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Research Article

Stability analysis and compensation of network-induced delays in communication-based power system control: A survey[☆]

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ABSTRACT

This survey is to summarize and compare existing and recently emerging approaches for the analysis and compensation of the effects of network-induced delays on the stability and performance of communication-based power control systems. Several important communication-based power control systems are briefly introduced. The deterministic and stochastic methodologies of analyzing the impacts of network-induced delays on the stability of the communication-based power control systems are summarized and compared. A variety of control approaches are reviewed and compared for mitigating the effects of network-induced delays, depending on several design requirements, such as model dependence and design difficulty. The summary and comparison of these control approaches in this survey provide researchers and utilities valuable guidance for designing advanced communication-based power control systems in the future.

1. Introduction

Most of power systems around the world have been in existence for many decades since they were developed. With the rapid development of industries and the living conditions of human beings, the need for energy has grown tremendously and the operational scenarios are quite different from which they were. Nowadays, traditional power systems are facing several unique challenges [1,2]. For instance, one of the challenges is the deregulation of the power industry, which divides the utility company monopolies by separating the production of energy from its distribution. This results in large uncertainties of power flow scenarios in the power industry. Another challenge is the rapid increasing penetration of renewable energy sources (RESs), such as wind and solar energy, to achieve sustainable growth and minimize environmental impacts. The large-scale integration of RESs could make the power generation in power systems more unpredictable, due to the variance of the power output from RESs. These challenges together make the management and control of power systems much more difficult than ever before.

Apparently, the traditional power systems are infeasible to handle these challenges. This can be seen from several large blackouts which happened recently, such as the 2003 North American and 2003 European blackouts [3]. There is thus a quite urgent demand for new and effective solutions to the monitoring and operation of large-scale power systems. Upgrading the traditional power systems into smart grids is increasingly recognized by industry and many national governments as the answer to address these challenges. 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 [4].

To facilitate the management and control of power systems and enhance the capability of situation awareness, a three-layer hierarchical smart grid communication architecture is agreed by researchers [5]. The three-layer communication architecture includes wide area network (WAN), neighborhood area network (NAN) and home area network (HAN). The details of each layer are introduced as follows.

- *Wide area network* (*WAN*): the upper layer of the three-layer communication architecture is WAN. It provides communication networks for upstream utility assets such as power plants,

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distributed generation sources, distributed storage units, substations and so on. The communication standards that can be used for WAN include fiber optics, WiMAX, power line communication (PLC), satellite communication and cellular communications.

- *Neighbor area network* (*NAN*): the middle layer of the three-layer communication architecture is NAN. It supplies communication networks for smart meters, field components, and gateways that form the backbone of the network between distribution system substations and HANs. The smart grid standards for NAN include WiMax, PLC, and Ethernet.
- *Home area network* (*HAN*): the lower layer of the smart grid communication architecture is HAN. It creates communications among home appliances including sensors, monitors, loads, etc.. The candidates of networking standards for HAN include ZigBee, WiFi, HomePlug, etc.

While the communication infrastructure supports the exchange of the vast amount of data over wide geographical areas, it brings new threats to the reliability and stability of power system control and management. As there inevitably exists unreliable factors in communication networks, such as time delays and packet losses, these factors will in turn affect the stability and dynamic performance of the communication-based power control systems if these unreliable factors are not well taken care of. Therefore, it deserves significant research efforts to analyze and mitigate the effects of unreliable factors in communication networks on the stability and performance of power control systems.

As one of the most important unreliable factors, the impact of network-induced delay on communication-based power control systems has attracted great investigation interests in the literature. In this paper, the existing and recently emerging communication-based power control systems are introduced. Also, a variety of methodologies for analyzing and compensating the effects of network-induced delays on the stability of these communication-based power control systems are reviewed and compared, based on several design criteria, such as design difficulty and levels of robustness. This survey is able to provide valuable guidance for designing advanced communication-based power control systems in future.

The reminder of this paper is organized as follows. In Section 2, several important communication-based power control systems are introduced. In Section 3, the methods of analyzing the effects of network-induced delays are summarized and compared. In Section 4, the approaches of mitigating the effects of network-induced delays on the stability and dynamics of communication-based power control systems are reviewed. In Section 5, challenges in the stability and control of the smart grid are summarized. Finally, in Section 6, conclusions are made for this paper.

2. Communication-based power system control

In this section, a variety of important communication-based power control systems for both large-scale power systems and microgrids are briefly introduced.

2.1. Wide area damping control

Low frequency electromechanical oscillation (LFEO) is inherently involved in the study of small-disturbance (small-signal) rotor angle stability [6]. There are mainly two types of LFEOs involved in power systems. One associated with a single generator or more generators within one area is called local mode oscillation, while the other related to a group of generators among different areas is called inter-area oscillation. If these oscillations are not sufficiently damped, synchronism among generators is lost and instability is thus caused. Inter-area oscillations also limit the amount of power transfer on the tie-lines between the areas containing coherent generator groups.

Usually, oscillation damping can be enhanced with local control (using local feedback signals such as generator speed deviations) or wide-area control (using global feedback signals obtained from synchrophasors). The control with local signals is convenient to employ but is not preferable for damping inter-area oscillations due to its low ability to observe inter-area oscillation modes. Consequently, wide-area-measurement-system (WAMS)-based wide area damping control (WADC) has gained popularity in suppression of inter-area oscillations.

The structure of WADC applied in power systems is shown in Fig. 1. As one of most important elements in WADC, a phasor measurement unit (PMU) is used to separate the fundamental frequency component and find its phasor representation [7]. PMUs are simultaneous measurements of phasors across a wide area of the power systems. These PMUs are synchronized from a common time source provided by a global positioning system (GPS) radio clock. Built on MUs and modern communication technology, a wide-area measurement system (WAMS) is an integrated application system that offers real-time control and operation service to power systems. A WAMS consists of master server, substation and digital communication network that connecting them, shown in Fig. 2. It was funded in 1995 by the U.S. Department of Energy to develop advanced tools for wide-area measurement, control, and operation in the Western North American power system (WECC). Because the WAMS is able to provide accurately both individual and sequential voltage and current phasors, it has been used in lots of power system applications, such as post event monitoring [3], power system state estimation [8], power system protection [9], and power system control [10].

In the WADC structure, PMU acts as the sensor to measure the power system variables needed for the WADC controller. After receiving control commands from WADC controller, power system stabilizer (PSS), high-voltage direct current (HVDC) system, and flexible alternate current transmission system (FACTS) can act as the actuator to dampen the power system oscillations through the controlled plant (power system). The sensor and actuator communicate with the WADC controller through communication networks.

2.2. Load frequency control

The frequency and power generation control in a power system is usually referred to load frequency control (LFC). It mainly keeps the frequency of the power system at a nominal value (i.e. 60 Hz) by adjusting power generation set point. The LFC is the major function of automatic generation control (AGC) systems in largely inter-connected power grids. It is also fundamental in determining the way in which the frequency will change when load changes happen. For load frequency control, power systems are usually decomposed into areas [12]. For an example, a four-area power system is shown in Fig. 3. In this power system, each area is interconnected with its neighbor areas through tie-lines. Each area

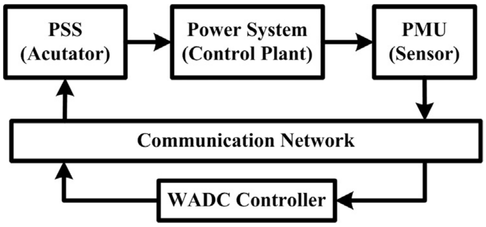

Fig. 1. Structure of wide area damping control.

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