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Synchronization of isolated microgrids with a communication infrastructure using energy storage systems

Jairo Giraldo [a,*], Eduardo Mojica-Nava [b], Nicanor Quijano [a]

[a] *Departamento de Ingeniería Eléctrica y Electrónica, Universidad de los Andes, Bogotá, Colombia*
[b] *Electrical and Electronics Department, National University of Colombia, Bogotá, Colombia*

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ABSTRACT

There exists an increasing interest in networked systems due to the wide number of applications in distributed and decentralized control of large scale systems, such as smart grids. We address the problem of distributed frequency synchronization of several isolated microgrids, each one described by a linear-time continuous system, composed by different types of generators, whose outputs are measured and sent through a communication infrastructure. We assume that each microgrid possesses renewable resources with storage capabilities that helps to improve stability of the network when small damping ratio is considered. Thus, using the smart grid communication infrastructure and the data flow through the network, we propose a cooperative control strategy based on the consensus algorithm that simultaneously manages the turbine governor input and the amount of energy that the storage devices have to absorb/inject from/into the grid. Nevertheless, physical constraints need to be included, which can be modeled using saturation non-linearities, and conditions to assure synchronization even with saturation are obtained based on multi-agent systems. Additionally, we consider that sensor measurements are sampled and we extend the results of frequency synchronization with saturation to the case of control discretization and sampling-period independence is demonstrated using passivity concepts.

Introduction

The power network is a large-scale and complex system that involves a wide number of elements (e.g., generators, loads, control devices) that are interconnected. This makes control in power networks a challenging research field that has been addressed in the last century, where the main objective is to preserve stability and avoid unnecessary and damaging oscillations [1]. Nevertheless, in the last few years the inclusion of small and medium voltage generators and the increasing penetration of renewable resources have introduced new advantages due to the possibility of producing clean, sustainable, and low cost energy [2]. However, new challenges have emerged because of the uncertainties induced by the renewable resources, and the high amount of information that needs to be processed [3]. Furthermore, the future power network (or smart grid) needs high speed, reliable, and secure data communication networks to manage the high amount of information coming from sensors all over the power network (from generation to user level) and take smart decisions [4].

On the other hand, considering the smart grid as only one large-scale system increases the difficulty of analysis and design due to the high amount of variables that need to be considered. In this respect, microgrids emerge as a solution to these problems. Microgrids (MGs) are smaller systems, usually of medium or small voltage, that include distributed generators (e.g., small hydro turbines, diesel generators, solar panels) and storage devices (e.g., energy capacitors, batteries, flywheels). Microgrids could increase the efficiency of power systems facilitating monitoring and control because of its reduced size and the possibility of using hierarchical control [5]. Therefore, we can see the power network as the interconnection of several microgrids, each one with control and energy generation capabilities, and a communication infrastructure that transmits data between them. In general, an MG can operate as a grid-connected system or as an island, where the latter takes place by unplanned events like faults in the network or by planned actions like maintenance requirements [6].

One of the main goals in control of a power system is *frequency synchronization*, where each node needs to work at the same frequency and voltage in order to avoid failures and malfunctioning. The importance of synchronization lies in the fact that if a generator works with a different speed (frequency) or voltage than the power system due to failures or sudden changes in loads,

* Corresponding author. Tel.: +57 3167277994.
E-mail address: ja.giraldo908@uniandes.edu.co (J. Giraldo).

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generators need to match frequency by accelerating or decelerating its own speed, provoking mechanical stresses, disturbances, and oscillations that affect not only the health of the unsynchronized generator, but also the stability of the grid [7]. In this perspective, if two microgrids are isolated and they work individually with different frequencies, at the time when they connect back together, the oscillations and disturbances may provoke failures or blackouts. Commonly, frequency control of power networks is developed using feedback gain control for each individual microgrid. Furthermore, PID controllers have been widely used in order to assure that the frequency deviation is regulated at zero. However, if several microgrids are isolated it is not possible to assure frequency synchronization between them only using its own state information. It is necessary that microgrids cooperate and exchange information between them in order to take smarter decisions.

In this work, we focus our attention on frequency synchronization of multiple isolated microgrids, each one modeled as a linear time-invariant (LTI) system with communication capacities and multiple sources. Linear models can be considered for small frequency changes. The problem is addressed using the concepts of synchronization of multi-agent systems [8,9], such that a decentralized controller is proposed based on the consensus algorithm [10]. The controller computes information from some neighbors (other microgrids), and handles the mechanical power generated by the turbine governor and simultaneously manages the injection/absorption of power to/from the microgrid using energy storage systems (ESS). Then, microgrids will tend to remain synchronized even when unknown changes in the loads occur, and we also show how the stability of the network is improved with the inclusion of storage devices, and instabilities provoked by small damping ratio and small inertia can be mitigated. Nevertheless, control limitations that emerge when the information is sent through communication links have to be addressed. For instance, phasorial measurement units (PMUs) measure the state of a node in the power network. This measurement is made each sampling instant, and the information is quantized, packed, and sent using a communication protocol through a wire or wireless link. That process introduces a variety of issues such as time-delays [11], packet losses [12], information lost due to quantization [13], and signal discretization, among others. However, we limit our attention to only sampled-data measurements.

On the other hand, it is necessary to consider physical limitations on the turbine governor and the storage devices. They both are limited by storage capabilities and actuator constraints due to costs and design parameters. As a consequence, we assume that inputs are constrained and synchronization criteria with saturation are established. Several works have addressed the problem of saturation using different models. In [14], authors have used the tangential hyperbolic function in order to model input saturations. On the other hand, [15] uses the anti-windup compensator in order to minimize degradation of the global performance of a linear system under saturating inputs. In this work, we use some tools presented in [16], where the authors illustrate different ways to manage saturations based on polytopic approaches. Therefore, we propose a distributed control strategy based on the sampled-data information flow between microgrids and the actuator constraints, (i.e., boundaries in the amount of power injected/absorbed by the turbine governor and the ESS).

The paper is organized as follows. Section 'Problem formulation' formulates the problem and the model of the smart grid. The linear time system analysis and the control method is introduced in Section 'Synchronization of a dynamic network'. Conditions for synchronization with saturation and sampling are analyzed in Sections 'Synchronization with saturation constraints and Synchronization with saturation and sampling' respectively. Finally, simulation results are presented in Section 'Synchronization of isolated microgrids'.

Preliminaries

We give here some necessary definitions adapted from [17] to follow the mathematical notation in this work.

Communication topology

Let $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ represents an undirected graph, where $\mathcal{V} = \{1, 2, \ldots, N\}$ is the set of nodes or vertices, and $\mathcal{E} = \{(i,j) \mid i,j \in \mathcal{V}\}$ is the set of pairs called edges. If a pair $(i,j) \in \mathcal{E}$, then i, j are said to be adjacent. The adjacency matrix $A_{\mathcal{G}} = [a_{ij}]$ is the symmetric matrix $N \times N$, where $a_{ij} = 1$ if (i,j) are adjacent, $a_{ij} = 0$ otherwise, and $a_{ii} = 0$ for all $i \in \mathcal{V}$. For the ith node, the set of neighbors is $\mathcal{N}_i = \{j \mid (i,j) \in \mathcal{E}\}$, and the degree of a vertex d_i is the number of neighbors that are adjacent to i, i.e., $d_i = \sum_{j=1}^{N} a_{ij}$ or $|\mathcal{N}_i|$. A sequence of edges $(i_1, i_2), (i_2, i_3), \ldots, (i_{r-1}, i_r)$ is called a path from node i_1 to node i_r. The graph $\mathcal{G}$ is said to be connected if for any i, $j \in \mathcal{V}$ there is a path from i to j. The degree matrix is $\mathcal{D} = \text{diag}\ (d_1, d_2, \ldots, d_N)$, and the Laplacian of $\mathcal{G}$ is defined as $\mathcal{L} = \mathcal{D} - A_{\mathcal{G}}$, which has the row sum property. A vector $\mathbf{1}_N$ is of the form $[1, \ldots, 1]$ of size N. A block diagonal matrix R of N blocks is constructed as blkdiag $\{R_1, \ldots, R_n\}$, and a diagonal matrix T with N scalars in its diagonal is $T = \text{diag}\ \{T_1, \ldots, T_N\}$.

Kronecker product

The Kronecker product, denoted by $\otimes$, is an operation of two matrices of arbitrarily size resulting in a block matrix, and it facilitates the manipulation of matrices [18]. Let us consider two matrices $E \in \mathbb{R}^{n \times m}$ and $F \in \mathbb{R}^{p \times q}$. The Kronecker product is an $np \times mq$ block matrix

$$E \otimes F = \begin{bmatrix} e_{11}F & \ldots & e_{1m}F \\ \vdots & \ddots & \\ e_{n1}F & \cdots & e_{nm}F \end{bmatrix}$$

which possesses some important properties: (i) $(E \otimes F)(Q \otimes R) = (EQ \otimes FR)$, (ii) $(E \otimes F)^{\top} = E^{\top} \otimes F^{\top}$, and (iii) $I_N \otimes E = \text{diag}\ (E, E, \ldots, E)$, where I_N is the identity matrix of size $N \times N$.

Problem formulation

Microgrids are a fundamental part of the future power networks, which have the capability to produce and store energy using distributed generation and energy storage systems. A power network may be formed by several microgrids that may interact between them. Then, a microgrid sends/receives information to/from other microgrids in order to take smart decisions through a communication infrastructure. In this context, we address the problem of synchronization of several isolated microgrids using linear time-invariant models and the inclusion of energy storage systems. Next, the microgrid model, the ESS, and the communication infrastructure for smart grids are briefly introduced.

Synchronous generators

Smart grids can be defined as the interaction of several microgrids with a high amount of communication and control devices. Microgrids are composed by different elements, such as synchronous generators, renewable resources with storage capabilities, and loads, where each generator can be synchronous (e.g., hydro turbine, diesel generator) and connected to a time-varying load. Microgrids can connect or disconnect between them (or to the utility network) at any time, depending on the needs of the network,