t),\ t \neq t_k^i \\ \dot{\widehat{x}}_i(t) &= \widehat{A}_i \widehat{x}_i(t) + \widehat{B}_{i_2} u_i(t),\ t \in [t_k^i, t_{k+1}^i) \\ \widehat{x}_i(t_k^i) &= x_i(t_k^i),\ \ k = 0, 1, 2, \cdots \end{aligned} \tag{2}$$

where $\widehat{x}_i$ is an estimate of x_i, $\widehat{A}_i$ and $\widehat{B}_{i_2}$ are estimates of A_i and B_{i_2}, respectively, which do not necessarily match the actual dynamics of the i–th DER, (i.e., in general $\widehat{A}_i \neq A_i$, $\widehat{B}_{i_2} \neq B_{i_2}$). The notation t_k^i is used to indicate the k-th transmission time for the sensor suite of the i-th DER in the collection. The model state is used by the controller as long as no measurements are transmitted, but is updated (or re-set) using the true measurement whenever it becomes available from the network.

3.2 Scheduling DER transmissions over the network

A key parameter in the analysis of the control and update laws in Eq.2 is the update period for each DER, $h^i := t_{k+1}^i - t_k^i$, which determines the frequency at which the sensor suite of the i-th DER collects and sends measurements to the supervisor through the network to update the corresponding model state. To simplify the analysis, we consider in what follows the case when the update period is constant and the same for all DERs, so that $t_{k+1}^i - t_k^i := h,\ i = 1, 2, \cdots, n$. The update period is also an important measure of the extent of network utilization, with a larger h indicating a larger reduction in network utilization. Because of the bandwidth limitations on the communication network and in order to further reduce network utilization, we perform sensor scheduling whereby only one DER is allowed to transmit its measurements to the supervisor at any one time, while the other DERs remain dormant for some time before the next DER is allowed to transmit its data (the results can also be generalized to configurations where multiple DERs transmit at the same time). The transmission schedule is defined by: (a) the sequence (or order) of transmitting suites of DERs: $\{s_i,\ i = 1, 2, \cdots, n\},\ s_i \in \mathcal{N} := \{1, 2, \cdots, n\}$,where s_i is a discrete variable that denotes the i-th transmitting entity in the sequence, and (b) the time at which each DER in the sequence collects and transmits measurements. To characterize the transmission times, we introduce the variable: $\Delta t_i := t_k^{s_{i+1}} - t_k^{s_i},\ i = 1, 2, \cdots, n-1$, which is the time interval between the transmissions of two consecutive DERs in the sequence.

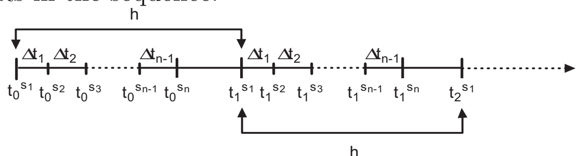

Fig. 1. A schematic of the time-line for the transmissions of DERs in an h-periodic schedule.

Fig.1 is a schematic representation of how DER scheduling is performed. Note that the schedule is h-periodic in the sense that the same sequence of transmitting DERs is executed repeatedly every h seconds (equivalently, each DER transmits its data every h seconds). Note also from the definitions of both h and Δt_i that the transmission times always satisfy the constraint $\sum_{i=1}^{n-1} \Delta t_i < h$. Since the update periods for all DERs are the same, the intervals between the transmission times of two specific DERs are constant, and within any single execution of the schedule (which lasts less than h seconds), each DER can only transmit its measurements through the network and update its model in the supervisor once. This can be represented mathematically by the condition: $s_i \neq s_j$ when $i \neq j$. By manipulating the time intervals Δt_i (i.e., the transmission times) and the order in which the DERs transmit, one can systematically search for the optimal transmission schedule that leads to the largest update period (or the smallest communication rate between the sensor suite of each DER and the supervisor).

4. PERFORMANCE CHARACTERIZATION OF THE SCHEDULED CLOSED-LOOP SYSTEM

4.1 A hybrid system formulation

Defining the model estimation errors by $e_i = x_i - \widehat{x}_i$, where e_i represents the difference between the state of the i-th DER and the state of its model embedded in the supervisor, and introducing the augmented vectors: $\mathbf{e} := [e_1^T\ e_2^T\ \cdots\ e_n^T]^T$, $\mathbf{x} := [x_1^T\ x_2^T\ \cdots\ x_n^T]^T$, it can be shown that the overall networked closed-loop system of Eqs.1-2 can be formulated as a combined discrete–continuous (hybrid) system of the form:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \Lambda_{11}\mathbf{x}(t) + \Lambda_{12}\mathbf{e}(t) + \bar{B}_N w(t) \\ \dot{\mathbf{e}}(t) &= \Lambda_{21}\mathbf{x}(t) + \Lambda_{22}\mathbf{e}(t) + \bar{B}_N w(t),\ \ t \neq t_k^i \\ e_i(t_k^i) &= 0,\ \ i = 1, 2, \cdots, n,\ \ k = 0, 1, 2, \cdots, \end{aligned} \tag{3}$$

where $\bar{B}_N = [B_{1_1}^T\ B_{2_1}^T\ \cdots, B_{n_1}^T]^T$, and the DER states evolve continuously in time while the estimation errors are reset to zero at each transmission instance. Note, however, that unlike the case of simultaneous DER transmissions (where no scheduling takes place) which was investigated in Sun et al. (2009), not all models within the supervisor are updated (and hence not all estimation errors are reset to zero) at each transmission time. Instead, only the model of the transmitting DER is updated using the measurements provided by its sensor suite.

Referring to Eq.3, Λ_{11}, Λ_{12}, Λ_{21}, and Λ_{22} are all $m \times m$ constant, block-diagonal matrices, where $m = \sum_{i=1}^{n} n_i$ and n_i is the dimension of the i-th state vector. These matrices are linear combinations of A_i, B_{i_2}, $\widehat{A}_i$, $\widehat{B}_{i_2}$, K_i, which are the matrices used to describe the dynamics, the models, and the control laws of the different DERs. The explicit forms of these matrices are given by: $\Lambda_{11} = \text{diag}\{A_i + B_{i_2}K_i\}$, $\Lambda_{12} = \text{diag}\{-B_{i_2}K_i\}$, $\Lambda_{21} = \text{diag}\{\widetilde{A}_i + \widetilde{B}_{i_2}K_i\}$, $\Lambda_{22} = \text{diag}\{\widehat{A}_i + \widehat{B}_{i_2}K_i\}$, where $\widetilde{A}_i = A_i - \widehat{A}_i$, and $\widetilde{B}_{i_2} = B_{i_2} - \widehat{B}_{i_2}$. Defining the augmented state vector $\xi(t) := [\mathbf{x}^T(t)\ \mathbf{e}^T(t)]^T$, the dynamics of the overall closed-loop system can be written as:

$$\begin{aligned} \dot{\xi}(t) &= \Lambda\xi(t) + B_N w(t),\ t \neq t_k^i \\ e_i(t_k^i) &= 0,\ \ i = 1, 2, \cdots, n,\ \ k = 0, 1, 2, \cdots \\ \mathbf{z}(t) &= C_N \xi(t) \end{aligned} \tag{4}$$

where $\Lambda = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} \\ \Lambda_{21} & \Lambda_{22} \end{bmatrix}$, $B_N = [\bar{B}_N^T\ \ \bar{B}_N^T]^T$, $C_N = [\text{diag}\{C_i + D_i K_i\}\ \ \text{diag}\{-D_i K_i\}]$, and $\mathbf{z} := [z_1^T\ z_2^T\ \cdots\ z_n^T]^T$ is the overall performance output of the DER collection.

4.2 Performance characterization using extended H_2-norm

Our objective in this section is to assess the performance of the networked scheduled closed-loop system subject to disturbances and explicitly characterize its dependence on the update period and the DER transmission schedule to determine an optimal schedule and update period that ensure minimal influence of the disturbances on the performance output of the closed-loop system. As a performance metric, we choose the extended H_2-norm introduced originally in Montestruque and Antsaklis (2006). This performance measure, which is an H_2-like norm that is suitable for analyzing periodic networked control systems, captures the 2-norm of the performance output response when the closed-loop system is initialized at the steady-state and an impulse disturbance is introduced in the input at $t = t_0$ (see Montestruque and Antsaklis (2006) for other types of performance measures that can be used). The following theorem explicitly characterizes the performance output response in terms of the control, communication and scheduling design parameters. The proof can be obtained by solving the system of Eq.4 within each subinterval of the time-line in Fig.1, and is omitted for brevity.

Theorem 1. Consider the system of Eq.4 with a transmission schedule $\{s_1, s_2, \cdots, s_n\}$ and the initial condition $\xi(t_0^{s_1}) = [\mathbf{0}\ \ \mathbf{e}^T(t_0^{s_1})]^T = \xi_0$, with $e_{s_1}(t_0^{s_1}) = 0$, subject to an impulse disturbance $w = \delta(t - t_0^{s_1})$. Then:

(a) For $t \in [t_k^{s_i},\ t_k^{s_{i+1}})$, $i = 1, 2, \cdots, n-1$, $k = 0, 1, 2, \cdots$, the performance output response is given by:

$$\mathbf{z}(t) = C_N e^{\Lambda(t - t_k^{s_i})}\Gamma_i(\Delta t_i, I_s^{s_i})M^k B_N \tag{5}$$

(b) For $t \in [t_k^{s_n},\ t_{k+1}^{s_1})$, $k = 0, 1, 2, \cdots$, the performance output response is given by:

$$\mathbf{z}(t) = C_N e^{\Lambda(t - t_k^{s_n})}\Gamma_n M^k B_N \tag{6}$$

where

$$M(h) = I_s^{s_1} e^{\Lambda(h - \sum_{i=1}^{n-1}\Delta t_i)}\Gamma_n \tag{7}$$

$$\Gamma_i = \left\{ \begin{array}{ll} \prod\limits_{i-1-\mu=0}^{i-2} I_s^{s_{\mu+1}} e^{\Lambda\Delta t_\mu}, & \text{for } i \geq 2 \\ I, & \text{for } i = 1 \end{array} \right\} \tag{8}$$

$$I_s^{s_i} = \begin{bmatrix} I & O & \cdots & O \\ O & H_1 & \cdots & O \\ \vdots & \vdots & & \vdots \\ O & O & \cdots & H_n \end{bmatrix},\ H_i = \begin{cases} I, & i \neq s_i \\ O, & i = s_i \end{cases} \tag{9}$$

for $i = 1, 2, \cdots, n$, $t_{k+1}^{s_i} - t_k^{s_i} = h$ and $\Delta t_i = t_k^{s_{i+1}} - t_k^{s_i}$, for $i = 1, 2, \cdots, n-1$.

Remark 1: The expression in Eq.5 captures the response of the performance output during the time periods between the transmissions of two consecutive DERs in a given execution of the schedule, while the expression in Eq.6 provides the response for the time period between the transmission of the last DER in a given execution and the transmission of the first DER in the next execution. As expected the responses are parameterized by the transmission sequence (which determines the structure of the matrices $I_s^{s_i}$) as well as the transmission times (which are determined by Δt_i). Note from the term M^k (which captures the growth of the response due to the repeated execution of the transmission schedule) that a necessary and sufficient condition for the responses to be stable is to have all the eigenvalues of the matrix M strictly inside the unit circle (e.g., see Sun and El-Farra (2008) for further details on the characterization of closed-loop stability).

Based on the result of Theorem 1, the extended H_2-norm for the scheduled networked closed-loop system, $\| G \|_{H_2}$, can be calculated using the following defining relation:

$$\| G \|_{H_2} = \text{trace}(B_N^T X B_N)^{1/2} \tag{10}$$

where X is the solution to the discrete Lyapunov equation:

$$M^T(h, I_s^{s_i}, \Delta t_i) X M(h, I_s^{s_i}, \Delta t_i) - X + \sum_{i=1}^{n} W_i = 0, \tag{11}$$

W_i is a matrix computed as:

$$W_i = \int_0^{\Delta t_i} \Gamma_i^T e^{\Lambda^T t} C_N^T C_N e^{\Lambda t}\Gamma_i dt,\ \ i = 1, 2, \cdots, n \tag{12}$$

and $\Delta t_n := h - \sum_{i=1}^{n-1}\Delta t_i$.

Remark 2: The relations of Eqs.10-12 provide a generalization of the extended H_2-norm calculation to networked control systems with scheduled sensor transmissions. In the limit as $\Delta t_i \to 0$, for $i = 1, \cdots, n-1$, (i.e., simultaneous transmissions), these relations reduce to the ones developed originally in Montestruque and Antsaklis (2006) for non-scheduled networked control systems.

Remark 3: By examining Eqs.10-12, it can be seen that $\| G \|_{H_2}$ depends on the interplay between the plant-model mismatch for each DER, the controller gains, the update period, the time intervals between transmissions, as well as the transmission sequence, which altogether provide handles that can be tuned to optimize the performance of the networked closed-loop system subject to disturbances. For example, the extended H_2-norm can be used to compare different schedules (by varying the transmission sequence and times) to determine which schedules achieve the best performance with the least communication rate between the DERs and the supervisor. Alternatively, if the schedule is fixed by the network access constraints, the performance index can be used to compare the performance levels achieved by using different models and different controllers. The performance criterion can therefore be used to formulate various kinds of optimization problems.

5. SIMULATION STUDY: A NETWORK OF SOLID OXIDE FUEL CELLS

As an illustrative example, we consider a network of three solid oxide fuel cell (SOFC) plants that communicate with the supervisor over a shared communication network . The plants have different dynamic characteristics due to the differences in sizes and capacities of the individual fuel cell stacks. The supervisor is responsible for maintaining the power output of each SOFC plant at a desired set-point by manipulating the inlet fuel flow rate in the presence of disturbances in the inlet air flow rate. Measurements from the sensor suite of each SOFC plant can be received by the supervisor only through the communication network, while the actuator suite of each plant is assumed to have un-interrupted access to the supervisor (ideal actuator-controller links). Under standard modeling assumptions, a dynamic model of the following form can be derived for each SOFC stack from material and energy balances (Mursheda et al. (2007)):

$$
\begin{aligned}
\dot{p}_{H_2} &= \frac{T_s}{\tau^*_{H_2} T^* K_{H_2}}(q^{in}_{H_2} - K_{H_2} p_{H_2} - 2K_r I) \\
\dot{p}_{O_2} &= \frac{T_s}{\tau^*_{O_2} T^* K_{O_2}}(q^{in}_{O_2} - K_{O_2} p_{O_2} - K_r I) \\
\dot{p}_{H_2O} &= \frac{T_s}{\tau^*_{H_2O} T^* K_{H_2O}}(q^{in}_{H_2O} - K_{H_2O} p_{H_2O} + 2K_r I) \\
\dot{T}_s &= \frac{1}{m_s C_{ps}} \sum q^{in}_i \int_{T_{ref}}^{T_{in}} C_{p,i}(T) dT \\
&\quad - \sum q^{out}_i \int_{T_{ref}}^{T_{in}} C_{p,i}(T) dT - \dot{n}^r_{H_2} \triangle \hat{H}^o_r - V_s I
\end{aligned}
\tag{13}
$$

where, p_i is the partial pressure of component i (i: H_2, O_2, H_2O), T_s is the stack temperature, q^{in}_i is the inlet molar flow rate of component i, m_s and C_{ps} are the mass and average specific heat of fuel cell materials excluding gases, $C_{p,i}$ is the specific heat of gas component i, $\triangle \hat{H}^o_r$ is the specific heat of reaction, I is the load current, $\tau^*_i := V/K_i R T^*$ is a time constant for i-th component, K_i is the valve molar constant for component i, and $K_r = N_0/4F$, N_0 is the number of cells in the stack, F is Faraday's constant, V_s is the overall stack voltage:

$$
V_s = N_0 \left[\triangle E_0 + \frac{RT_s}{2F} \ln \frac{p_{H_2} p^{(0.5)}_{O_2}}{p_{H_2O}} \right] - r_0 \exp \left[\alpha \left(\frac{1}{T_s} - \frac{1}{T_0} \right) \right] I \tag{14}
$$

where r_0 is the internal resistance at T_0, α is the resistance slope (only ohmic losses are included, while activation and concentration losses are neglected), and $\triangle E_0$ is the standard cell potential. Linearizing the SOFC plants around the desired set-points yields a system of the form of Eq.1 with $n = 3$, where x_i, u_i, w_i and z_i are the dimensionless state, manipulated input (inlet fuel flow rate), disturbance (inlet air flow rate) and power output for the i-th plant, respectively. To regulate the power output of each fuel cell, a feedback controller of the form $u_i = K_i x_i$, is designed and implemented. The explicit forms of the plants and controller matrices are omitted due to space limitations.

5.1 Performance under scheduled sensor transmissions

In this section, we investigate the impact of varying the DER transmission schedule, the intervals between transmissions, and the plant-model mismatch on the total power output of the SOFC network which is chosen as the performance output. As mentioned in Section 3, we focus on scheduling configurations where at each transmission time, only the sensor suite of one SOFC plant is allowed to transmit its measurement updates to the supervisor. To quantify the mismatch between each plant and its model that is embedded in the supervisor, we consider as an example parametric uncertainty in Cp_{H_2} and define $\delta_1 = (Cp^m_{H_2} - Cp_{H_2})/Cp_{H_2}$, where $Cp^m_{H_2}$ is a nominal value used in the model, as a measure of model accuracy (any other set of uncertain parameters can also be considered and analyzed in a similar fashion). We initialize the closed-loop SOFC plants at the desired set-points and introduce a unit impulse disturbance in the inlet flow rate of air to each plant. The power outputs of the individual fuel cells are chosen as the performance outputs. Fig.2(a) shows the dependence of the extended H_2-norm of the entire SOFC network on the update period, h, under the six possible sensor transmission schedules listed in Table 1 when imperfect models are embedded in the supervisor (each model with parametric uncertainty $\delta_1 = 5$) and the transmission times are fixed such that $\Delta t_1 = \Delta t_2 = h - \Delta t_1 - \Delta t_2$. It can be seen that among all possible schedules, schedule 4 provides the best performance since for any update period it yields the smallest $\parallel G \parallel_{H_2}$. Note also that this schedule yields an improved performance over the non-scheduled (i.e., concurrent) transmission configuration shown by the solid profile. Not only is the minimum extended H_2-norm smaller for the scheduled configuration, but the optimal update period is also larger, which implies that the rate at which each plant needs to collect and transmit measurements to the supervisor under the scheduled configuration is smaller, thus leading to bigger savings in the overall utilization of the communication network resources. The reason for the performance improvement can be understood in light of the fact that forcing the different SOFC plants to transmit their data and update their target models in the supervisor at different times (rather than simultaneously) creates opportunities for providing a more targeted correction to the estimation errors of the different models, where the models with the largest plant-model mismatch can receive more timely updates than would be feasible under simultaneous transmissions. This in turn helps reduce the rate at which each SOFC plant in the communication network must collect and transmit data.

Table 1. SOFC plant transmission schedules

Schedule	$s_1, s_2, s_3, s_1, s_2, s_3, \cdots$
1	$1, 2, 3, 1, 2, 3, \cdots$
2	$1, 3, 2, 1, 3, 2, \cdots$
3	$2, 1, 3, 2, 1, 3, \cdots$
4	$2, 3, 1, 2, 3, 1, \cdots$
5	$3, 1, 2, 3, 1, 2, \cdots$
6	$3, 2, 1, 3, 2, 1, \cdots$

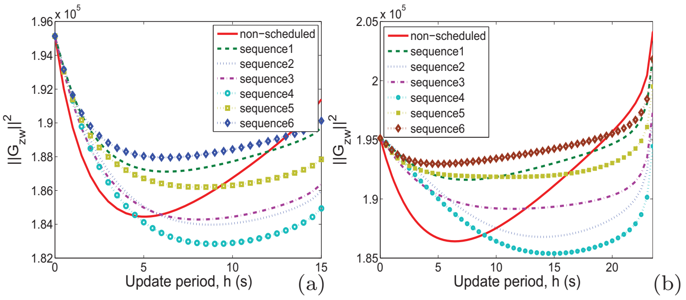

Fig. 2. Dependence of the norm of the power output vector for the SOFC network on the update period for different sensor transmission sequences under (a) a model-based scheme, and (b) a zero-order hold scheme.

Fig.2(b) shows how the extended H_2-norm of the overall SOFC network under each schedule varies as h is varied when a zero-order hold scheme is used. In this case, the supervisor holds the last measurement received from the individual SOFC plant until the next time a measurement is transmitted and received from the network (this corresponds to using models with $\widehat{A}_i = O$ and $\widehat{B}_{i_2} = O$). It can be seen that the optimal update period obtained under scheduling is also larger in this case than the one obtained under simultaneous transmissions.

5.2 Dependence of overall performance on model quality

In this part, we investigate the effect of model uncertainty on the overall SOFC network performance. Fig.3 depicts the dependence of $\| G \|_{H_2}$ of the entire SOFC network on both δ_1 and the update period when the sensors' transmission follows schedule 4. As expected, for a given overall performance level, the range of feasible update period shrinks as the plant-model mismatch increases. The predictions of Fig.3(a) are further confirmed by the closed–loop power output profile in Fig.3(b) which shows that under the same update period of $h = 9$ s and sensor transmission sequence 4, the networked closed-loop system performs better with a relatively accurate model ($\delta_1 = -2$) than the one with an inaccurate model ($\delta_1 = -10$).

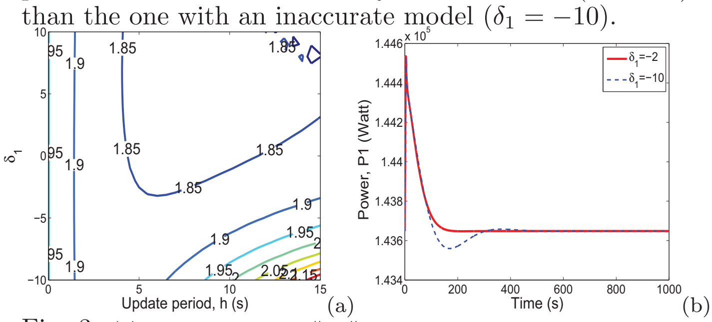

Fig. 3. (a): Dependence of $\| G \|_{H_2}$ on plant-model mismatch for various h. (b): First SOFC plant power output profile under the networked control system with different models.

5.3 Performance dependence on the transmission times

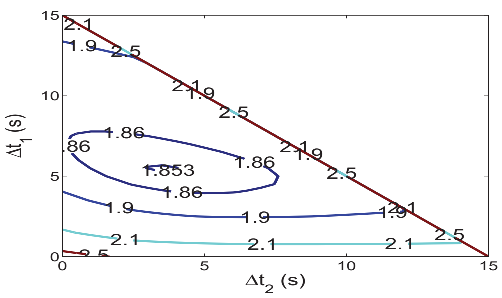

Fig. 4. Dependence of $\| G \|_{H_2}$ on Δt_1 and Δt_2 under schedule 4.

Fig.4 is a contour plot showing the dependence of $\| G \|_{H_2}$ on Δt_1 and Δt_2 for a fixed update period ($h = 15$ s) when the SOFC plants transmit according to schedule 4 and a zero-order hold model is considered. In comparison with the performance achieved in the case when $\Delta t_1 = \Delta t_2 = h - \Delta t_1 - \Delta t_2$ ($\| G \|_{H_2} = 1.854 \times 10^5$; see Fig.2(b)), it can be seen that an improved performance is attained ($\| G \|_{H_2} = 1.853 \times 10^5$) by varying the transmission times such that $\Delta t_1 = 5.5$ s and $\Delta t_2 = 3.5$ s.

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