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# Modeling and distributed gain scheduling strategy for load frequency control in smart grids with communication topology changes

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ABSTRACT

In this paper, we investigate the modeling and distributed control problems for the load frequency control (LFC) in a smart grid. In contrast with existing works, we consider more practical and real scenarios, where the communication topology of the smart grid changes because of either link failures or packet losses. These topology changes are modeled as a time-varying communication topology matrix. By using this matrix, a new closed-loop power system model is proposed to integrate the communication topology changes into the dynamics of a physical power system. The globally asymptotical stability of this closed-loop power system is analyzed. A distributed gain scheduling LFC strategy is proposed to compensate for the potential degradation of dynamic performance (mean square errors of state vectors) of the power system under communication topology changes. In comparison to conventional centralized control approaches, the proposed method can improve the robustness of the smart grid to the variation of the communication network as well as to reduce computation load. Simulation results show that the proposed distributed gain scheduling approach is capable to improve the robustness of the smart grid to communication topology changes.

## 1. Introduction

Nowadays, traditional power systems are experiencing rapid changes, such as the deregulation of the power industry and the integration of renewable energy resources. These changes make the monitoring and operation of power systems among large-scale interconnected areas much more challenging than ever before. Several large blackouts have happened because of the lack of system-level situation awarenesses in the past few decades, such as the well-known 2003 North American and European blackouts [1]. It is thus a quite urgent demand for new and effective solutions to the monitoring and operation of large-scale power systems. Upgrading traditional power systems into smart grids is increasingly recognized as one of the most promising solutions. According to the definition given by the U.S. Department of Energy (DOE)'s Office of Electricity Delivery and Energy Reliability, a smart grid integrates advanced two-way communication network technology and intelligent computer processing technology into the current power systems, from large-scale generation through delivery systems to electricity consumers [2]. The primary characteristics of smart grids include the ability for self-healing, self-organizing and robustness to both physical elements and communication links failures etc. [3,4].

To improve the monitoring/operation and the robustness of a smart grid to random faults, it is well agreed that distributed control approaches (shown in Fig. 2) work better than their centralized counterparts (see Fig. 1) [5–7]. For distributed control strategies, the entire power system can be divided into multiple interconnected areas [8–10] or micro-grids with distributed generations (DGs) [5,11,12]. Each area is a subsystem with its own control center. Two-way communications of sensing measurements and control inputs are needed within each area and among different areas. To support the vast amount of information exchange in a real-time power system, high-speed open communication infrastructures are urgently required to be implemented in large-scale power systems [13,14]. In [9], GridStat, a prototype of a new communication framework, is proposed for delivering real-time information and operational commands. For a substation automation, Local Area Networks (LANs) are introduced for the communication among Intelligent Electronic Devices (IEDs) within substations under the communication standard IEC 61850, while Wide Area Networks (WANs) are used for data exchange among substations [15–17].

Although high speed open communication infrastructures are critical for distributed control schemes and for meeting the need of vast amount of information exchange in smart grids, they make it challenging to ensure the reliability and stability of smart grids.

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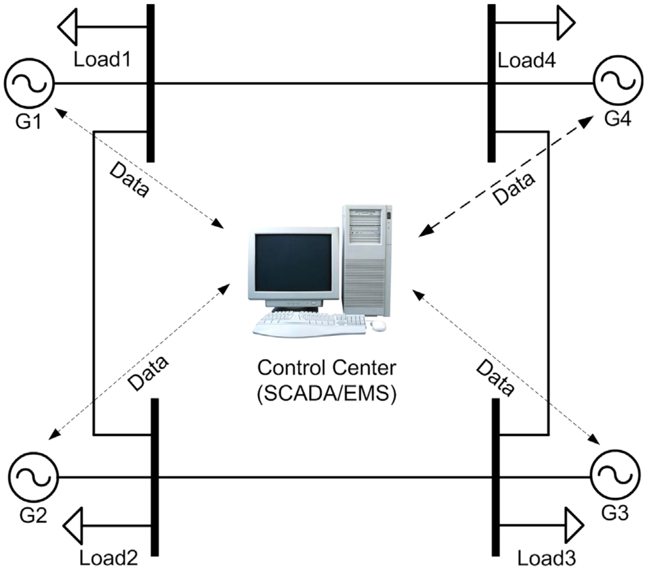

**Fig. 1.** Centralized control scheme.

It is well-known that communication networks, especially wireless networks, are unreliable because of time delays, packet losses and random communication failures. Among these unreliable communication factors, both packet losses and communication failures can be treated as communication topology changes. If these factors are not properly considered in the control scheme of smart grids, the network-associated problems will degrade the dynamic performance of power systems and/or even make the entire power system unstable. For instance, a series of $M/M/1$ queuing models are used to calculate communication delays for measurement and control signals in a power system [18]. The authors point out that a wide-area monitoring system will experience a degraded response due to control signal latency for wide-area applications. In [10], communication infrastructures are investigated in IEEE 118-bus test network for both centralized and decentralized control strategies. It emphasizes that communication failures of a power grid may cause very serious problems for both system operation and control.

Control algorithms for power systems under the condition of communication time delays have been investigated intensively in these years, such as [19–22], however, the effects of communication topology changes on the distributed control of power systems are not well addressed. Recently, there are few results reported on this topic. In [23], joint controller and communication topology design is formulated as a mixed-integer optimization problem for the distributed damping control of power systems. In [24], a cooperative control approach is applied for the self-organization of distributed photovoltaic (PV) generators. For the wide-area control and monitoring of smart grids, it is very important that the distributed controllers are robust to communication topology changes which can be caused by either packet losses or communication failures.

In this paper, we propose a new distributed control method for the load frequency control (LFC) of a smart grid. Instead of assuming that communication links are free of faults, we consider practical cases where there exist communication link failures and packet losses. As their impacts on the communication topology of the smart grid are considered, both packet losses and communication failures are modeled as communication topology changes [25,26]. A time-varying communication topology matrix is defined and used to model the communication topology changes of the smart grid. A new closed-loop power system model is built to integrate the communication topology changes into the physical dynamics of the smart grid. A distributed gain scheduling LFC strategy is proposed to compensate for the degraded performance due to the communication topology changes. Simulation results of a four-area power system show that the proposed distributed gain scheduling approach can improve the robustness of the smart grid to communication topology changes caused either by link failures or packet losses.

The remainder of this paper is organized as follows. In Section 2, a new power system model is proposed to integrate the changes of communication topology into the physical dynamics. In Section 3, the stability analysis of this new power system is conducted. The distributed gain scheduling algorithm is described in Section 4. In Section 5, simulations are conducted by using a four-area power system model under six communication topologies. Finally, Section 6 concludes the paper with some remarks.

*Notation*: $\mathbb{R}^n$, $\mathbb{R}^m$ denotes the $n$-dimensional and $m$-dimensional Euclidean space, respectively. The superscript ’$T$ denotes the transposition of vectors or matrix. Notation $P>0$ means positive definite.

## 2. Modeling of the multi-area interconnected power system with communication topology changes

The operation of frequency control is fundamental in determining the way in which the frequency will change when load changes happen [27–29]. In this paper, we mainly consider load frequency control (LFC), sometimes also called automatic generation control (AGC), for multi-area interconnected power systems.

For LFC studies, each area is represented equivalently by one single machine. For area i, the dynamics are described by [30]

$$\Delta\dot{f}_i = -\frac{D_i}{M_i}\Delta f_i + \frac{1}{M_i}\Delta P_{m_i} - \frac{1}{M_i}\Delta P_{tie}^{ij} - \frac{1}{M_i}\Delta P_{L_i}$$

$$\Delta\dot{P}_{m_i} = -\frac{1}{T_{ch_i}}\Delta P_{m_i} + \frac{1}{T_{ch_i}}\Delta P_{v_i}$$

$$\Delta\dot{P}_{v_i} = -\frac{1}{R_iT_{g_i}}\Delta f_i - \frac{1}{T_{g_i}}\Delta P_{v_i} + \frac{1}{T_{g_i}}\Delta P_{c_i}$$

$$\Delta\dot{P}_{tie}^{ij} = \sum_{j=1,j\neq i}^{N} T_{ij}(\Delta f_i - \Delta f_j) \tag{1}$$

where $\Delta f_i$ – frequency deviation; $\Delta P_{m_i}$ – generator mechanical power deviation; $\Delta P_{v_i}$ – turbine valve position deviation; $\Delta P_{c_i}$ – load reference set-point; $\Delta P_{tie}^{ij}$ – tie-line power flow between area $i$ and $j$; $\Delta P_{L_i}$ – load deviation; $M_i$ – moment of inertia of generator $i$; $D_i$ – damping coefficient of generator $i$; $T_{g_i}$ – time constant of governor i; $T_{ch_i}$ – time constant of turbine $i$; $T_{ij}$ – synchronizing power coefficient; $R_i$ – speed droop coefficient.

Furthermore, we assume that there are $N$ interconnected areas in the power system. We write the state space model of the above dynamics for LFC in area $i$ as follows:

$$\dot{x}_i = A_ix_i + B_iu_i + \sum_{j=1,\ j\neq i}^{N} A_{ij}x_j + F_i\Delta P_{L_i}, \quad i\in\{1,2,\ldots,N\} \tag{2}$$

where

$$x_i = [\Delta f_i \ \ \Delta P_{m_i} \ \ \Delta P_{v_i} \ \ \Delta P_{tie}^{ij}]^T;$$

$$u_i = \Delta P_{c_i};$$