POWER SYSTEM MONITORING AND CONTROL

Hassan Bevrani • Masayuki Watanabe • Yasunori Mitani

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Hassan Bevrani
University of Kurdistan, Iran
Kyushu Institute of Technology (Visiting Professor), Japan

Masayuki Watanabe
Kyushu Institute of Technology, Japan

Yasunori Mitani
Kyushu Institute of Technology, Japan

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CONTENTS

PREFACE

Power system monitoring and control (PSMC) is an important issue in modern electric power system design and operation. It is becoming more significant today due to the increasing size, changing structure, introduction of renewable energy sources, distributed smart/microgrids, environmental constraints, and complexity of power systems.

The wide-area measurement system (WAMS) with phasor measurement units (PMUs) provides key technologies for monitoring, state estimation, system protection, and control of widely spread power systems. A direct, more precise, and accurate monitoring can be achieved by the technique of phasor measurements and global positioning system (GPS) time signal. A proper grasp of the present state with flexible wide-area control and smart operation addresses significant elements to maintain wide-area stability in the complicated grid, with the growing penetration of distributed generation and renewable energy sources.

In response to the existing challenge of integrating advanced metering, computation, communication, and control into appropriate levels of PSMC, this book provides a comprehensive coverage of PSMC understanding, analysis, and realization. The physical constraints and engineering aspects of the PSMC have been fully considered, and developed PSMC strategies are explained using recorded real data from practical WAMS via distributed PMUs and GPS receivers in Japan and Southeast Asia (Singapore, Malaysia, and Thailand). In addition to the power system monitoring, protection, and control, the application of WAMS in emergency control schemes, as well as the control of distributed microgrids, is also emphasized.

This book will be useful for engineers and operators in power system planning and operation, as well as for academic researchers. It describes both monitoring and control issues in power systems, from introductory to advanced steps. This book can also be useful as a supplementary text for university students in electrical engineering at both undergraduate and postgraduate levels in standard courses of Power System Dynamics, Power System Analysis, and Power System Stability and Control. This book is organized into 10 chapters.

Chapter 1 introduces power system monitoring and control, especially with wide-area phasor measurement applying PMUs. Some applications of WAMS globally, as well as information and communication technology (ICT) architecture used in the phasor measurement system are outlined as an introduction.

Chapter 2 describes the oscillatory dynamics in the wide-area power system by using acquired monitoring data with phasor measurement units. Particularly, interarea low-frequency oscillations in Japan and Southeast Asia power systems have been investigated by adopting band-pass filtering based on the fast Fourier transform (FFT) technique. Since both systems have the longitudinal configuration, the low-frequency mode oscillates in the opposite phase between both ends of the power network. The oscillatory dynamics can be captured successfully by wide-area phasor measurements.

Chapter 3 emphasizes the small-signal stability assessment with phasor measurements. Particularly, the stability of the interarea low-frequency oscillation mode has been investigated by adopting the method to identify the oscillation dynamics with a simple oscillation model. The filtering approach improves the accuracy of the estimated eigenvalues. The stability can be evaluated successfully by the presented approach.

Chapter 4 introduces graphical tools for power system stability and security assessment, such as angle–voltage deviation, voltage–frequency deviation, frequency–angle deviation, and electromechanical wave propagation graphs. The necessity of using the graphical tools rather than pure analytical and mathematical approaches in wide-area power system stability and security issues is explained. Applications for designing of wide-area controllers/coordinators as well as emergency control plans are discussed.

Chapter 5 introduces the general aspects of power system stability and control. Fundamental concepts and definitions of angle, voltage, frequency stability, and existing controls are emphasized. The timescales and characteristics of various power system controls are described. The supervisory control and data acquisition (SCADA) and energy management system (EMS) architectures in modern power grids are explained. Finally, various challenges and new research directions are presented.

Chapter 6 describes a method for tuning power system stabilizers (PSSs) based on wide-area phasor measurements. The low-order system model, which holds the characteristics of the interarea oscillation mode and control unit, is identified by monitoring data from wide area phasor measurements. The effectiveness of the proposed method has been demonstrated through the power system simulation. The results show that the appropriate controller can be designed by using the identified low-order model.

Chapter 7 addresses two control strategies to achieve stability and voltage regulation, simultaneously. The first control strategy is developed using the H_∞ static output feedback control technique via an iterative linear matrix inequalities algorithm. The proposed method was applied to a four-machine infinite bus power system through a laboratory real-time experiment, and the results are compared with a conventional automatic voltage regulator–PSS design. The second control strategy uses a criterion in the normalized phase difference versus voltage deviation plane. Based on the introduced criterion, an adaptive angle-based switching strategy and negative feedback are combined to obtain a robust control methodology against load/generation disturbances.

Chapter 8 emphasizes the necessity of using both voltage and frequency data, specifically in the presence of high wind power penetration, to develop an effective load shedding scheme. First, it is shown that the voltage and frequency responses may behave in opposite directions, following contingencies, and concerning this issue, a new load shedding scheme is proposed. Then, an overview on the electromechanical waves in power systems is presented, and the amplification of a propagated wave due to reflections or in combination with waves initiated from other disturbances is studied. Finally, based on a given descriptive study of electrical measurements and electromechanical wave propagation in large electric power systems, an emergency control scheme is introduced to detect the possible plans.

Chapter 9 proposes a comprehensive review on various microgrid control loops, and relevant standards are given with a discussion on the challenges of microgrid controls. In addition to the main MG concepts, the required control loops in the microgrids are classified into primary control, secondary control, global control, and central/emergency control levels.

Chapter 10 addresses several synthesis methodology examples based on robust, intelligent, and optimal/adaptive control strategies for controller design in the microgrids. These examples cover all control levels; that is, primary, secondary, global, and central/emergency controls.

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Most of the contributions, outcomes, and insight presented in this book were achieved through long-term teaching and research conducted by the authors and their research groups on power system monitoring and control issues over the years. Since 2000, the authors have intensively worked on various projects in the area of power system monitoring, dynamic stability analysis, and advanced control issues.

Some previous research and project topics are power system stabilization using superconducting magnetic energy storage (Osaka University, Japan); Campus WAMS project (for the sake of monitoring of power system dynamics, stability, and power flow status using installed PMUs in several university campuses in Japan, Thailand, Malaysia, and Singapore); high-tech green campus project (Kyushu Institute of Technology and Kyushu Electric Co., Japan); intelligent/robust automatic generation control (Frontier Technology for Electrical Energy, Japan and West Regional Electric Co., Iran); power system emergency control (Queensland University of Technology, and Australian Research Council, Australia); and sophisticated smart grid controls (Kyushu Institute of Technology, Japan; and University of Kurdistan, Iran). It is a pleasure to acknowledge the support and awards the authors received from all the mentioned sources.

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1

AN INTRODUCTION ON POWER SYSTEM MONITORING

The power system is a huge system as a result of interconnections between each service area to improve reliability and economic efficiency. The social system has been mainly developed based on electrical energy for a better life and economic growth. On the other hand, the power system is exposed to the natural environment at all times; thus, the system has some small or large disturbances, for example, by lightning, storm, and apparatus faults. Under these conditions, the system should maintain stable operation to avoid blackouts in the whole system using appropriate protection and control schemes. However, in a large-scale interconnected system, there are some difficulties in evaluating and maintaining the stability of the whole system.

Recently, a new issue in power systems has come out, which is the penetration of renewable energy sources, bringing more uncertainty that requires more severe operation. For energy security, the introduction of renewable energy sources is indispensable; therefore, to maintain system reliability and make efficient use of sustainable energy, power system monitoring should be a key technology to achieve flexible operation in the system.

On the other hand, in recent years, the development of information and communication technology (ICT) has enabled more flexibility in wide-area monitoring of power systems with fast and large data transmission. Especially, the wide-area measurement

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system (WAMS) with phasor measurement units (PMUs) is a promising technique as one of the smart grid technologies in the trunk power grid. In this chapter, basic concepts around power system monitoring are emphasized.

1.1 SYNCHRONIZED PHASOR MEASUREMENT

To monitor the power system, many measuring instruments and apparatuses are installed. Typically, the active power, reactive power, node voltage, and frequency must be monitored at all times. So far, the supervisory control and data acquisition (SCADA) system is a widely adopted monitoring system. On the other hand, the phase angle is also known as an important quantity that should be monitored for state estimation. If the phase angle can be measured, more flexible and precise monitoring could be expected.

The most important reason to measure the voltage phasor is to determine the phase reference of the measured sinusoidal voltage at all measuring points. This can be achieved by time synchronization. However, synchronized measurement is impossible by using the independent timers at the measurement points since at least 0.1 ms accuracy is required to measure the accurate phasor. On the other hand, since the global positioning system (GPS) has been opened for private use, it becomes easy to determine the precise time at a point on the globe; thus, the synchronized phasor measurement became a feasible technique.

The concept of synchronized phasor measurement was reported in the early 1980s [1]. In the literature, the method for time synchronization by GPS to calculate the phasor with high speed from the measured voltage has not been reported. In December 1993, the GPS system officially started its operation. The concept of synchronized phasor measurement using the GPS system was contributed to the *IEEE Computer Applications in Power* by Phadke [2]. Later, some advanced applications adopting phasor measurements, state estimation, instability monitoring, adaptive relay, controller tuning, and so on, were introduced. In 1998, the IEEE Standard for Synchrophasors for Power Systems was issued [3]. The synchronized phasor measurement system has been applied to the trunk power grid since the middle of the 1990s, especially in Europe and the United States. The synchronized phasor measurement can be considered as a powerful means for monitoring wide-area power systems. Some cases of worldwide blackouts have been fully monitored by the developed measurement systems [4–6].

1.2 POWER SYSTEM MONITORING AND CONTROL WITH WIDE-AREA MEASUREMENTS

Recently, some reports have been issued by the International Council on Large Electric Systems (CIGRE) on “power system security assessment” (CIGRE WG C4.601). A technical report dealing with power system monitoring on the “wide area monitoring and control for transmission capability enhancement” was also issued in 2007 [7].

In Switzerland, PMUs are installed at four substations to monitor the operating state since the system has a heavy load to the Italy system. System stability is monitored by using PMUs installed at other countries. On the other hand, in Italy, the PMUs are installed at 30 sites since the system experienced a large blackout in September 28, 2003.

There are some PMU projects at Hydro Kebec in Canada, Western Electricity Coordinating Council in the United States, and the eastern interconnected system. Virginia Tech has a project on synchronized frequency monitoring called the Frequency Monitoring Network with original measurement units.

In China, a project was started at the initiative of Tsinghua University in 1996. In the beginning, there were some issues on the communication speed and accuracy; however, the installation of PMUs has been supported since 2002. The PMUs were installed at about 88 sites by 10 new projects between 2002 and 2005. The system with functions of a graphical user interface, database, replay capability, and so on has been developed in order to monitor wide-area power system dynamics. The installation of several hundreds of PMUs has been reported at the IEEE General Meeting in 2007 [8]. The PMU is a prospective technology for the analysis of whole power system dynamics with huge networks.

In Sweden, wide-area stability is monitored by the PMUs installed at universities/institutes. Both 400 V and 400 kV nodes are measured to investigate the similarities. The monitoring network extends across three countries in Northern Europe. The interface for cooperative wide-area monitoring by sharing webpage-based online monitoring has been developed.

In Denmark, a large amount of wind generation has been accomplished, and almost all conventional generation is of the cogeneration type. The voltage and phasor of the eastern 400 and 132 kV systems are monitored to grasp the operation status for research purposes by the cooperative work of Elkraft Power Co. and the Centre for Electric Technology at Technical University of Denmark.

In Austria, the system is interconnected with many neighboring countries. The generated power at the northeast and south areas is transmitted via 200 kV lines. A number of PMUs are installed at Wien and Ternitz to monitor the power flow and temperature of transmission lines.

In Thailand, the Electricity Generating Authority of Thailand has a power system, which extends north and south, interconnected with Laos and Malaysia; therefore, the power flow is constrained by power oscillations with poor damping. The PMUs are installed at Surat Thani and Bang Saphan to monitor the state of tie-line between the central and south areas.

In Australia, the system consists of a 30 GW network of 110 and 500 kV with a distance of 5000 km. There is an issue of oscillation stability at the interarea network between the east coast and south area. The measurement network called Power Dynamic Management has been developed by the cooperation of the National Electricity Market Management Company as an independent system operator and PowerLink as the transmission company.

In Hungary, monitoring units are installed at six sites as part of the monitoring network of the Union for the Coordination of the Transmission of Electricity interconnected system called Power Log, which can measure three-phase voltage and current.

The result of monitoring interarea oscillations is used for tuning of the installed power system stabilizers.

1.3 ICT ARCHITECTURE USED IN WIDE-AREA POWER SYSTEM MONITORING AND CONTROL

It should be a very important aspect to collect the data measured by each PMU for system monitoring, state estimation, protection, and control. The measured data could be locally saved and then collected for postanalysis, or sent to a remote location in real time for system protection or real-time control. Therefore, it should be useful to know the ICT architecture. This section briefly introduces the ICT architecture used in phasor measurement systems.

Figure 1.1 shows a typical schema for a wide-area phasor measurement system including the communication and application levels. The measured data are collected by phasor data concentrators (PDCs) via a communication network. The concentrated data could be exchanged between utilities by using the standard data format including the time stamp of the synchronized GPS time. The important function of a PDC is to receive, parse, and sort incoming data frames from the multiple PMUs.

The basic requirements for a PDC are simple; however, usually the actual implementation requires a heavy computer processing task and a wideband communication. Therefore, the number of measurement units will be limited by the hardware of a PDC unit being used to handle the data concentration.

In addition, the data transmission type and communication protocols should be considered. The standards of the phasor data transmission protocol are established in IEEE C37.118. This protocol allows data-receiving devices to start and stop data flow as well as request configuration information about the sending data. Measurement systems can self-configure by requesting scaling and signal names from sending devices. This includes a notification bit to alert downstream devices for any changes in configuration.

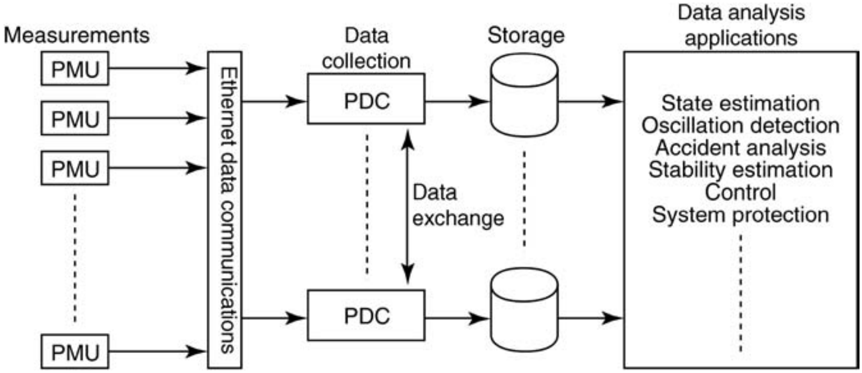

Figure 1.1. A schema of PMU/WAMS.

This protocol applies to sending data from the PMU as well as PDC devices, so it is scalable to the whole measurement system [9].

A wide variety of communication systems are used for the data collection. These include utility-owned communications, which can be a narrowband analog, digital, or wideband digital communication system. The public Internet with direct access or virtual private network technology, which is easy to implement, is now widely available. The most important aspects of choosing communications are availability, reliability, and bandwidth [9], especially for a real-time application, in which delay or interruption cannot be allowed. A narrowband communication channel could be enough to transfer data from a single measurement device. Data exchange between utilities requires a wideband communication channel since concentrated data by a PDC are accumulated data from many measurement devices.

Typical storage of data archiving for the phasor measurement system is in data files. The IEEE COMTRADE Standard (C37.110), which supports binary and floating point formats for time sequence phasor data, is widely used. The utilization of the standard file formats simplifies data exchange, analysis, and application development.

1.4 SUMMARY

This chapter introduces power system monitoring and control, especially with wide-area phasor measurement applying PMUs. Some global applications of WAMS and the ICT architecture used in the phasor measurement system have been outlined as an introduction.

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2

OSCILLATION DYNAMICS ANALYSIS BASED ON PHASOR MEASUREMENTS

Modern interconnected wide-area power systems around the world are faced with serious challenging issues in global monitoring, stability, and control mainly due to increasing size, changing structure, emerging new uncertainties, environmental issues, and rapid growth in distributed generation. Under this circumstance, any failure in the planning, operation, protection, and control in a part of the power system could evolve into the cause of cascading events that may even lead to a large area power blackout.

These challenging issues set new demand for the development of more flexible, rapid, effective, precise, and intelligent approaches for power system dynamics monitoring, stability/security analysis, and control problems. The advent and deployment of phasor measurement units (PMUs) provides a powerful tool to enable the measurement-based methodologies for building an online dynamic snapshot-model of power systems based on real measurements to solve the mentioned problems.

This chapter introduces basic concepts of power system oscillation dynamics using phasor measurements and presents some examples for real data monitoring and analysis. Interarea low-frequency oscillations are characteristic phenomena in the interconnected power systems [1–3]. These oscillations have poor damping characteristics in heavy loading conditions on tie-lines, mainly due to the power exchange and complex power contracts under a deregulated environment. Therefore, proper estimation of the present

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state with flexible wide-area operation and control should become key issues to keep the power system stability properly.

On the other hand, the real-time monitoring based on wide-area phasor measurements [4] attracts the attention of power system engineers for the state estimation, system protection, and control subjects [5–8]. This chapter presents a brief overview on the power system oscillation characteristics, and wide-area monitoring system (WAMS) using PMUs. To find a clear sense, the real power system in Japan and some Southeast Asian countries (Thailand, Malaysia, and Singapore) are considered as case studies. Some results for the electromechanical dynamics of real power systems are also investigated.

2.1 OSCILLATION CHARACTERISTICS IN POWER SYSTEMS

2.1.1 Eigenvalue Analysis and Participation Factor

The power swing equations of generators in an n-machine power system can be represented by [9]:

$$\begin{aligned} M_i\dot{\omega}_i &= -D_i(\omega_i - 1) + P_{\mathrm{m}i} - P_{\mathrm{e}i} \\ \dot{\delta}_i &= \omega_{\mathrm{r}}(\omega_i - 1) \end{aligned} \tag{2.1}$$

where $i = 1, 2, \ldots, n$; ω is the angular velocity; δ is the rotor angle; M is the inertia constant; D is the damping coefficient; P_{m} is the mechanical input to the generator; P_{e} is the electrical output; and ω_{r} is the rated angular velocity. When including the effect of other generators and controller dynamics, it is just assumed that their responses are sufficiently faster than the responses of dominant modes. Interarea oscillations are mainly caused by the swing dynamics with a large inertia represented by Equation (2.1). Now in this system suppose that a specific mode associated with power oscillation becomes unstable with variation of a parameter such as changing the loading condition. Here, consider a generator (e.g., number k) that significantly participates in the critical dominant oscillation mode. This generator can be easily selected by calculating the linear participation factor, which is defined in Reference [10].

The system dynamics is represented in general by the following equation:

$$\dot{x} = f(\mathbf{x}, p),\ \mathbf{x} \in \mathbf{R}^n,\ p \in \mathbf{R} \tag{2.2}$$

Linearizing (2.2) around an equilibrium point $\boldsymbol{x} = \boldsymbol{x}_1$ gives

$$\dot{x} = \mathbf{A}\mathbf{x}, \mathbf{A} \equiv D_x(\mathbf{x}_1, p_1) \tag{2.3}$$

The right eigenvector $\mathbf{u}_i$ and the left eigenvector $\mathbf{v}_i$ of the matrix $\mathbf{A}$ are defined as follows:

$$\begin{aligned} \mathbf{A}\mathbf{u}_i &= \mathbf{u}_i\lambda_i \\ \mathbf{v}_i^{\mathrm{T}}\mathbf{A} &= \lambda_i\mathbf{v}_i^{\mathrm{T}} \end{aligned} \tag{2.4}$$

where λ_i is the ith eigenvalue of the matrix $\mathbf{A}$. It is noteworthy that the eigenvectors should be normalized to satisfy the following condition:

$$v_i^{\mathrm{T}} u_j = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases} \tag{2.5}$$

The participation factor (p_{ki}) represents a suitable tool to measure the participation of the kth machine state in the trajectory of the ith mode. It can be defined as

$$p_{ki} = u_{ki} v_{ik} \tag{2.6}$$

Oscillation characteristics could be explained using the participation factor [10] and the mode shape [11], which provide critical information for operational control actions. As an example, the swing characteristics of the western Japan 60 Hz system have been evaluated by calculating eigenvalues of a simulation model [2]. So far, the estimation of the participation weights has been developed based on a WAMS [12].

2.1.2 Oscillation Characteristics in an Interconnected Power System

Here, an example of the oscillation dynamics in a longitudinally interconnected power system based on the eigenvalue analysis is described. Figure 2.1 shows the West Japan 10-machine system model [13,14] that is considered in this study. The model represents a standard model for the western Japan 60 Hz power system, which was developed by the technical committee of the Institute of Electrical Engineers of Japan (IEEJ), used for the verification of simulation studies. Table 2.1 shows the system constants. Each generator is equipped with an automatic voltage regulator (AVR), which is shown in Fig. 2.2.

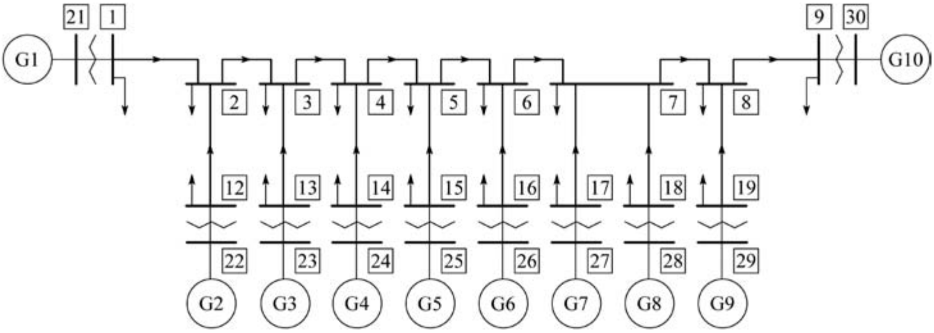

Figure 2.1. IEEJ WEST 10-machine system model.