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Brief paper

Sliding mode observers for a network of thermal and hydroelectric power plants ☆

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ABSTRACT

This paper deals with the design of a novel sliding mode observer-based scheme to estimate and reconstruct the unmeasured state variables in power networks including hydroelectric power plants and thermal power plants. The proposed approach reveals to be flexible to topological changes to power networks and can be easily updated only where changes occur. The discussed numerical simulations validate the effectiveness of the proposed estimation scheme.

1. Introduction

Nowadays, the design and validation of advanced and robust schemes to monitor and control power networks represent an important field of research (Bevrani, 2009). The installed capacity of distributed renewable power plants increases worldwide. The resulting growing intermittent power generation of this kind of plants can destabilize an entire power network (Gautam, Vittal, & Harbour, 2009). In order to solve this issue, on one side, advanced strategies have been designed to monitor and control distributed renewable power plants in a more intelligent and smarter way (Fang, Misra, Xue, & Yang, 2012). On the other side, big attention has been paid to conceive more robust and efficient control methods for conventional power plants (such as thermal, nuclear and hydroelectric power plants), dealing also with the uncertainties caused by the increasing distributed generation. Having in mind the aforementioned issues, sliding mode control techniques have been proposed for the Load Frequency Control (LFC) in power networks. In Prasad, Purwar, and Kishor (2017), a sliding mode control technique dealing with matched and unmatched uncertainties has been employed for LFC purposes. In Trip, Cucuzzella, Ferrara, and De Persis (2017) and Trip, Cucuzzella, Persis, van der Schaft, and Ferrara (2018) passivity- and energy-based sliding mode control schemes have been proposed in order to regulate the frequency, and also minimize the generation costs or maintain the scheduled power flows, respectively. The use of estimation schemes, specifically the so-called state observers, can be seen as a way to enhance the monitoring and thus the control of a power network, in the sense that they represent an additional tool to check the validity of some measurements or to reconstruct the unmeasured states, especially when one deals with large-scale networks. Few relevant works have dealt with the design of sliding mode observers in power systems. For example, in Liu et al. (2017), an extended state observer (ESO) based second-order sliding-mode (SOSM) control has been designed for three-phase two-level grid-connected power converters. In Rinaldi, Menon, Edwards, and Ferrara (2017), a combination of original super-twisting-like sliding mode observers and algebraic observers have been proposed to robustly estimate the unmeasured state variables in power grids in a distributed fashion. In Rinaldi, Cucuzzella, and Ferrara (2017), a third order sliding mode observer-based approach has been designed for optimal load frequency control in power networks partitioned into control areas. In Mellucci, Menon, Edwards, and Ferrara (2017), a robust multi-variable super-twisting sliding mode observer has been employed to detect the position and to reconstruct the time evolution of load alterations in power networks.

The main contribution of the present paper is the design of a novel decentralized sliding mode observer-based estimation scheme with application to power networks comprising thermal

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power plants and hydroelectric power plants. In Mellucci et al. (2017), Rinaldi, Cucuzzella et al. (2017), Rinaldi, Menon et al. (2017), and Vrdoljak, Perić, and Petrović (2010), simplified mathematical models of the power networks have been used as a starting base to design the estimation schemes (neglecting both the hydrothermal turbine–governor dynamics and the nonlinearities in the synchronous generators dynamics). With respect to the aforementioned works, the mathematical model of the power network is significantly detailed in our approach. Specifically, the turbine+governor dynamics are considered for the two types of power plants (thermal and hydroelectric). Moreover, differently from Vrdoljak et al. (2010), in which Luenberger's state observers have been designed, in our paper sliding mode observers are proposed to robustly estimate all the unmeasured state variables for the turbine–governor dynamics, which can be considered as a perturbed linear system for both thermal and hydraulic plants. The recently proposed nonlinear swing equations (Monshizadeh, De Persis, Monshizadeh, & van der Schaft, 2016) are adopted to model the synchronous generators in a more realistic and accurate way in each plant. A sub-optimal sliding mode observer is designed to estimate the frequency deviation of each generator. All the observers for each plant require only local information and local measurements, so that the proposed estimation scheme results in being completely decentralized. In addition, the proposed solution is easily adaptable to topological changes affecting power network, such as the opening or the closing of power transmission line switches, or the plugging-in or -out of some plants. In such case, it is necessary only to re-tune the gains of the preexisting sub-optimal observers for the generators directly connected to the new neighboring plants, leaving the other observers gains untouched. These advantages are possible thanks to the robustness features of the adopted sliding mode approach. The observer-based scheme is also assessed in simulation to verify its effectiveness.

The rest of the present paper is structured as follows. In Section 2, the description of the hydro-thermal power network is recalled. In Section 3, the design procedure of the novel observer-based scheme is presented. In Section 4, the proposed observers are assessed in simulations, whilst in Section 5 the conclusions are reached. Table 1 shows the physical meanings and the measurement units of the states variables and the model parameters adopted in the present paper. In this paper, the following (standard) notation is adopted. For a given state variable x, $\hat{x}$ denotes the estimated value of x. For a given matrix or vector X, X^T denotes its transpose. Expression $\mathrm{sgn}(\cdot)$ denotes the signum function.

2. Power network description

2.1. Graph theory recalls

A power network can be interpreted as an undirected graph $\mathcal{G}(\mathcal{V},\mathcal{E})$ (Kundur, Balu, & Lauby, 1994). Specifically, $\mathcal{V}$ represents the set of nodes of the graph (which are n_t thermal power plants and n_h hydroelectric power plants), and it consists of two subsets, i.e., $\mathcal{V} = \mathcal{V}_t \cup \mathcal{V}_h$. The set $\mathcal{V}_t$ denotes all the n_t thermal power plants, whilst $\mathcal{V}_h$ denotes all the n_h hydroelectric power plants. The set of edges $\mathcal{E} = \{1,\ldots,k,\ldots,m\}$ comprises all the power transmission lines linking the plants. Each kth edge is denoted as $k \triangleq \left[(i,j);\ X_{ij}\right]$, where (i,j) is the unordered pair of the distinct nodes linked by the kth power transmission line, and X_{ij} is the reactance of the kth power transmission line. The topology of the graph can be encapsulated in the Laplacian Matrix $\mathcal{X} \in \mathbb{R}^{N\times N}$, where $N = n_t + n_h$, and its elements are defined as follows (Kundur et al., 1994)

$$\mathcal{X} = \begin{cases} \mathcal{X}_{ii} = \sum_{j\in\mathcal{N}_i} X_{ij} & \\ \mathcal{X}_{ij} = -X_{ij} & \text{if } \exists\, k = \left[(i,j);\ X_{ij}\right] \in \mathcal{E} \\ \mathcal{X}_{ij} = 0 & \text{otherwise,} \end{cases} \tag{1}$$

Table 1
State variables and model parameters adopted in the paper.

Symbols	Meanings	Units
$P_{m_{a_i}}$, $P_{m_{b_i}}$, $P_{m_{c_i}}$	a, b, c turbines powers	(p.u.)
P_{g_i}	Governor power	(p.u.)
P_{m_i}	Total mechanical power	(p.u.)
P_{d_i}	Electrical power demand	(p.u.)
u_i	Control input	(p.u.)
$T_{a_i} \in [0.1,\ 0.4]$	a-turbine time constant	(s)
$T_{b_i} \in [4,\ 11]$	b-turbine time constant	(s)
$T_{c_i} \in [0.3,\ 0.5]$	c-turbine time constant	(s)
$T_{g_i} \in [0.2,\ 0.3]$	Governor time constant	(s)
α_i, β_i, γ_i	Power conversion constants	–
P_{c_i}	Transient compensator power	(p.u.)
W_i	Water speed	(p.u.)
$T_{c_{1_i}} \approx 5$	Compensator time constant 1	(s)
$T_{c_{2_i}} \approx 50$	Compensator time constant 2	(s)
$T_{h_i} \in [1,\ 2]$	Hydro turbine time constant	(s)
δ_i	Generator angle	(rad)
ω_i	Generator frequency deviation	(rad/s)
ω^*	Network nominal frequency	(rad/s)
J_i	Generator inertia	(kg m^2)
D_i	Generator damping	(N m s)
V_i	Voltage magnitude	(p.u.)
X_{ij}	Reactance of the line	(p.u.)

where $\mathcal{N}_i$ is the set of nodes directly connected to the ith node via power transmission lines.

Remark 1. From the point of view of the power network operations, it is reasonable to suppose that the use of power transmission lines changes with respect to time due to scheduled electricity trade among the plants. Therefore, the set of edges $\mathcal{E}$ represents all the possible interconnections among the plants in the most conservative situation, which means that all the available power transmission lines are used. Consequently, also the Laplacian Matrix in (1) encapsulates the power grid topology in the most conservative situation, as well as the set $\mathcal{N}_i$ for each node.

2.2. Steam turbines and governor dynamics

The so-called single tandem reheat arrangement is adopted in the present work. This comprises three steam turbines, denoted as a_i, b_i, and c_i, which are attached to the same shaft, and it represents the most common configuration used for large thermal power plants (Machowski, Bialek, & Bumby, 2011). The following dynamics yield:

$$\begin{aligned} \dot{P}_{m_{a_i}} &= -\frac{1}{T_{a_i}}P_{m_{a_i}} + \frac{1}{T_{a_i}}P_{g_i} \\ \dot{P}_{m_{b_i}} &= -\frac{1}{T_{b_i}}P_{m_{b_i}} + \frac{1}{T_{b_i}}P_{m_{a_i}} \\ \dot{P}_{m_{c_i}} &= -\frac{1}{T_{c_i}}P_{m_{c_i}} + \frac{1}{T_{c_i}}P_{m_{b_i}} \\ \dot{P}_{g_i} &= -\frac{1}{T_{g_i}}P_{g_i} + \frac{1}{T_{g_i}}u_i - \frac{1}{R_iT_{g_i}}\omega_i \\ y_{t_{i_1}} &= \alpha_iP_{m_{a_i}} + \beta_iP_{m_{b_i}} + \gamma_iP_{m_{c_i}} = P_{m_i}. \end{aligned} \tag{2}$$

The reader can refer to Table 1 for the physical meanings and the measurement units of the introduced state variables and model parameters. Typical values for the constants are $\alpha_i = 0.3$, $\beta_i = 0.4$, $\gamma_i = 0.3$, and the fundamental relation $\alpha_i + \beta_i + \gamma_i = 1$ holds (Machowski et al., 2011). It is possible to compactly rewrite