A Gain Scheduling Approach to The Load Frequency Control in Smart Grids

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The undersigned recommend to
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Control in Smart Grids**

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in partial fulfilment of the requirements for the degree of
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Abstract

As an indispensable technology that enables smart grid operations, the two-way communication networking technology greatly facilitates the vast amount of information exchange involved in the operations. However, this technology also makes it challenging to ensure the reliability and stability of smart grids. It is well-known that communication networks, especially wireless networks, are unreliable because of communication delays and random communication failures. If these factors are not properly considered in the control scheme of a smart grid, they may degrade the dynamic performance of a power system and/or even make the entire power system unstable.

In this thesis, two important issues related to the effects of these unreliable network-associated factors on the load frequency control of smart grids are investigated. One of them is that how communication delays can affect the load frequency control of low-voltage microgrids. To study this issue, a thorough small-signal analysis is presented for an islanded microgrid. By conducting this analysis, the maximal communication delay below which the microgrid can maintain stable (usually defined as a delay margin) is determined and its relationships with secondary frequency control gains are identified. To improve the robustness of the microgrid to communication delays, a gain scheduling method is proposed for the load frequency control. Simulation results of the Canadian urban benchmark distribution system verify the correctness of the small-signal analysis results and the effectiveness of the proposed gain scheduling load frequency control. The other is that how communication failures can influence the load frequency control of high-voltage largely interconnected power grids. To investigate this issue, two particular scenarios that can result in communication failures are considered, including cognitive radio networks and denial of service attacks. By modeling power systems with communication failures as linear switched

systems, the effects of these two scenarios on the load frequency control of largely interconnected power systems are respectively analyzed. To compensate the effects of the communication failures, a distributed gain scheduling method is also proposed for the load frequency control. Simulation results of a four-area interconnected power system show the proposed gain scheduling control can greatly improve its robustness to communication failures.

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List of Acronyms

Acronyms	Definition
AGC	automatic generation control
ACC	area control center
AMI	advanced metering infrastructure
CR	cognitive radio
CTD	communication topology detector
DG	distributed generation
DS	distributed storage
EMS	energy management system
HAN	home area network
IED	intelligent electronic devices
LFC	load frequency control
LC	local controller
LTI	linear time-invariant

LQR	Linear quadratic regulators
MGCC	microgrid centralized controller
MC	Markov chain
MSE	mean square error
NAN	neighborhood area network
NCS	networked control system
PMU	phasor measurement units
PV	photovoltaic
PLL	phase-locked loop
PU	primary user
QoS	quality of service
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SU	secondary users
WAN	wide area network
WAMCP	wide-area monitoring, control and protection
WAMCS	wide area monitor and control systems
ZOH	zero-order-holds

List of Symbols

Symbols	Definition
$\mathbf{A}$	state matrix of descriptor system small-signal models
$\mathbf{A}_\tau$	state matrix of delayed system small-signal models
$\mathbf{B}$	input matrix of descriptor system small-signal models
$\mathbf{C}_0, \mathbf{S}_0$	diagonal matrices of dq-to-xy transformation
$\bar{\mathbf{C}}, \mathbf{C}$, and $\mathbf{M}$	matrices for estimating eigenvalues of small signal models
$\mathbf{D}_\mathbf{N}$	Chebyshev's differentiation matrix of dimension $\{N + 1\} \times \{N + 1\}$
D_i	equivalent damping coefficient
$\mathbf{E}$	singular matrix of descriptor system small-signal models
e_i	frequency errors
G_i, H_i	symmetric positive definite matrices
i_{drefi}, i_{qrefi}	inverter current regulator current set point
i_{di}, i_{qi}	inverter output currents on dq-axis

$\mathbf{i}_x, \mathbf{i}_y$	network currents on $x - y$ frame
J	cost function
K_{pii}, K_{iii}	inverter current controller gains
K_{pwi}, K_{iwi}	secondary frequency controller gains
K_{pPLLi} and K_{iPLLi}	PLL controller gains
$\bar{K}_{iwi}, \bar{K}_{pwi}$	equivalent gains of the secondary frequency controller with gain schedulers
K_{ij}^*	optimal inter-connective gains
$L(k)$	communication matrix
$l_{ij}(k)$	elements in the communication matrix
P_{refi}^{DC}	inverter corrective power set point
P_{refi}^{SF}	inverter supplementary real power set point
P_{refi}^{DC}	corrective real power set point
P_i, Q_i	instantaneous real and reactive power
Q_{refi}	reactive power set point
R_i	speed droop coefficient
S_1, S_2	switch postions
T_{chi}	time constant of turbine
T_{ij}	synchronizing power coefficient

t_k, t_{k+1}	two consecutive state jump instants
T_{g_i}	time constant of governor
$u(l)$	the state feedback controller at time slot $l \in [t_k, t_{k+1})$
v_{di}, v_{qi}	inverter terminal voltages on dq-axis
$V(x(k))$	composite Lyapunov function of the linear system
$V_i(x_i(k))$	Lyapunov function of each subsystem in the linear system
$\mathbf{V}_x, \mathbf{V}_y$	network voltages on $x - y$ frame
$\mathbf{x}$	small-signal variable vector
$\mathbf{x}(\mathbf{t} - \tau)$	small-signal variable vector
$\tilde{\mathbf{x}}(k)$	state vector of the system under DoS attacks
$\mathbf{z}(k)$	augmented state
ω_0	nominal frequency reference
ω_i	instantaneous frequency
ω_{PLL_i}	inverter terminal voltage frequency acquired by PLL
Δ	small-signal variables
δ_i	inverter terminal voltage phase angle on $x - y$ frame
τ	time delay
λ	system eigenvalue
τ_d	delay margin

τ_{ci}	critical time delays
$\beta_{i\omega i}, \beta_{p\omega i}$	gain scheduling variables
ω_i^0	frequency of the original DG
ω_i^d	frequency of the original DG with communication delays
ΔP_{m_i}	generator mechanical power deviation
ΔP_{v_i}	turbine valve position deviation
Δf_i	frequency deviation
ΔP_{c_i}	angular velocity
ΔP_{tie}^i	net tie-line power flow
ΔP_{L_i}	load deviation
θ_k	communication channel state at the k th time slot
$\{\tau_1, \tau_2, \dots, \tau_i, \dots, \tau_{k+1}\}$	sojourn time sequence
τ_i	sojourn time variable
τ_{min}, τ_{max}	sojourn time bounds
σ_i	switch position variable
Φ_1, Φ_2	system matrices with augmented state
α	normalized DoS attacks launching time
σ_i	switch position variable
$\lambda_m(*), \lambda_M(*)$	the minimum and maximum eigenvalues of matrix $*$

Chapter 1

Introduction

1.1 Smart Grids

As the next generation of power grids, smart grids have been attracting increasing attention from both academic and industrial communities around the world. In this chapter, technologies that enable smart grid operations are summarized. Among these technologies, the two-way communication technology plays a very important role in building smart grids. The requirements and architectures of the smart grid communication are also introduced. As one critical smart grid operation, load frequency control (LFC) in both large interconnected power systems and microgrids is discussed. Challenges brought by the two-way communication technology in the power system control are also presented. Finally, the thesis structure is summarized.

1.1.1 Smart Grid Technology

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. According to [1, 2], these challenges include:

- (1) 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.
- (2) The increasingly large penetration of renewable energy, such as wind and solar energy, to achieve sustainable growth and minimize environmental impact. This further increases the uncertainty in power supply.
- (3) The increasing demand for a highly reliable and efficient power supply, to support both industrial and everyday power utilization.
- (4) The threat of possible attacks on either the physical or the cyber assets of the power grid.

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, 2003 European and 2012 Indian blackouts [3, 4]. 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. According to the definition given by the U.S. Department of Energy (DOE) 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 [5], shown in Fig 1.1. A comparison between the main characteristics of a traditional power grid and a smart grid is made in Fig 1.2.

Figure 1.1: The structure of a smart grid

Traditional Power Grid	Smart Grid
Centralized Generation	Distributed Generation
Hierarchical	Networked
One-Way Communication	Two-Way Communication
Manual Restoration	Self-Healing
Few Customer Choices	Many Customer Choices
Limited Control	Pervasive Control

Figure 1.2: The main characteristics of a smart grid compared with a traditional power grid

1.1.2 Smart Grid Communication Requirements and Architecture

In this section, critical requirements for communications in smart grids are listed and a three-layer smart grid communication architecture is described in detail.

Requirements:

Several important requirements that the smart grid communication have to meet are listed as follows.

Security : Advanced two-way communication and intelligent computation technologies are critical to enable smart grid applications and functionalities, such as wide-area monitoring, control and protection (WAMCP), distributed generation management, advanced metering infrastructure (AMI), real-time pricing, etc. While these technologies facilitate the aggregation and communication of both system-wide information and local measurement data in selected locations, they expose smart grids to both cyber attacks and physical attacks. There were several reported attacks on power grids in U.S. [6, 7]. The compromise of communication networks and/or computers will severely endanger the stability and reliability of smart grid monitoring and control functionalities. Therefore, developing efficient security mechanism for smart grid communication networks and computers is one of the most critical issues.

Quality of Service (QoS) : QoS in communication networks refers to latency, bit-error rate, packet-loss rate, throughput, jitter, connect outage probability etc.. In smart grids, different applications have different QoS specifications. Some applications are time sensitive, such as inter-area oscillation damping control in wide-area monitoring, control and protection (WAMCP) and anti-islanding protection in distributed generation management. Low latency should be carefully ensured in these applications. Other applications could be quality sensitive, such as dynamic stability

assessment in the energy management system (EMS). Specifying the QoS requirements for communication networks according to a variety of smart grid applications, is important and challenging. In order to fulfill this task, both simulations of power dynamics and field tests of demo projects are necessary.

Scalability : Smart grid applications involve a vast amount of devices such as smart meters, intelligent sensors, data collectors, electric vehicles, and distributed generators. The amount of these devices will keep increasing. Therefore, a smart grid should be able to handle the scalability issue as more and more network nodes will be integrated into the smart grid.

Inter-operability : Smart grid communication networks need to be able to support the data flow over the whole smart grid, from bulk generations through delivery units (transmission systems and distribution systems) to electricity consumers. A three-layer hybrid communication architecture which include wide area network (WAN), neighborhood area network (NAN) and home area network (HAN) should be used to support this largely geographical coverage of data flow. This hybrid communication architecture has to involve a large variety of communication standards in order to be implemented in practice. The inter-operability among these various communication standards and subnetworks should be guaranteed, in order to keep smart grid monitoring and control stable and reliable. Many regulation groups, such as GridWise architecture council and NIST, are working collaboratively to address the inter-operability issue. NIST even announced an IEEE P2030 inter-operability project in June 2009.

Smart Grid Communication Architecture

The three-layer communication architecture for smart grids includes wide area network (WAN), neighborhood area network (NAN) and home area network (HAN).

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, 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.

1.2 Load Frequency Control in Smart Grids

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. 60Hz) by adjusting power generation set point. In this section, LFC in both high-voltage largely interconnected power grids and low-voltage microgrids is described.

1.2.1 Load Frequency Control in High-voltage Largely Inter-connected Power Grids

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

Figure 1.3: Three-layers of a load frequency control system

which the frequency will change when load changes happen. The main objectives of the LFC in largely inter-connected power grids are summarized as follows [8]:

- (1) Maintain frequency at the scheduled point;
 - (2) Maintain the net tie-line power interchanges with neighboring control areas at their scheduled values;
 - (3) Maintain power allocation among generators in accordance with area dispatching needs.
- The structure of the LFC is illustrated in Fig 1.3. As shown in this figure, there are following three control layers in the LFC.

Primary Control: It is the turbine governing system, which is decentralized because it is installed in power plants situated at different geographical areas, The action of turbine governors due to frequency changes when reference values of regulators are kept constant is referred as primary frequency control;

Secondary Control: It is composed of frequency control and tie-line control to force primary control to eliminate the frequency and net tie-line interchange deviations.

Being equipped only with primary controllers, the power system will not be able to return to the initial frequency without any additional action when a change in total demand happens. In order to eliminate the frequency and net tie-line interchange deviations, an area control error is defined as $ACE = \Delta P_{TL} - \beta \Delta f$. ACE is combined of frequency bias Δf and net tie-line power deviations ΔP_{TL} , while β is a weighting parameter. By zeroing the ACE, the objective of eliminating the frequency and net tie-line power biases can be fulfilled;

Tertiary Control: Tertiary control sets the reference values of power in individual generating units to the values calculated by optimal dispatch in such a way that the overall demand is satisfied together with the schedule of power interchanges. By adjusting manually or autonomously the set points of individual turbine governors, tertiary control ensures the following:

- (1) Adequate spinning reserve in the units participating in primary control;
- (2) Optimal dispatch of units participating in secondary control;
- (3) Restoration of the bandwidth of secondary control in a given cycle.

In the LFC, there are two data exchange loops. One of them is the feed-forward loop in which control centers send control signals to remote terminal units (RTUs) and turbine governors of local power plants. The other is the feedback loop where measurement signals are transmitted from RTUs to the control centers over communication links. The open communication links used in these two loops can facilitate data exchange in the LFC.

1.2.2 Load Frequency Control in Microgrids

Being different with the high-voltage interconnected power systems mentioned in the previous section, a microgrid is usually used to better organize the low-voltage distribution system. It is an integrated energy system comprising interconnected loads, distributed generation (DG) and distributed storage (DS) units [2,9,10]. There

Figure 1.4: Two-level hierarchical load frequency control of a microgrid

are three operation modes for a microgrid, including the grid-connected mode, the islanded mode and the transition mode between the former two modes [11]. In the grid-connected mode, the frequency of the microgrid is synchronized with the nominal frequency of the main grid. The microgrid only adjusts real and reactive power profiles by injecting a certain amount of real and reactive power into the main grid or absorbing from it. However, in the islanded mode, due to lack of the main grid as a reference, excursions of the frequency of the microgrid may happen if there is no proper frequency control in the microgrid [12].

Being similar to the frequency control of high-voltage interconnected power systems, the LFC of a microgrid also has a hierarchical structure shown in Fig 1.4. The two-level hierarchical control structure includes

Primary Control: A local controller (LC) for each inverter-based distributed generator usually acts fast to counteract an imbalance between load and generation. The LC usually refers to an inverter controller due to the fact that a DG here is interfaced with the prime mover via a power-electronic inverter, including a constant power controller and a droop controller, as shown in Fig 1.4. However, since there is no

reference frequency for the microgrid to follow when it is in islanded mode, with only LCs, the microgrid frequency is not able to return to the given nominal reference. With the help of a secondary frequency controller, the frequency of the microgrid can be restored to its nominal frequency. It will facilitate the reconnection of the microgrid to the main grid when the reconnection is detected to be applicable.

Secondary Control: A microgrid centralized controller (MGCC) is located at the low voltage side of a substation in a microgrid and only runs when the microgrid is in the islanded mode. To restore the frequency of the microgrid to the nominal value fixed by the utility, the MGCC generates supplementary real power set points for LCs of DGs and DSs and sends them to the corresponding LCs through low bandwidth communication channels.

1.3 Literature Review: Challenges for Smart Grid Control over Open Communication Links

In microgrids, the LFC involves communications between MGCC and LCs. In interconnected power grids, the LFC also needs the communication between control centers and RTUs. When open communication infrastructures are embedded into these power grids, they will support the vast amount of data exchange. However, there are several inherently unreliable factors existing in these open communication links, mainly including communication delays and communication failures. It is critical to understand the effects of the two factors on the power system control. In this section, existing work in the literature on the smart grid control with these two factors are summarized.

1.3.1 Communication Delays in Power Grids

When the effect of the communication delay on largely interconnected power systems is considered, it mainly refers to its effect on wide-area monitor and control systems (WAMCS). A communication delay in the WAMCS consists of two parts, including one communication delay caused when control centers send control signals to RTUs and the other caused when measurements signals are transmitted from RTUs to the control centers.

The existence of time delays in communication links may endanger the stability of power systems and degrade their dynamic performance. The impact of time delays on the wide-area control design of power systems is firstly investigated by H. Wu and G.T. Heydt [13]. In this work, it is shown that the overshoot value of active power variation increases and the settling time is lengthened in the presence of time delays which are modeled by Pade approximations. Instead of using the simple Pade approximation, a more complicated stochastic model is proposed to study the effect of communication delays on wide-area damping control by J. W. Stahlhut and G.T. Heydt et. al [14]. In their work, it is found that the time delays of control signals can degrade the performance of a wide area control system, by modeling the time delay as a M/M/1 queue. For the LFC in largely interconnected power systems, G/G/1 queues are used to model both constant and random time delays with different network protocols [15]. In practice, communication delays are investigated and tested in China Southern Grid [16]. In their tests, the Ethernet is used as the communication network. The measured time delay varies from 60 ms to 210 ms. Although the previous results are very promising, they have been obtained only by time domain simulations and field tests. Solid theoretical analysis of the time delay effect on power system was still missing until recently. In 2012, the impact of time delays on power system stability is analyzed via small-signal models by F. Milano and M. Anghel [17].

The presence of communication delays can harm not only the stability of largely interconnected power systems, but also low-voltage microgrids. Due to their low inertias, DGs in microgrids can response to disturbances very fast. Therefore, the effect of communication delays could be more critical than largely interconnected power grids which usually have large inertias. Recently, it has been found that communication delays can badly affect load sharing control in microgrids [18, 19]. The effect of communication delays on load frequency control has been investigated in [20, 21]. It is noted that communication delays may cause the instability of power systems and the degradation of power system performances.

1.3.2 Communication Failures in Power Grids

Besides time delays existing in communication links, the stability of power system control can also be jeopardized by communication failures, especially largely interconnected power grids. The communication element failure has been assessed as one of the dominant risks that could threat the reliability and safety of power systems [22, 23]. Series of probabilistic assessment studies reveal that the increase of the communication failure rate results in an increase of the load shedding when system operators try to restore the stability of a power system [24]. Besides the probabilistic methods, by conducting time-domain simulations of power systems, it is also found that communication failures can disturb power system state estimations and cause load losses [25, 26]. Cascade failures in power systems could even be worsen if communication failures happen during the restoration process [27]. In [28], communication infrastructures are investigated in the IEEE 118-bus test network for both centralized and decentralized control strategies. It emphasizes that the communication failures of a power grid may cause very serious problems for both system operation and control.

1.3.3 Control Algorithms for Compensating The Two Communication Factors

Since communication delays and failures may create stability issues in power systems, increasing research efforts have been devoted to designing advanced control methods to overcome the communication-induced instability. For the compensation of communication delays, some of these control methods are robust control in which time delays are dealt as uncertainties to power systems, such as sliding mode control [29], H_2/H_∞ control [30, 31], and delay-dependant control [32, 33]. Other control methods include smith predictor [34], hierarchical control [35, 36], model predictive control [37], and Kalman filter [38]. For counteracting the effect of communication failures, there are also a few advanced control methods in existence. For instance, a joint control and communication topology design is formulated as mixed-integer optimization problem for distributed damping control of power systems [39]. For a wide-area power system, a redundant supplementary damping controller is designed to achieve the resiliency to communication failures [40]. For multiple generators in a distribution system, co-operative control theory is applied for self-organization of distributed photovoltaic (PV) generators [41].

While these control algorithms mentioned above are very promising, the communication delays between centralized controllers and power plants are either estimated or viewed as uncertainties by the centralized controllers. However, this kind of communication delays can only be measured after control outputs are received in power plants. Thus, the centralized control outputs cannot exactly compensate this kind of communication delays. In the thesis, a novel gain scheduling approach is proposed for each local power plant controller to compensate the communication delays between a centralized secondary controller and local power plant. Instead of estimating the communication delay resulted from control output transmission, it can be measured

by marking time stamps when the centralized secondary controller sends control outputs and the local controllers embedded with gain schedulers receive them. These gain schedulers can then adjust the delayed control outputs to compensate the time delay. A distributed gain scheduling method is also proposed to counteract the effect of communication failures on the performance of the LFC of largely interconnected power systems.

1.4 Contributions

While all the work in the literature has made great contributions to understanding the effects of unreliable factors in open communication links on power system control, there are at least two issues that have not been well addressed. On the one hand, the effect of communication delays on the low-voltage microgrid control (in specific, load frequency control) has only been studied by trial simulations, while a comprehensive theoretical analysis has still been missing. On the other hand, although a lot of work on the impact of communication delays on high-voltage largely interconnected power system control have been done, the communication failure effect on the power system control, particularly load frequency control, has not been covered.

In the thesis, a set of results are developed that deal with the above two issues involved in the LFC of smart grids. Several contributions in this thesis are summarized as follows.

- 1. For the first time, at our best knowledge, a thoroughly theoretical small-signal analysis of the effect of communication delays on the load frequency control of an islanded microgrid is presented.
- 2. A gain scheduling method is proposed to improve the robustness of the microgrid load frequency control to communication delays.

- 3. For the first time, at the best knowledge of authors, the impact of communication failures on the load frequency control of high-voltage largely interconnected power grids is considered and comprehensively analyzed.
- 4. A distributed gain scheduling method is developed for the load frequency control to compensate the impact of communication failures.

1.5 Thesis Organization

The remaining chapters of this thesis are summarized as follows. In Chapter 2, the effect of communication delays on the LFC in an islanded multi-DG microgrid is studied. In Chapter 3, based on the small-signal model of the microgrid formulated in the previous chapter, a gain scheduling approach is proposed to compensate the communication delay effect on the LFC performance of the microgrid. In Chapter 4, for largely interconnected power systems, a CR network is considered as the source of communication failures. By modeling the CR network as a On-Off switch with sojourn times, a novel switched power system model is proposed for the LFC of the interconnected power systems. In Chapter 5, the DoS attack is considered as another reason that results in communication failures for the largely interconnected power systems. In Chapter 6, a distributed gain scheduling strategy is proposed to compensate the potential degradation of the performance of the LFC caused by communication failures in largely interconnected power systems. Finally, in Chapter 7, conclusions of the thesis are summarized.

Chapter 2

The Effect of Communication Delays on Load Frequency Control in An Islanded Microgrid

2.1 Introduction

In this chapter, we study the communication delay effect on the stability of the load frequency control (LFC) in an islanded microgrid. To achieve this objective, a time-delay small-signal system model is formulated for the microgrid system. Based on the analysis of this model, the relationships between load frequency control parameters and delay margins below which the system can stay stable are found. Simulation studies illustrate the effect of communication delays on the microgrid stability and validate the proposed small-signal analysis results.

The rest of this chapter is organized as follows. The studied microgrid system is introduced in Section 2.2. A small-signal model is proposed and the effect of load frequency control parameters are analyzed in Section 2.3. Delay margins are determined and the effect of load frequency control parameters on delay margins are also analyzed in Section 2.4. The analysis results are verified by simulation studies

Figure 2.1: The Canadian urban benchmark distribution system

of a multi-DG microgrid in Section 2.5. Finally, Conclusions are summarized in Section 2.6.

2.2 The Studied Microgrid System

The Canadian urban benchmark distribution system introduced in [42, 43] is used to investigate the dynamic performance of the LFC here. The schematic diagram of the test system is shown in Fig 2.1. The data of the system can be seen in Table A.1 and Table A.2 in Appendix A. The utility source is 120 kV and the 12.5 kV substation is connected to the grid through a circuit breaker (CB) and a substation transformer with a capacity of 10 MVA. A 2.75 Mvar capacitor bank is located at the substation. Four inverter-based DGs (three-phase 208 V) are evenly distributed along the feeder. They are connected to the feeder through the step-down transformers and the DG terminals are from Node 6 to Node 9 in sequence. The constant impedance load model with power factor 0.95 is adopted to represent the local load of each generator.

A microgrid central controller (MGCC) is installed at low-voltage side of the

Figure 2.2: Structure of the multi-DG system model

120kV/12.5kV substation (Bus 1 in Fig 2.1), to manage the operation of the microgrid. The MGCC provides all kinds of references (such as real and reactive power references) to the local controller (LC) of each DG unit, while each LC sends its measurements (such as frequency and power signals) back to the MGCC through communication channels. Among all kinds of functionalities of the MGCC, its load frequency control is mainly investigated in this work. Although the frequency-droop controller is able to stabilize the frequency dynamics in case of small disturbances, it cannot remove the frequency steady-state error to the nominal frequency given by the utility source. In order to restore the frequency of the microgrid to its nominal set point, a centralized secondary frequency controller is designed at the MGCC.

2.3 Small-Signal Model of The Microgrid

In this section, the small-signal model of the studied microgrid is presented. Although it is for the Canadian urban benchmark distribution system, the process of building this small-signal model is generic and can be extended to any other microgrid. The model of the microgrid with multiple DGs is shown in Fig 2.2, where n is the number of DGs and m is the number of loads. The model consists of three blocks, including

Figure 2.3: Structure of the multi-DG system two-level control

the DG block, the network and load block, as well as the interface block.

2.3.1 Model of The Inverter-based DG with Two-level Controllers

The control structure of the microgrid including both MGCC and a LC is shown in Fig 2.3. The power control loop of the local controller of an DG inverter consists of a power control and an inner current loop, to regulate the inverter output power by tracking given real power set points. Both the power and current controller are Proportional-Integral (PI) controllers.

The power controller is

$$i_{drefi} = (K_{ppi} + \frac{K_{ipi}}{s})(P_{refi}^{SF} + P_{refi}^{DC} - P_i) \quad (2.1)$$

$$i_{qrefi} = (K_{ppi} + \frac{K_{ipi}}{s})(Q_{refi} - Q_i) \quad (2.2)$$

where, i_{drefi} and i_{qrefi} are the current set points of the i th DG, K_{pii} and K_{ipii} are proportional and integral control gains of the i th DG, respectively, P_{refi}^{SF} is the i th DG supplementary real power set point assigned by the secondary frequency controller of MGCC, P_{refi}^{DC} is the corrective real power set point generated by the power control of i th DG, P_i and Q_i are the instantaneous real and reactive power. Q_{refi} is the reactive power set point of i th DG. Since the focus of this work is the frequency control, only the real power control structure is shown in Fig 2.3.

The inverter current controller is

$$v_{di} = (K_{pii} + \frac{K_{iii}}{s})(i_{drefi} - i_{di}) \quad (2.3)$$

$$v_{qi} = (K_{pqi} + \frac{K_{iii}}{s})(i_{qrefi} - i_{qi}) \quad (2.4)$$

where, v_{di} and v_{qi} are inverter terminal voltages on dq-axis, i_{di} and i_{qi} are the i th DG inverter output currents on dq-axis, K_{pii} and K_{iii} are the gains of the current controller.

The $\omega - P$ characteristic of the frequency droop control can be described as

$$P_{refi}^{DC} = K_{\omega i}(\omega_0 - \omega_i) \quad (2.5)$$

where, $K_{\omega i}$ is the droop control gain, P_{refi}^{DC} is the corrective power set point due to frequency variations.

The secondary frequency control is

$$P_{refi}^{SF} = (K_{p\omega i} + \frac{K_{i\omega i}}{s})(\omega_0 - \omega_i) \quad (2.6)$$

where, P_{refi}^{SF} is the supplementary power set point of the i th DG assigned by the secondary frequency controller, $K_{p\omega i}$ and $K_{i\omega i}$ are proportional and integral control

gains, respectively, ω_0 is the nominal frequency reference, ω_i is the instantaneous frequency obtained from a phase-locked loop (PLL).

The PLL model can be expressed as

$$\omega_{PLL i} = (K_{pPLL i} + \frac{K_{iPLL i}}{s})V_{qi} - \omega_0 \quad (2.7)$$

where, $\omega_{PLL i}$ is the inverter terminal voltage frequency acquired by PLL, V_{qi} is the q axis voltage obtained by using the $abc - dq$ transformation, ω_0 is the nominal frequency, $K_{pPLL i}$ and $K_{iPLL i}$ are the PI controller gains of the i th DG.

Consider now a microgrid consisting of $n+1$ buses. The first n buses are connected with DGs, while the Bus $n+1$ is the infinite bus (here is the utility generator). Define variables as

$$\begin{aligned} \delta &= [\delta_1, \delta_2, \dots, \delta_n]^T, \omega = [\omega_1, \omega_2, \dots, \omega_n]^T, \mathbf{v}_d = [v_{d1}, v_{d2}, \dots, v_{dn}]^T, \\ \mathbf{v}_q &= [v_{q1}, v_{q2}, \dots, v_{qn}]^T, \mathbf{V}_d = [V_{d1}, V_{d2}, \dots, V_{dn}]^T, \mathbf{V}_q = [V_{q1}, V_{q2}, \dots, V_{qn}]^T, \\ \mathbf{i}_d &= [i_{d1}, i_{d2}, \dots, i_{dn}]^T, \mathbf{i}_q = [i_{q1}, i_{q2}, \dots, i_{qn}]^T, \mathbf{i}_{dref} = [i_{dref1}, i_{dref2}, \dots, i_{drefn}]^T, \\ \mathbf{i}_{qref} &= [i_{qref1}, i_{qref2}, \dots, i_{qrefn}]^T, \mathbf{P} = [P_1, P_2, \dots, P_n]^T, \mathbf{Q} = [Q_1, Q_2, \dots, Q_n]^T, \\ \mathbf{P}_{ref} &= [P_{ref1}, P_{ref2}, \dots, P_{refn}]^T, \end{aligned}$$

After being linearized around a steady-state operating point, the small-signal equations of the inverter-based DGs are written as

$$\Delta \dot{\delta} = \Delta \omega \quad (2.8)$$

$$\Delta \dot{\omega} - K_{pPLL} \Delta \dot{\mathbf{V}}_q = K_{iPLL} \Delta \mathbf{V}_q \quad (2.9)$$

$$K_{pi} \Delta \dot{\mathbf{i}}_d + \Delta \dot{\mathbf{v}}_d - K_{pi} \Delta \dot{\mathbf{i}}_{dref} = K_{ii} \Delta \mathbf{i}_{dref} - K_{ii} \Delta \mathbf{i}_d \quad (2.10)$$

$$K_{pi} \Delta \dot{\mathbf{i}}_q + \Delta \dot{\mathbf{v}}_q - K_{pi} \Delta \dot{\mathbf{i}}_{qref} = K_{ii} \Delta \mathbf{i}_{qref} - K_{ii} \Delta \mathbf{i}_q \quad (2.11)$$

$$\mathbf{L}_s \Delta \dot{\mathbf{i}}_d = \Delta \mathbf{v}_d \quad (2.12)$$

$$\mathbf{L}_s \Delta \dot{\mathbf{i}}_{\mathbf{q}} = \Delta \mathbf{v}_{\mathbf{q}} \quad (2.13)$$

$$\Delta \dot{\mathbf{i}}_{\mathbf{dref}} + K_{pp} \Delta \dot{\mathbf{P}} = -K_{ip} \Delta P + K_{ip} \Delta \mathbf{P}_{\mathbf{ref}} \quad (2.14)$$

$$\Delta \dot{\mathbf{i}}_{\mathbf{qref}} + K_{pp} \Delta \dot{\mathbf{Q}} = -K_{ip} \Delta Q \quad (2.15)$$

$$\Delta \dot{\mathbf{P}}_{\mathbf{dref}} + (K_{p\omega} + K_{\omega}) \Delta \dot{\omega} = -K_{i\omega} \Delta \omega + K_{i\omega} \Delta \omega_0 \quad (2.16)$$

$$\mathbf{0} = \mathbf{V}_{\mathbf{d}0} \Delta \mathbf{i}_{\mathbf{d}} + \mathbf{i}_{\mathbf{d}0} \Delta \mathbf{V}_{\mathbf{d}} + \mathbf{V}_{\mathbf{q}0} \Delta \mathbf{i}_{\mathbf{q}} + \mathbf{i}_{\mathbf{q}0} \Delta \mathbf{V}_{\mathbf{q}} - \Delta \mathbf{P} \quad (2.17)$$

$$\mathbf{0} = \mathbf{V}_{\mathbf{d}0} \Delta \mathbf{i}_{\mathbf{q}} + \mathbf{i}_{\mathbf{d}0} \Delta \mathbf{V}_{\mathbf{d}} - \mathbf{V}_{\mathbf{q}0} \Delta \mathbf{i}_{\mathbf{d}} - \mathbf{I}_{\mathbf{d}0} \Delta \mathbf{V}_{\mathbf{q}} - \Delta \mathbf{Q} \quad (2.18)$$

2.3.2 Network Model

The network model in a common reference frame can be written as:

$$\begin{bmatrix} \Delta \mathbf{i}_{\mathbf{x}} \\ \Delta \mathbf{i}_{\mathbf{y}} \end{bmatrix} = \begin{bmatrix} \mathbf{G} & -\mathbf{B} \\ \mathbf{B} & \mathbf{G} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{V}_{\mathbf{x}} \\ \Delta \mathbf{V}_{\mathbf{y}} \end{bmatrix} \quad (2.19)$$

where, the matrices $\mathbf{G}$ and $\mathbf{B}$ are acquired from the network system admittance matrix and $\mathbf{V}_{\mathbf{x}} = [V_{x1}, V_{x2}, \dots, V_{xn}]^T$, $\mathbf{V}_{\mathbf{y}} = [V_{y1}, V_{y2}, \dots, V_{yn}]^T$, $\mathbf{i}_{\mathbf{x}} = [i_{x1}, i_{x2}, \dots, i_{xn}]^T$, $\mathbf{i}_{\mathbf{y}} = [i_{y1}, i_{y2}, \dots, i_{yn}]^T$.

2.3.3 Interface Equations

Among mathematic equations obtained above, each DG model is developed in its own $d - q$ reference frame. To develop the small-signal model of the microgrid, all the voltages and currents must be transformed to the common reference $x - y$ frame. The reference frame transformation between local $d - q$ reference frame and the common $x - y$ reference frame is shown in Fig 2.4.

Figure 2.4: Reference frame transformation

The interface equations are

$$\Delta \mathbf{V}_d = \mathbf{C}_0 \Delta \mathbf{V}_x - \mathbf{V}_{x0} \mathbf{S}_0 \Delta \delta + \mathbf{S}_0 \Delta \mathbf{V}_y + \mathbf{V}_{y0} \mathbf{C}_0 \Delta \delta \quad (2.20)$$

$$\Delta \mathbf{V}_q = \mathbf{S}_0 \Delta \mathbf{V}_x - \mathbf{V}_{x0} \mathbf{C}_0 \Delta \delta + \mathbf{C}_0 \Delta \mathbf{V}_y + \mathbf{V}_{y0} \mathbf{S}_0 \Delta \delta \quad (2.21)$$

$$\Delta \mathbf{i}_x = \mathbf{C}_0 \Delta \mathbf{i}_d - \mathbf{i}_{d0} \mathbf{S}_0 \Delta \delta - \mathbf{S}_0 \Delta \mathbf{i}_q - \mathbf{i}_{q0} \mathbf{C}_0 \Delta \delta \quad (2.22)$$

$$\Delta \mathbf{i}_y = \mathbf{S}_0 \Delta \mathbf{i}_d + \mathbf{i}_{d0} \mathbf{C}_0 \Delta \delta + \mathbf{C}_0 \Delta \mathbf{i}_q - \mathbf{i}_{q0} \mathbf{S}_0 \Delta \delta \quad (2.23)$$

where δ_i is the individual inverter terminal voltage phase angle in $x - y$ reference frame, and the diagonal matrices $\mathbf{C}_0$ and $\mathbf{S}_0$ are defined as $\mathbf{C}_0 = \text{diag}\{\cos(\delta_{i0})\}$ and $\mathbf{S}_0 = \text{diag}\{\sin(\delta_{i0})\}$, respectively.

2.3.4 Small-signal Analysis of The Load Frequency Control

The state space of the overall system is formulated as the following descriptor system

$$\mathbf{E} \Delta \dot{\mathbf{x}} = \mathbf{A} \Delta \mathbf{x} + \mathbf{F} \mathbf{r}_0 \quad (2.24)$$

where $\mathbf{x} = [\delta, \omega, \mathbf{i}_d, \mathbf{i}_q, \mathbf{i}_{d\text{ref}}, \mathbf{i}_{q\text{ref}}, \mathbf{v}_d, \mathbf{v}_q, \mathbf{P}, \mathbf{Q}, \mathbf{P}_{\text{ref}}, \mathbf{V}_d, \mathbf{V}_q, \mathbf{i}_x, \mathbf{i}_y, \mathbf{V}_x, \mathbf{V}_y]^T$, $\mathbf{r}_0 = [\omega_0]^T$, $\mathbf{E}$ is a parameter matrix which is singular, $\mathbf{A}$ is the system matrix, $\mathbf{F}$ is a

parameter matrix.

Definition. 2.3.1 [44, 45] The descriptor system (2.24) is asymptotically stable if all general roots of $\det(\lambda E - A) = 0$ are in the open left-hand plane.

With the small-signal model of the microgrid in hand, we are able to investigate the effect of the load frequency control gains $K_{p\omega}$ and $K_{i\omega}$ on the stability of the microgrid. The Canadian urban benchmark distribution system shown in Fig 2.1 is considered and the initial power generation reference is $P_0 = 0.3$. Without loss of generality, four DGs in this microgrid are considered to be identical inverter-based DGs. Parameters of the system including the distribution system and inverters can be seen in Table A.1 and Table A.2 in Appendix A.

Firstly, the effect of the proportional gain $K_{p\omega}$ on the system stability is analyzed. The integral gain $K_{i\omega}$ is fixed at $K_{i\omega} = 60$. The root loci of $\det(\lambda E - A) = 0$ with increasing $K_{p\omega}$ in the range of $[0.1, 2]$ is shown in Fig 2.5. By analyzing this root loci, λ_{11} and λ_{12} are identified as the critical eigenvalues which are the closest eigenvalues to the imaginary axis. The root loci of these two eigenvalues with increasing $K_{p\omega}$ in the range of $[0.1, 3]$ is shown in Fig 2.6. It can be seen that λ_{11} and λ_{12} are moving toward the right-half plane as the $K_{p\omega}$ increases. The observation of their root loci shows that the upper bound of $K_{p\omega}$ that guarantees the microgrid stable is $K_{p\omega} = 2.8$. Therefore, the stable proportional gain set is obtained.

Then, the impact of the integral gain $K_{i\omega}$ on the system stability is studied. The proportional gain $K_{p\omega}$ is fixed at $K_{p\omega} = 2$, the root loci of $\det(\lambda E - A) = 0$ with increasing $K_{i\omega}$ in the range of $[1, 60]$ is shown in Fig 2.7. The root loci of the critical eigenvalues λ_{11} and λ_{12} with increasing $K_{i\omega}$ in the range of $[1, 70]$ is shown in Fig 2.8. It can be found that λ_{11} is moving towards the right-half plane as the $K_{i\omega}$ increases. This observation shows the upper bound of $K_{i\omega}$ that guarantees the microgrid stable is $K_{i\omega} = 66$. Thus, the stable integral gain set is also obtained.

Figure 2.7: Root loci of the multi-DG system with $K_{p\omega} = 2$ Figure 2.8: Root loci of the critical eigenvalues with $K_{p\omega} = 2$

2.4 The Effect of Time Delays on The Microgrid Stability

A total time delay τ is considered to exist in the communication channels between MGCC and LCs. The overall system model becomes a delayed descriptor system, written as

$$\mathbf{E}\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{A}_\tau\Delta\mathbf{x}(\mathbf{t} - \tau) + \mathbf{F}\mathbf{r}_0 \quad (2.25)$$

where τ denotes a time delay, $\mathbf{x}(\mathbf{t} - \tau)$ is the time delayed state, and $\mathbf{A}_\tau$ is the state matrix of the delayed descriptor system.

The characteristic equation of the delayed descriptor system is

$$\det(\lambda\mathbf{E} - \Delta(\lambda, \tau)) = 0 \quad (2.26)$$

where

$$\Delta(\lambda, \tau) = \mathbf{A} + \mathbf{A}_\tau e^{-\lambda\tau} \quad (2.27)$$

Definition. 2.4.1 [44, 45] For a given τ , the delayed descriptor system (2.25) is asymptotically stable if all general roots of its characteristic equation (2.26) are in the open left-hand plane.

Definition. 2.4.2 A critical delay denoted by τ_d is called a delay margin if the delayed descriptor system (2.25) is stable for $\tau < \tau_d$ and it is unstable for $\tau > \tau_d$.

2.4.1 Determination of Delay Margin

The approaches to determine the delay margin for power systems have been discussed in [33, 46]. In this work, an eigenvalue approach in [46] is extended to the delayed descriptor system (2.25).

Given a pair of conjugate eigenvalues on the imaginary axis, they are denoted by

$\lambda_{imag} = \pm j\omega$. The following equation is satisfied

$$j\omega = eig(\Delta(\omega, \tau)) \quad (2.28)$$

where $eig(\star)$ denotes eigenvalues of $\star$, and

$$\Delta(\omega, \tau) = \mathbf{A} + \mathbf{A}_\tau e^{-j\omega\tau} \quad (2.29)$$

Define a variable $\eta = \omega\tau$. Then, the equation (2.29) can be expressed as

$$\Delta(\eta) = \mathbf{A} + \mathbf{A}_\tau e^{-j\eta} \quad (2.30)$$

$e^{-j\eta}$ changes periodically with η and the period is 2π . Thus, $\Delta(\eta)$ also changes periodically with a 2π period. We can change η within one period $[0, 2\pi]$ and get the root loci of the eigenvalues of $\Delta(\eta)$ within the range $\eta \in [0, 2\pi]$. If there exist eigenvalues $\pm j\omega_c$ on the imaginary axis at η_c , the corresponding critical time delay τ_c can be obtained by the following:

$$\tau_c = \eta_c / \omega_c \quad (2.31)$$

Consider a case there exist communication time delays in the studied system with the secondary frequency control gains $K_{p\omega} = 2$, $K_{i\omega} = 60$ and initial power reference $P_0 = 0.3$. For this case, the root loci of the eigenvalues of $\Delta(\eta)$ within the range $\eta \in [0, 2\pi]$ is shown in Fig 2.9.

It can be seen from Fig 2.9 that there are two pairs of conjugate eigenvalues on the imaginary axis denoted as $\pm j\omega_{d1}$ and $\pm j\omega_{d2}$. Their corresponding critical time delays are denoted as τ_{c1} and τ_{c2} , respectively. The delay margin τ_d is the minimum one between τ_{c1} and τ_{c2} , described as $\tau_d = \min\{\tau_{c1}, \tau_{c2}\}$. In this case, $\tau_d = 0.2053s$.

Figure 2.9: Root loci of $\Delta(\eta)$ when the secondary frequency control gains are $K_{p\omega} = 2$ and $K_{i\omega} = 60$

Provided there exist L critical time delays denoted as $\tau_{c1}, \tau_{c2}, \dots, \tau_{cL}$, the delay margin τ_d is

$$\tau_d = \min\{\tau_{c1}, \tau_{c2}, \dots, \tau_{cL}\} \quad (2.32)$$

2.4.2 Relationships between Load Frequency Control Gains and Delay Margins

In this subsection, delay margins with respect to different $K_{p\omega}$ and $K_{i\omega}$ are obtained for the studied system by using the described method above. The results are shown in Fig 2.10.

It can be found that the delay margin τ_d increases with the increase of the proportional gains $K_{p\omega}$ when $K_{i\omega}$ are fixed, while for fixed $K_{p\omega}$, the delay margin τ_d increases with the decrease of the integral gains $K_{i\omega}$. By obtaining the relationships between the delay margin and load frequency control gains, we can choose proper

Figure 2.10: Relationship between delay margin τ_d and secondary frequency control gains K_{pw} and K_{iw}

gains for a corresponding delay margin.

In order to guarantee a larger delay margin for the microgrid system, the load frequency controller should have relatively bigger K_{pw} and smaller K_{iw} within their applicable ranges.

2.5 Validation Studies

The microgrid shown in Fig 2.1 is used to study the effect of communication delays on dynamic performances of the microgrid with a load frequency controller. Also, delay margins calculated in the previous section are verified by the corresponding time domain simulations. The circuit breaker at 120 kV and the 12.5 kV substation is considered to be initially open that means the microgrid is islanded at $t = 0s$. The simulation platform for this microgrid is developed in the Matlab/SimPower R2007b

Figure 2.11: Structure of the simulation platform in Matlab/SimPower

environment shown in Fig 2.11. The load frequency control gains are initially set to be $K_{p\omega} = 2$ and $K_{i\omega} = 60$ based on the results of the small-signal analysis of the microgrid. The nominal frequency is chosen as $\omega_0 = 377 \text{ rad/s}$ (60 Hz) for the load frequency control. This nominal frequency is identical to the current Northern American standard frequency, which guarantees the easy reconnection of the microgrid to the utility main grid.

Firstly, in order to illustrate the effect of communication delays and verify the calculated delay margin, the following four cases are investigated.

- Case 1: there is no communication delay in the microgrid;
- Case 2: there is a constant total communication delay $\tau = 0.1 \text{ s}$ in the microgrid;
- Case 3: there is a constant total communication delay $\tau = 0.15 \text{ s}$ in the microgrid;

- Case 4: there is a constant total communication delay $\tau = 0.21s$ in the microgrid.

The simulation results for these four cases are shown from Fig 2.12 to Fig 2.15, respectively.

When there is no communication delay in the microgrid, it can be seen that the frequency dynamic of the microgrid with four identical DGs converge fast, shown in Fig. 2.12. The steady-state voltages of the four DGs can be kept as the nominal $1pu$. The real power set points for the four DGS are also same.

When the time delay increases to $\tau = 0.1s$ and $\tau = 0.15s$, the dynamics of the microgrid can still converge although they spend longer to damp oscillations, shown in Fig. 2.13 and Fig. 2.14. It can be found the real power set points for the four DGs are not identical any more in Fig. 2.13(b) and Fig. 2.14(b). This is the reason that the nominal frequency set point is the only input to the secondary frequency control, while real power set points are modified to keep the frequency at the nominal set point $\omega_0 = 377rad/s$. Thus, the function of the secondary frequency controller in the microgrid is verified.

When we continue increasing the time delay to $\tau = 0.21s$, the dynamic performances of the microgrid become unstable, shown in Fig. 2.15. It can be noticed that the calculated delay margin for $K_{p\omega} = 2$ and $K_{i\omega} = 60$ is $\tau_d = 0.2053s$, shown in Fig. 2.10. This calculated delay margin closely coincides with the delay margin estimated by the time-domain simulation. Therefore, the presented delay margin calculation method also works well.

In the above cases, the communication delays for all the DGs are considered to be identical. To evaluate more general cases, the following two cases in which the communication delay for each DG is different from each other, defining four time delays as τ_1 for DG1, τ_2 for DG2, τ_3 for DG3, τ_4 for DG4, respectively.

Figure 2.12: Dynamic performance of the microgrid when $\tau = 0s$ Figure 2.13: Dynamic performance of the microgrid when $\tau = 0.1s$

Figure 2.14: Dynamic performance of the microgrid when $\tau = 0.15s$ Figure 2.15: Dynamic performance of the microgrid when $\tau = 0.21s$

Figure 2.16: Dynamic performance of the microgrid in Case 5

- Case 5: four time delays are less than the delay margin, $\tau_1 = 0.1s$, $\tau_2 = 0.15s$, $\tau_3 = 0.1s$, $\tau_4 = 0.18s$;
- Case 6: the time delay for DG4 is larger than the delay margin $\tau_4 = 0.25s$, while $\tau_1 = 0.1s$, $\tau_2 = 0.15s$, $\tau_3 = 0.1s$.

The results are shown in Fig. 2.16 and Fig. 2.17. It can be seen from Fig. 2.16 that the dynamics of the microgrid are still stable when the four different time delays are shorter than the delay margin. However, the observations from Fig. 2.17 show that the microgrid becomes unstable as long as the communication delay for one DG is longer than the delay margin (such as DG4 in Case 6).

2.6 Summary

The impact of communication delays on an islanded multi-DG microgrid with a load frequency control is studied in this chapter. Based on a small-signal model of the

Figure 2.17: Dynamic performance of the microgrid in Case 6

microgrid without considering communication delays, the effect of the load frequency control gains on the microgrid stability is firstly analyzed. A delayed small-signal system model is then formulated for this microgrid system with communication delays. By tracing critical eigenvalues of the characteristic equation of this model, a delay margin which indicates the maximum communication delay that the microgrid maintains stable is determined. For $K_{p\omega} = 2$ and $K_{i\omega} = 60$, the maximum allowable communication delay for the microgrid is $\tau_d = 0.2053s$. By conducting an extensive sensitivity study, it has been found that the delay margin increases with the increase of the proportional gains while it decreases with the increase of the integral gains. A validation study of a microgrid with 4 inverter-based DGs is also conducted. It has illustrated the effect of communication delays on the stability of the microgrid load frequency control and the effectiveness of the obtained method to determine the delay margin. It has also verified the relationships between the delay margin and the load frequency control gains.

Chapter 3

Gain Scheduling Approach for Compensating The Communication Delay Effect on Load Frequency Control of An Islanded Microgrid

3.1 Introduction

In the previous chapter, it has been found that communication delays can badly affect the dynamic performance of an islanded microgrid. Therefore, it is critical to develop advanced control algorithms for the LFC of the microgrid to compensate the communication delay effect. To handle this issue, a gain scheduling approach is proposed in this chapter. Studies of an islanded microgrid with 4 inverter-based DGs show the proposed gain scheduling method can greatly improve the dynamic performance of the microgrid, compared to a fixed gain load frequency controller.

The rest of this chapter is organized as follows. In Section 3.2, the general control structure is described. In Section 3.3, the proposed gain scheduling method is presented. In Section 3.4, simulations of an islanded microgrid are used to evaluate the effectiveness of the proposed gain scheduling method. Finally, conclusions are made

Figure 3.1: Structure of the multi-DG system model

in Section 3.5.

3.2 General Control Structure of An Islanded Microgrid with PMUs and Gain Schedulers

A gain scheduling approach is proposed to compensate the effect of communication delays on the dynamic performance of the islanded microgrid shown in Fig 2.1. The microgrid control structure including both the MGCC and one LC is shown in Fig 3.1. The secondary frequency controller is a proportion and integral (PI) controller. This PI controller adjusts the real power set points for each DG to restore their frequencies to the nominal one and sends them to each LC. For each LC, it is equipped with a phasor measurement unit (PMU) and a gain scheduler embedded with a GPS receiver. When PMUs measure frequencies at each DG bus of the microgrid, they mark these

measurements with time stamps generated by GPS. After the MGCC receives these frequency measurements and calculates real power set points for each LC, it sends these set points to LCs. Since the time spent in MGCC calculation is very short, it is omitted when we consider time delays in the microgrid. In each LC, a gain scheduler receives the corresponding real power set point and marks it also with a time stamp. By comparing the time stamps marked by PMUs and by gain schedulers, round-trip communication delays are calculated. Then, gain schedulers in LCs adjust corresponding gains and generate new real power set points to compensate these communication delays. The gain adjustment is done according to feasible gain sets which are obtained by offline root locus analysis and trial simulations, with a quadratic state error as the cost index.

3.3 Gain Scheduling Methodology

Due to the presence of communication delays in the load frequency control loop, the performance of the original microgrid may be degraded. In order to remain good system performances, with respect to a certain cost function, the load frequency controller gains in the microgrid need to be adjusted according to the measured communication delays. In this section, we add a local gain scheduler denoted by a variable β_{wi} in each DG controller of the microgrid, to compensate the degradation of the microgrid performance. The integral gain scheduling variable β_{iwi} and proportional gain scheduling variable β_{pwi} are investigated, respectively.

3.3.1 Feasible Gain Sets

To find feasible β_{iwi} and β_{pwi} that correspond to communication delays, we need to investigate root locus of the characteristic equation of the time-delay small-signal model of the microgrid with respect to β_{iwi} and β_{pwi} .

Here, we define

$$\bar{K}_{i\omega i} = \beta_{i\omega i} K_{i\omega i} \quad (3.1)$$

and

$$\bar{K}_{p\omega i} = \beta_{p\omega i} K_{p\omega i} \quad (3.2)$$

where, $K_{i\omega i}$ and $K_{p\omega i}$ are the original load frequency control gains located in the MGCC. The changeable parts are $\beta_{i\omega i}$ or $\beta_{p\omega i}$ located in each local DG controller. The reason behind this is that the round-trip communication delays can be known only in local DG controllers which receive load frequency controller outputs, while it cannot be known in the MGCC which only generate the load frequency controller outputs. $\bar{K}_{i\omega i}$ and $\bar{K}_{p\omega i}$ represent the equivalent gains of the secondary frequency controller after gain schedulers are equipped in each LC. We consider gain schedulers change only one gain variable, either $\beta_{i\omega i}$ or $\beta_{p\omega i}$.

Then, the equalized load frequency controller has the following form:

$$P_{refi}^{SF} = (K_{p\omega i} + \frac{\bar{K}_{i\omega i}}{s})(\omega_0 - \omega_i) \quad (3.3)$$

or

$$P_{refi}^{SF} = (\bar{K}_{p\omega i} + \frac{K_{i\omega i}}{s})(\omega_0 - \omega_i) \quad (3.4)$$

The time-delay small signal model of the microgrid is built as follows.

$$\bar{\mathbf{E}}\Delta\dot{\mathbf{x}} = \bar{\mathbf{A}}\Delta\mathbf{x} + \bar{\mathbf{A}}_\tau\Delta\mathbf{x}(\mathbf{t} - \tau) + \bar{\mathbf{F}}\mathbf{r}_0 \quad (3.5)$$

where $\bar{\mathbf{E}}$ and $\bar{\mathbf{A}}$ are system matrices, $\bar{\mathbf{A}}_\tau$ is a parameter matrix related to the delayed state $\mathbf{x}(\mathbf{t} - \tau)$, and $\bar{\mathbf{F}}$ is a parameter matrix. While most elements of the matrices are still the same as the ones in Chapter 2, the original $K_{i\omega i}$ is replaced by $\bar{K}_{i\omega i}$ or $K_{p\omega i}$ by $\bar{K}_{p\omega i}$. The gain scheduler vector $\beta_{i\omega}$ and $\beta_{p\omega}$ denote four integral gain schedulers

and proportional gain schedulers, respectively.

Since the characteristic equation $\det(\bar{\mathbf{E}} - \bar{\mathbf{A}} - \bar{\mathbf{A}}_\tau e^{-\lambda\tau}) = 0$ is transcendental, it has infinitely many roots. Therefore, we can only approximate its solution by computing a reduced set of its roots. One effective technique to approximate its solution is to approximate the roots of $\det(\bar{\mathbf{E}} - \bar{\mathbf{A}} - \bar{\mathbf{A}}_\tau e^{-\lambda\tau}) = 0$ by a finite element method [17]. In this method, a matrix $\mathbf{M}$ which has the following form is defined.

$$\mathbf{M} = \begin{bmatrix} & \bar{\mathbf{C}} \otimes \mathbf{I}_n & \\ \mathbf{A}_\tau & \mathbf{0} & \mathbf{A} \end{bmatrix} \quad (3.6)$$

where $\otimes$ indicates Kronecker's product, $\mathbf{I}_n$ is the identity matrix of order n , and $\bar{\mathbf{C}}$ is a matrix composed of the first $N - 1$ rows of $\mathbf{C}$ defined as follows:

$$\mathbf{C} = -2\mathbf{D}_N/\tau \quad (3.7)$$

where $\mathbf{D}_N$ is a Chebyshev's differentiation matrix of dimension $N + 1 \times N + 1$ (See Appendix B for details). Then, the eigenvalues of M are an approximated spectrum of the characteristic equation of (3.5).

For the simplicity of calculations, N is chosen as 2 for $\mathbf{D}_N$. Then, root locus of the critical eigen pair are investigated for both β_{iwi} and β_{pwi} under different time delays $\tau = \{0.1, 0.2, 0.3\}$, shown in Fig 3.2 and Fig 3.3. From these two figures, for both β_{iwi} and β_{pwi} , it can be seen that feasible gain sets that guarantee the microgrid system stable become smaller as time delays increase in communication links.

Figure 3.2: Root locus for β_{iw} under different time delays (Arrows direct the increasing gains)

Figure 3.3: Root locus for β_{pw} under different time delays (Arrows direct the increasing gains)

3.3.2 Feasible Gains with Respect to The Microgrid Performance

To find relationships between the gain scheduler variables ($\beta_{i\omega}$ and $\beta_{p\omega}$) and the system performance of the microgrid, the following average squared error is defined the cost function.

$$J = \frac{1}{T} \int_{t=0}^T e_i^2(t) \quad (3.8)$$

where T is the simulation horizon, $e_i(t) = \omega_i^d(t) - \omega_i^0(t)$ is the frequency error with respect to the nominal frequency reference $\omega_i^0(t)$ for DG i . The nominal reference $\omega_i^0(t)$ is the frequency of the original DG i when there are no communication delays with initial gains $K_{i\omega} = 60$ and $K_{p\omega} = 2$, while $\omega_i^d(t)$ is the frequency of the DG i when there are communication delays in the microgrid.

Time domain simulation trials of the microgrid in Matlab/SimPower R2007b are carried out. The nominal references are the dynamics of the original microgrid without communication delays with initial gains $K_{i\omega} = 60$ and $K_{p\omega} = 2$. The $\beta_{i\omega}$ and $\beta_{p\omega}$ are investigated respectively. The performance cost curves with respect to $\beta_{i\omega 1}$ and $\beta_{p\omega 1}$ for DG 1 are shown in Fig 3.4 and Fig 3.5, respectively. From Fig 3.4, it can be seen that cost when $\tau = 0.1s$ and $\tau = 0.2s$ increase slowly, while the cost when $\tau = 0.3s$ changes sharply. That means the microgrid is not stable any more when $\tau = 0.3s$. Also, in Fig 3.5, for $\beta_{p\omega 1}$, among all the costs for three different time delays, cost when $\tau = 0.3s$ is still the largest.

The procedure of the gain scheduling approach includes the following steps:

- Step 1: Calculate the communication delay by comparing the time stamps of two signals $P_{refiT2}^{SF'}$ and ω_{iT1} . The total time delay $\tau_i = T_2 - T_1$, omitting the time spent in calculating control outputs by the MGCC.
- Step 2: For a given cost index, by looking up in cost curves such as Fig 3.4 and

Figure 3.4: Cost curve with respect to $\beta_{i\omega 1}$ when $K_{p\omega} = 2$ Figure 3.5: Cost curve with respect to $\beta_{p\omega 1}$ when $K_{i\omega} = 60$

Fig 3.5 built by the offline analysis, the local gain scheduler adjusts the value of its gain scheduler variable according to the measured communication delay.

3.4 Simulations

The microgrid shown in Fig 2.1 is used to study the effect of different kinds of time-varying delays on the performance of the microgrid with a load frequency controller. Then, the effectiveness of the proposed gain scheduling approach is evaluated, with comparison to fixed gain controllers.

The simulation platform for this microgrid is developed in Matlab/SimPower R2007b environment. The load frequency controller gains are initially set to $K_{p\omega} = 2$ and $K_{i\omega} = 60$ based on the results of the small-signal analysis of the microgrid in Chapter 2. The nominal frequency is chosen as $\omega_0 = 377\text{rad/s}$ for the load frequency control which is identical to the current Northern American standard frequency and guarantees the easy reconnection of the microgrid to the utility main grid. The circuit breaker at 120 kV and the 12.5 kV substation is considered to be initially open that means the microgrid is islanded at $t = 0\text{s}$.

To investigate the impact of communication delays, the following scenarios are considered.

- Case 1: there is a constant total communication delay $\tau = 0.1\text{s}$ in the microgrid;
- Case 2: there is a constant total communication delay $\tau = 0.2\text{s}$ in the microgrid.

The results of these two cases are shown in Fig 3.6 and Fig 3.7. Since four DGs in the microgrid are identical, only the dynamics of DG1 are presented. From these results, it can be noted that the frequency and real power of DG1 oscillate a lot in the presence of time delays.

Figure 3.6: Dynamic performance of DG1 with $\tau = 0.1s$ Figure 3.7: Dynamic performance of DG1 with $\tau = 0.2s$

To evaluate the effectiveness of the proposed gain scheduling approach, the following cases are considered.

- Case 3: there is a time-varying delay following a uniform distribution with $\tau \in \{0, 0.1, 0.2\}$ in the microgrid with β_{iwi} gain-schedulers are installed in local controllers of DGs.
- Case 4: there is a time-varying delay following a uniform distribution with $\tau \in \{0, 0.1, 0.2\}$ in the microgrid with β_{pwi} gain-schedulers are installed in local controllers of DGs.

Simulation results of these two cases are presented from Fig 3.8 to Fig 3.12. A part of the time-varying delay trajectory is shown in Fig 3.8. The uniform distribution was used for estimating time delays in [47]. With comparison to other distributions, the uniform distribution illustrates a worse communication delay process which may happen in practice. We use it in this study to show the performance of the microgrid. With this time-varying delay process, dynamic performances of DG1 are shown in Fig 3.9. Apparently, with the β_{iwi} gain scheduler, the frequency dynamic of DG 1 behaves better than that without the gain scheduler. A part of the gain scheduling process is shown in Fig 3.10. As shown in Fig 3.11 and Fig 3.12, similar conclusions also are made for the DG 1 with the β_{pwi} gain scheduler.

3.5 Summary

A gain scheduling approach has been presented for compensating the impact of communication delays on the load frequency control performance of an islanded microgrid in this chapter. This approach consists of two steps. For the first step, feasible gain sets with respect to a given cost function are found by offline small-signal analysis. For the second step, via GPS embedded in PMUs and gain schedulers, each local

Figure 3.8: The dynamic of the time-varying delay (only showing first 100 samples)

Figure 3.9: Dynamic performances of DG1 with a $\beta_{i\omega 1}$ gain-scheduler

Figure 3.10: The dynamic of the β_{iw1} gain-scheduler (only showing first 100 samples)

Figure 3.11: Dynamic performances of DG1 with a β_{pw1} gain-scheduler

Figure 3.12: The dynamic of the β_{pw1} gain-scheduler (only showing first 100 samples)

controller can calculate current communication delays and then schedule the corresponding load frequency controller gains. Simulations of an islanded microgrid with 4 inverter-based DGs under different time-delay cases have verified the effectiveness of the proposed gain scheduling method.

Chapter 4

Stability Analysis of Load Frequency Control over Cognitive Radio Networks in Largely Interconnected Power Grids

4.1 Introduction

In the previous two chapters, we investigate the analysis and control the effects of communication delays on the microgrid load frequency control (LFC). In the following two chapters, the impacts of communication failures on largely interconnected power grids are analyzed. Two specific situations that can result in communication failures in smart grids are considered. One of them is the utilization of cognitive radio (CR) networks to support smart grid communication which is presented in this chapter. The other is the denial of service (DoS) attack to smart grid communication links which will be presented in Chapter 5.

In this chapter, the stability of the LFC of a largely interconnected power system for which CR networks are used as the communication infrastructure is analyzed. For this purpose, a new switched power system model is proposed for the LFC of the power system by modeling the CR network as an On-Off switch with sojourn times.

Sufficient conditions are obtained for the stability of the LFC of the power system with two different kinds of CR networks. Simulation results show the effect of CR networks on the dynamic performance of the LFC of the power system and illustrate the usefulness of the developed sufficient conditions in the design of CR networks in smart grids.

The rest of this chapter is organized as follows. In Section 4.2, the CR network issues in smart grid applications are introduced. In Section 4.3, a new switched system model is proposed to investigate the effect of CR networks on the stability of the LFC of a largely interconnected power grid. In Section 4.4, the stability of the LFC of the power grid over CR networks is studied for both deterministic and stochastic sojourn time situations. In Section 4.5, a two-area power system is used for simulation studies. Finally, Section 4.6 concludes the chapter.

4.2 Cognitive Radio Networks in Smart Grids

A smart grid integrates advanced two-way communication networks and advanced intelligent computing technologies into current power systems, from large-scale generation through delivery units to electricity consumers [2, 48, 49]. The applications of a smart grid include wide-area monitoring, control and protection (WAMCP), distributed generation management, advanced metering infrastructure (AMI), real-time pricing, etc. [1, 50–52]. To support these applications, there are several unique challenges to be addressed for smart grid communications [53–56].

Limited bandwidth: Since WAMCP and AMI involve tremendous amounts of information exchange over wide geographical areas, it needs large bandwidths for both data transmission and collection.

Interference: As most of AMI communication architectures are normally formed among smart meters for data routing in the 2.4 GHz industrial, scientific, and medical

(ISM) band, signal interferences will be severe among these types of radio systems.

Inter-operability: Last but not least, because a smart grid communication architecture consists of wide area network (WAN), neighborhood area network (NAN) and home area network (HAN), this heterogeneous network architecture requires the capability to coordinate communications within each subarea and between different areas. However, most of the traditional communication technologies are infeasible to meet all these requirements.

Due to its great potentials to enhance the overall performance of data communications with its dynamic and adaptive spectrum management capabilities, the CR networking technology has been increasingly considered as the networking and communication infrastructure for smart grids [55–57]. In view of the fact that a large portion of the licensed radio spectrum remains severely under-utilized, the CR technology is proposed to achieve the efficient usage of the assigned radio spectrum [47, 58–60]. In a CR network, there are two kinds of users. Primary users (PUs) are the users who are licensed with certain bands of the current spectrum, while secondary users (SUs) do not have the licenses for the utilization of those spectrum bands. However, SUs can opportunistically sense and identify the unused channels in the licensed spectrum. Based on the sensed results, SUs are able to use the available channels, coordinate the spectrum access with other users, and return the channel back to PUs when PUs reclaim the spectrum usage right. With this capability of the dynamic and opportunistic spectrum allocation, CR networks can increase spectrum efficiency, enable large-scale different spectrum regulations, and coordinate radio spectrum sharing among different area networks in smart grids.

Although the CR networking technology has great potentials to address the unique challenges for smart grid communications in comparison with many other networking technologies, it brings in a new problem. Specifically, a SU of a CR network has to be squeezed out from the channel that it is using when a PU reclaims to use the

spectrum and this may occur in a randomized fashion. The random interruption of SU traffics will unavoidably cause data packet losses and delays for SU data. Besides the traffic interruption resulted from PUs, data packets could also be lost due to traffic congestions resulted from other SUs who also want to send data at the same time. These lost data packets can be of any natures: control commands from control centers to substations, sensed data from remote terminal units (RTUs), real-time pricing information between utilities and customers, etc.. The loss of these data may lead to very severe and adverse effects on the monitoring and control processes of a smart grid. In [28], it is emphasized that communication failures of a power grid may cause very serious problems for both system operation and control.

Therefore, it is very important to deal with the above problem and to understand the effects of the random interruptions of SU traffics in CR networks on the stability and performance of the smart grid monitoring and control processes. To our best knowledge, there is no existing work to address this issue. In this chapter, we study this problem and investigate stabilities of the LFC of a largely interconnected power grid for which CR networks are used as the infrastructure for the aggregation and communication of both system-wide information and local measurement data.

4.3 Modeling of The LFC over A Cognitive Radio Network in A Largely Interconnected Power System

The LFC over a CR network in a two-area power system is shown in Fig 4.1. In this LFC, there are two data exchange loops. One of them is the feed-forward loop in which control centers send control signals to RTUs. The other is the feedback loop where measurement signals are transmitted from RTUs to the control centers over the

Figure 4.1: Two-area power system over cognitive radio (CR) networks

CR wireless network. It can be noticed that the LFC is a typical networked control system (NCS), of which the control loop is closed via communication links [61–64].

In this section, a new On-Off switch model of the CR network for smart grid communications is proposed. By using this On-Off switch model, a linear switched system is proposed to integrate the dynamic of the CR network in the cyber layer into the physical power system in the smart grid.

4.3.1 The Model of Cognitive Radio Networks

As shown in Fig 4.2, we consider a licensed spectrum band consisting of N non-overlapping channels in the CR network used by the smart grid. Both PUs and SUs in this CR network are operated synchronously in a time-slotted fashion. In this chapter, we consider the situation in which each cognitive user can sense only one channel at each time slot. The availability of each channel is modeled as a 2-state Markov chain in the literature [47, 59, 60]. However, in terms of the system performance of the

Figure 4.2: The cognitive radio channel illustration

Figure 4.3: The proposed On-Off cognitive channel model

smart grid, we should take account of not only the state transitions, but also the time staying in each state. From each SU point of view, the sensed channel state is either free or occupied by other users. This means the communication channel for data exchange is either ON or OFF. Thus, we model the communication channel as an ON-OFF switch with sojourn times, shown in Fig 4.3. A sojourn time τ_i is a time interval the communication channel continuously stays in a state, either ON or OFF [65]. The channel state at k th time instant is denoted by $\theta_k \in \Theta = \{0, 1\}$, where $\Theta = \{0, 1\}$ is the state space of θ_k , 0 denoting OFF state of the channel, 1 denoting ON state.

4.3.2 The Switched System Model for The LFC over A Cognitive Radio Network

The operation of the frequency control in power systems is fundamental in determining the way in which the frequency will change when load changes happen [8, 32, 66]. LFC mainly keeps the frequency of the power system at a nominal value (i.e 60Hz) by adjusting power generation set points. For the LFC of a largely interconnected power system, the power system is decomposed into several control areas which are interconnected by high voltage tie-lines. In each control area, it comprises a group of generators and a number of loads. Commonly, the generators are represented equivalently by one single machine and the loads by one single load. Furthermore, although power systems are usually non-linear, linearized models are used because the LFC operation only involves relatively small disturbances.

The control structure of an equivalent linearized model in the i th control area is shown in Fig 4.4. A non-reheat steam turbine is considered. When the governor senses the frequency changes Δf_i , it adjusts the valve position ΔP_{v_i} . By doing this, the input of steam flowing into the turbine is regulated and thus the mechanical power ΔP_{m_i} is controlled. As a result, the frequency is kept constant. The governor and turbine compose the primary frequency control of this generating unit. However, the system frequency is usually not able to be restored to the nominal value (i.e. 60Hz) by only using the primary control. A secondary frequency controller $K(s)$ is necessary to adjust the load reference set point ΔP_{c_i} for the turbine to make the power generation ΔP_{m_i} track the load changes ΔP_{L_i} and restore the system frequency.

The turbine dynamic is described by

$$\Delta \dot{P}_{m_i} = -\frac{1}{T_{ch_i}} \Delta P_{m_i} + \frac{1}{T_{ch_i}} \Delta P_{v_i} \quad (4.1)$$

where, ΔP_{m_i} is the generator mechanical power deviation, ΔP_{v_i} is turbine valve position deviation, and T_{ch_i} is the time constant of turbine i .

The governor dynamic is described by

$$\Delta \dot{P}_{v_i} = -\frac{1}{R_i T_{g_i}} \Delta f_i - \frac{1}{T_{g_i}} \Delta P_{v_i} + \frac{1}{T_{g_i}} \Delta P_{c_i} \quad (4.2)$$

where, Δf_i is the frequency deviation of area i , ΔP_{c_i} is the load reference set-point, T_{g_i} is the time constant of governor i , and R_i is the speed droop coefficient.

The overall load-generation dynamic is described by

$$\Delta \dot{f}_i = -\frac{D_i}{2H_i} \Delta f_i + \frac{1}{2H_i} \Delta P_{m_i} - \frac{1}{2H_i} \Delta P_{tie}^i - \frac{1}{2H_i} \Delta P_{L_i} \quad (4.3)$$

where, ΔP_{tie}^i is the net tie-line power flow in area i , ΔP_{L_i} is the load deviation, H_i is the equivalent inertia constant of area i , and D_i is the equivalent damping coefficient of area i .

The dynamic of the net tie-line power flow dynamic is

$$\Delta \dot{P}_{tie}^i = \sum_{j=1, j \neq i}^N 2\pi T_{ij} (\Delta f_i - \Delta f_j) \quad (4.4)$$

where T_{ij} synchronizing power coefficient, and Δf_j is the of area j .

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

$$\dot{x}_i = A_{ii}x_i + B_i u_i + \sum_{j=1, j \neq i}^N A_{ij}x_j + F_i \Delta P_{L_i}, x_i(0) = x_0 \quad (4.5)$$

where

$$x_i = \begin{bmatrix} \Delta f_i & \Delta P_{m_i} & \Delta P_{v_i} & \Delta P_{tie}^{ij} \end{bmatrix}^T; u_i = \Delta P_{c_i};$$

Figure 4.4: The block diagram of the control area i

$$A_{ii} = \begin{bmatrix} -\frac{D_i}{2H_i} & \frac{1}{2H_i} & 0 & -\frac{1}{2H_i} \\ 0 & -\frac{1}{T_{chi}} & \frac{1}{T_{chi}} & 0 \\ -\frac{1}{R_i T_{gi}} & 0 & -\frac{1}{T_{gi}} & 0 \\ \sum_{j=1, j \neq i}^N 2\pi T_{ij} & 0 & 0 & 0 \end{bmatrix}; A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -2\pi T_{ij} & 0 & 0 & 0 \end{bmatrix};$$

$$B_i = \begin{bmatrix} 0 & 0 & \frac{1}{T_{gi}} & 0 \end{bmatrix}^T; F_i = \begin{bmatrix} -\frac{1}{M_i} & 0 & 0 & 0 \end{bmatrix}^T.$$

For the whole multi-area power system, a centralized linear time-invariant (LTI) interconnected model is given by:

$$\dot{\mathbf{x}} = \mathbf{A_c} \mathbf{x} + \mathbf{B_c} \mathbf{u} + \mathbf{F} \Delta \mathbf{P_L}, \mathbf{x}(0) = \mathbf{x_0} \quad (4.6)$$

where

$$\mathbf{x} = \begin{bmatrix} x_1 & x_2 & \cdots & x_N \end{bmatrix}^T; \mathbf{u} = \begin{bmatrix} u_1 & u_2 & \cdots & u_N \end{bmatrix}^T;$$

$$\Delta \mathbf{P}_L = \begin{bmatrix} \Delta P_{L1} & \Delta P_{L2} & \cdots & \Delta P_{LN} \end{bmatrix}^T;$$

$$\mathbf{A}_c = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1N} \\ A_{21} & A_{22} & \cdots & A_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ A_{N1} & A_{N2} & \cdots & A_{NN} \end{bmatrix}; \mathbf{B}_c = \text{diag} \left\{ B_1 \quad B_2 \quad \cdots \quad B_N \right\}^T;$$

The above state-space model can be written in a more convenient form as the steady state is denoted by $\mathbf{x}_{ss}$ [67]:

$$\dot{\mathbf{x}} = \mathbf{A}_c \mathbf{x} + \mathbf{B}_c \mathbf{u}, \mathbf{x}(0) = -\mathbf{x}_{ss}$$

Due to the CR network has been modeled as an ON-OFF switch in the slotted time fashion (inherently a discrete-time model), the following discrete-time model of the power system is considered:

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k) \quad (4.7)$$

where, $\mathbf{A} = e^{\mathbf{A}_c h}$, $\mathbf{B} = \int_0^h e^{\mathbf{A}_c \tau} \mathbf{B}_c d\tau$, h is the sampling period.

The above power model is under the assumption that the communication channel between the control center and RTUs is perfect. However, as we discussed in the previous section, the fact that PUs reclaim the channel usages will cause packet losses when data are transferring within SUs. The channel state at the k th time slot is denoted by $\theta_k \in \Theta = \{0, 1\}$, where 0 denoting OFF state of the channel (packets are lost), 1 denoting ON state (packets are received successfully). Therefore, a new switched system model is proposed for the LFC over CR networks in smart grids. Zero-order-holds (ZOHs) are used in the control center [68]. Considering the time

interval $l \in [t_k, t_{k+1})$, where t_k, t_{k+1} are two consecutive state jump instants, the state feedback controller for the LFC becomes the following two modes:

$$u(l) = \begin{cases} \mathbf{K}\mathbf{x}(l), \theta_{t_k} = 1 \\ \mathbf{K}\mathbf{x}(t_k), \theta_{t_k} = 0 \end{cases} \quad (4.8)$$

Plugging the above state feedback controller into the power system (4.7), the dynamics of the closed-loop power system have the following linear switched system form during the time interval $l \in [t_k, t_{k+1})$:

$$\mathbf{x}(l+1) = \begin{cases} (\mathbf{A} + \mathbf{BK})\mathbf{x}(l), \theta_{t_k} = 1 \\ \mathbf{A}\mathbf{x}(l) + \mathbf{BK}\mathbf{x}(t_k), \theta_{t_k} = 0 \end{cases} \quad (4.9)$$

From the iterative deduction of the power system (4.7), we can get the following equations of $\mathbf{x}(l)$ for $l \in [t_k, t_{k+1})$, based on $\mathbf{x}(t_k)$.

$$\mathbf{x}(l) = \begin{cases} (\mathbf{A} + \mathbf{BK})^{l-t_k}\mathbf{x}(t_k), \theta_{t_k} = 1 \\ (\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{BK})\mathbf{x}(t_k), \theta_{t_k} = 0 \end{cases} \quad (4.10)$$

The initial instant is denoted by t_0 and the initial state $\mathbf{x}(t_0)$ and θ_{t_0} are the initial conditions. Until t_{k+1} , the sojourn time sequence is $\{\tau_1, \tau_2, \dots, \tau_i, \dots, \tau_{k+1}\}$. In view of the fact that PUs opportunistically reclaim the communication channel back from SUs in the CR network, the sojourn time $\tau_i = t_{i+1} - t_i$ is a time-varying variable and is independent of other sojourn times within the sequence $\{\tau_1, \tau_2, \dots, \tau_i, \dots, \tau_{k+1}\}$. Correspondingly, the closed-loop power system is a time-varying linear switched system.

4.4 Stabilities of LFC over Cognitive Radio Networks

In the previous section, we propose a time-varying linear switched system model for the closed-loop power system over a CR network. In this section, the stabilities of the LFC over CR networks are going to be studied and sufficient conditions will be given for both the asymptotical stability and the mean-square stability of the power system under two different kinds of CR networks. Here, we consider the cases that sojourn time variables $\{\tau_1, \tau_2, \dots, \tau_i, \dots, \tau_{k+1}\}$ are independent to each other.

4.4.1 Asymptotical Stability for Arbitrary but Bounded Sojourn Times

Definition. 4.4.1 For arbitrary sojourn times $\tau_i \in [\tau_{min}, \tau_{max}], i \in \{0, 1, \dots, k+1\}$, the state trajectory $\mathbf{x}(l)$ in equation (4.10) with initial conditions $\mathbf{x}(t_0) = \mathbf{x}_0$ and $\theta_{t_0} = \theta_0 \in \Theta = \{0, 1\}$ is globally asymptotically stable if for any $\epsilon > 0$, there exists a $\beta > 0$, whenever $\|\mathbf{x}_0\| < \beta$, $\mathbf{x}_l$ satisfies $\|\mathbf{x}(l, t_0, \mathbf{x}_0)\| < \epsilon$ for any $l > t_0$, and $\lim_{l \rightarrow \infty} \|\mathbf{x}(l, t_0, \mathbf{x}_0)\| = 0$.

Theorem 4.4.1. *The power system (4.10) is globally asymptotically stable for arbitrary sojourn time $\tau_i \in [\tau_{min}, \tau_{max}], i \in \{0, 1, \dots, k+1\}$ if all the eigenvalues of the matrices $(\mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{B} \mathbf{K})$ are inside the unity circle*

Proof. When a sojourn time variable follows an arbitrary but bounded distribution, it changes randomly in a give range such as $\tau_i \in [\tau_{min}, \tau_{max}], i \in \{0, 1, \dots, k+1\}$. Without loss of generality, we consider the initial conditions $\mathbf{x}(t_0) = \mathbf{x}_0$ and $\theta_{t_0} = 1$ which means the communication channel is ON and packets are successfully transmitted. On the time interval $l \in [t_k, t_{k+1})$, the sojourn time sequence is $\{\tau_1, \tau_2, \dots, \tau_i, \dots, \tau_k, \tau_{k+1}\}$, and the corresponding state sequence is

$\{1, 0, 1, 0, \dots, 1, 0\}$. On the time interval $l \in [t_k, t_{k+1})$, $\theta_{t_k} = 0$, the system (4.10) has the following state response:

$$\mathbf{x}(l) = (\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{B} \mathbf{K}) \mathbf{x}(t_k)$$

Using the system equation (4.10), $\mathbf{x}(t_k)$ has the following response:

$$\mathbf{x}(t_k) = (\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_k} \mathbf{x}(t_{k-1})$$

And,

$$\mathbf{x}(t_{k-1}) = (\mathbf{A}^{\tau_{k-1}} + \sum_{r=0}^{\tau_{k-1}-1} \mathbf{A}^r \mathbf{B} \mathbf{K}) \mathbf{x}(t_{k-2})$$

By this deduction, the state $\mathbf{x}(l)$ has finally the following form:

$$\mathbf{x}(l) = (\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{B} \mathbf{K}) (\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_k} (\mathbf{A}^{\tau_{k-1}} + \sum_{r=0}^{\tau_{k-1}-1} \mathbf{A}^r \mathbf{B} \mathbf{K}) \cdots (\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_1} \mathbf{x}_0 \quad (4.11)$$

The state response norm is given as follows,

$$\begin{aligned} & \|(\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{B} \mathbf{K}) (\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_k} (\mathbf{A}^{\tau_{k-1}} + \sum_{r=0}^{\tau_{k-1}-1} \mathbf{A}^r \mathbf{B} \mathbf{K}) \cdots (\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_1} \mathbf{x}_0\| \\ & \leq \lambda_{max} \{ \mathbf{A}^{\tau_{max}} + \sum_{r=0}^{\tau_{max}-1} \mathbf{A}^r \mathbf{B} \mathbf{K} \} \|(\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_k} \cdots (\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_1}\| \|\mathbf{x}_0\|. \end{aligned} \quad (4.12)$$

If all the eigenvalues of both $(\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_i}$ and $(\mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{B} \mathbf{K})$ are inside the unity circle for $\tau_i \in [\tau_{min}, \tau_{max}]$, $i \in \{0, 1, \dots, k+1\}$, the convergence of the matrix products is guaranteed. In view of the fact that the original closed-loop system $\mathbf{A} + \mathbf{B} \mathbf{K}$ is stable, all the eigenvalues of the matrix $(\mathbf{A} + \mathbf{B} \mathbf{K})^{\tau_i}$ are inside the unity circle. Therefore, the system (4.10) is globally asymptotically stable if all the eigenvalues of the matrices $(\mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{B} \mathbf{K})$ are inside the unity circle for $\tau_i \in [\tau_{min}, \tau_{max}]$, $i \in \{0, 1, \dots, k+1\}$.

Thus, sufficient conditions for the globally asymptotical stability of the system (4.10) are obtained. $\square$

With this theorem, we are able to find the largest interval $[\tau_{min}, \tau_{max}]$ for τ_i , below which the globally asymptotical stability of the system (4.10) can be guaranteed. By calculating the maximum eigenvalues for $(\mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{B} \mathbf{K})$ with τ_i , the τ_{max} will be the values of τ_i that $(\mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{B} \mathbf{K})$ have the maximum eigenvalues outside of unity circle for the first time.

4.4.2 Mean-square Stability for Random Sojourn Times with Independent Identical Distribution

In this section, we study the stochastic stability (mean square stability) of the power system (4.10) with random sojourn times $\{\tau_1, \tau_2, \dots, \tau_i, \dots, \tau_k, \tau_{k+1}\}$ which follow the identical probability density function (p.d.f) $p(\tau_i)$ for all $i \in \{1, 2, \dots, k+1\}$.

Definition. 4.4.2 For i.i.d sojourn times which follow the probability density function (p.d.f) $p(\tau_i)$, for all $i \in \{1, 2, \dots, k+1\}$, the state trajectory $\mathbf{x}(l)$ in system (4.10) with initial conditions $\mathbf{x}(t_0) = \mathbf{x}_0$ and $\theta_{t_0} = \theta_0 \in \Theta = \{0, 1\}$ is mean square stable if $\mathbf{x}_l$ satisfies $\lim_{l \rightarrow \infty} E\{\|\mathbf{x}(l, t_0, \mathbf{x}_0)\|^2\} = 0$.

We give sufficient conditions under which the system (4.10) is mean square stable with random sojourn times.

Theorem 4.4.2. *The system (4.10), with sojourn times τ_i , $i \in \{1, 2, \dots, k+1\}$, which follow the identical probability density function (p.d.f) $p(\tau_i)$, is mean square stable, if the following inequalities hold for all $i \in \{1, 2, \dots, k+1\}$:*

- (a) *The expected maximum singular value of the matrices $\Psi(\tau_i)$ is convergent, that is $\sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{max}(\Psi(\tau_i)) < \infty$, where $\Psi(\tau_i) = (\mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{B} \mathbf{K})$;*

- (b) The expected maximum singular value of the matrices $\Upsilon(\tau_i)$ is convergent, that is $\sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{\max}(\Upsilon(\tau_i)) < \infty$, where $\Upsilon(\tau_i) = (\mathbf{A} + \mathbf{BK})^{\tau_i}$;
- (c) $\sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{\max}(\Upsilon(\tau_i))^2 < \infty$;
- (d) $\sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{\max}(\Psi(\tau_i))^2 < \infty$, where, $\sigma_{\max}(\ast)$ denotes the maximum singular value of the matrix $\ast$.

Proof. We consider the initial conditions $\mathbf{x}(t_0) = \mathbf{x}_0$ and $\theta_{t_0} \in \Theta = \{0, 1\}$. For each initial state case, the final state can be either $\theta_{t_k} = 0$ or $\theta_{t_k} = 1$. The sojourn time sequence during the time interval $[t_0, t_{k+1})$ is denoted by $\{\tau_1, \tau_2, \dots, \tau_i, \dots, \tau_k, \tau_{k+1}\}$. On the last state interval $[t_k, t_{k+1}]$, for any $l \in [t_k, t_{k+1})$, the state $\mathbf{x}(l)$ of the system (4.10) has the following possible forms.

(i) When the initial state of communication channel is OFF and the final state is OFF, the $\mathbf{x}(l)$ has the following form.

$$\mathbf{x}(l) = (\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{BK})(\mathbf{A} + \mathbf{BK})^{\tau_k} \dots (\mathbf{A} + \mathbf{BK})^{\tau_2} (\mathbf{A}^{\tau_1} + \sum_{r=0}^{\tau_1-1} \mathbf{A}^r \mathbf{BK}) \mathbf{x}_0 \quad (4.13)$$

Let $\Phi(\tau_k) = (\mathbf{A} + \mathbf{BK})^{\tau_k} \dots (\mathbf{A} + \mathbf{BK})^{\tau_2} (\mathbf{A}^{\tau_1} + \sum_{r=0}^{\tau_1-1} \mathbf{A}^r \mathbf{BK})$. The expectation of the square norm of $\mathbf{x}(l)$ is

$$\begin{aligned} E \{ \|\mathbf{x}(l)\|^2 \} &= E \left\{ \mathbf{x}_0^T [\Phi(\tau_k)^T (\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{BK})^T (\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{BK}) \Phi(\tau_k)] \mathbf{x}_0 \right\} \\ &\leq E \{ \sigma_{\max}(\mathbf{A}^{\tau_{k+1}} + \sum_{r=0}^{\tau_{k+1}-1} \mathbf{A}^r \mathbf{BK}) \} E \{ \Phi(\tau_k)^T \Phi(\tau_k) \} \|\mathbf{x}_0\|^2 \end{aligned} \quad (4.14)$$

where, $\sigma_{\max}(\ast)$ denotes the maximum singular value of the matrix $\ast$.

Due to

$$\begin{aligned} E \left\{ \Phi(\tau_k)^T \Phi(\tau_k) \right\} &\leq E \left\{ \|(\mathbf{A} + \mathbf{BK})^{\tau_k}\|^2 \right\} \cdots E \left\{ \|(\mathbf{A} + \mathbf{BK})^{\tau_2}\|^2 \right\} \\ &\quad E \left\{ \left\| \mathbf{A}^{\tau_1} + \sum_{r=0}^{\tau_1-1} \mathbf{A}^r \mathbf{BK} \right\|^2 \right\} \end{aligned}$$

, we have the following inequality.

$$\begin{aligned} E \left\{ \|\mathbf{x}(l)\|^2 \right\} &\leq E \left\{ \sigma_{\max}(\mathbf{A}^{\tau_{k+1}} + \sum_{r=0}^{\tau_{k+1}-1} \mathbf{A}^r \mathbf{BK}) \right\} E \left\{ \|(\mathbf{A} + \mathbf{BK})^{\tau_k}\|^2 \right\} \\ &\quad \cdots E \left\{ \|(\mathbf{A} + \mathbf{BK})^{\tau_2}\|^2 \right\} E \left\{ \left\| \mathbf{A}^{\tau_1} + \sum_{r=0}^{\tau_1-1} \mathbf{A}^r \mathbf{BK} \right\|^2 \right\} \|\mathbf{x}_0\|^2 \end{aligned}$$

Since all the sojourn times $\tau_i, i \in \{0, 1, \dots, k+1\}$ follow the identical p.d.f $p(\tau_i)$, if the following inequalities hold true:

$$E \left\{ \sigma_{\max}(\Psi(\tau_i)) \right\} = \sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{\max}(\Psi(\tau_i)) < \infty \quad (4.15)$$

where, $\Psi(\tau_i) = (\mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{BK})$, $p(\tau_i)$ is the probability density function of τ_i , and,

$$E \left\{ \|(\mathbf{A} + \mathbf{BK})^{\tau_i}\|^2 \right\} = \sum_{\tau_i=1}^{\infty} p(\tau_i) \|\Upsilon(\tau_i)\|^2 < \infty \quad (4.16)$$

where, $\Upsilon(\tau_i) = (\mathbf{A} + \mathbf{BK})^{\tau_i}$,

and,

$$E \left\{ \left\| \mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{A}^r \mathbf{BK} \right\|^2 \right\} = \sum_{\tau_i=1}^{\infty} p(\tau_i) \|\Psi(\tau_i)\|^2 < \infty \quad (4.17)$$

then, $E \left\{ \|\mathbf{x}(l)\|^2 \right\} < \infty$ and $\sum_{l=0}^{\infty} E \left\{ \|\mathbf{x}(l)\|^2 \right\} < \infty$. Therefore, system (4.10) is mean square stable.

(ii) If the initial state of communication channel is OFF and the final state is

ON, then

$$\mathbf{x}(l) = (\mathbf{A} + \mathbf{BK})^{1-t_k} (\mathbf{A}^{\tau_k} + \sum_{r=0}^{\tau_k-1} \mathbf{BK}) \cdots (\mathbf{A} + \mathbf{BK})^{\tau_2} (\mathbf{A}^{\tau_1} + \sum_{r=0}^{\tau_1-1} \mathbf{A}^r \mathbf{BK}) \mathbf{x}_0 \quad (4.18)$$

Following the same procedure as (i), we get the same results for (ii), except the following fact

$$E \{ \sigma_{\max}(\Upsilon(\tau_i)) \} = \sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{\max}(\Upsilon(\tau_i)) < \infty \quad (4.19)$$

$p(\tau_i)$ is the probability density function of τ_i .

(iii) If the initial state of the communication channel is ON and the final state is OFF, then

$$\mathbf{x}(l) = (\mathbf{A}^{l-t_k} + \sum_{r=0}^{l-t_k-1} \mathbf{A}^r \mathbf{BK}) (\mathbf{A} + \mathbf{BK})^{\tau_k} \cdots (\mathbf{A}^{\tau_2} + \sum_{r=0}^{\tau_2-1} \mathbf{A}^r \mathbf{BK}) (\mathbf{A} + \mathbf{BK})^{\tau_1} \mathbf{x}_0 \quad (4.20)$$

Following the same procedure as (i), we get the same results as (i).

(iv) If the initial state of the communication channel is ON and the final state is ON, then

$$\mathbf{x}(l) = (\mathbf{A} + \mathbf{BK})^{1-t_k} (\mathbf{A}^{\tau_{k-1}} + \sum_{r=0}^{\tau_{k-1}-1} \mathbf{A}^r \mathbf{BK}) \cdots (\mathbf{A}^{\tau_2} + \sum_{r=0}^{\tau_2-1} \mathbf{A}^r \mathbf{BK}) (\mathbf{A} + \mathbf{BK})^{\tau_1} \mathbf{x}_0 \quad (4.21)$$

Following the same procedure as (i), we get the same results as (ii).

If $\Psi(\tau_i)$ and $\Upsilon(\tau_i)$ are matrices with the ranks are m and n respectively, their singular values are denoted by $\sigma_j(\Psi(\tau_i))$ and $\sigma_j(\Upsilon(\tau_i))$. According to the properties of the singular values [69], $\|\Psi(\tau_i)\|^2 = \sum_{j=1}^m \sigma_j^2(\Psi(\tau_i))$, and $\|\Upsilon(\tau_i)\|^2 = \sum_{j=1}^n \sigma_j^2(\Upsilon(\tau_i))$. Thus, the condition (4.16) is equivalent to,

$$\begin{aligned} E \{ \|\mathbf{A} + \mathbf{BK}\|^2 \} &= \sum_{\tau_i=1}^{\infty} p(\tau_i) \|\Upsilon(\tau_i)\|^2 = \sum_{\tau_i=1}^{\infty} p(\tau_i) \sum_{j=1}^n \sigma_j^2(\Upsilon(\tau_i)) \\ &\leq n \sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{\max}(\Upsilon(\tau_i))^2 < \infty \end{aligned} \quad (4.22)$$

and the condition (4.17) is equivalent to

$$\begin{aligned} E \left\{ \left\| \mathbf{A}^{\tau_i} + \sum_{r=0}^{\tau_i-1} \mathbf{B}\mathbf{K} \right\|^2 \right\} &= \sum_{\tau_i=1}^{\infty} p(\tau_i) \|\Psi(\tau_i)\|^2 = \sum_{\tau_i=1}^{\infty} p(\tau_i) \sum_{j=1}^m \sigma_j^2(\Psi(\tau_i)) \\ &\leq m \sum_{\tau_i=1}^{\infty} p(\tau_i) \sigma_{\max}(\Psi(\tau_i))^2 < \infty \end{aligned} \quad (4.23)$$

In summary, if the inequalities (4.16), (4.19), (4.22), (4.23) hold, the system (4.7) is mean square stable. This completes the proof. $\square$

A maximum singular value is usually used as an important indicator to the robust stability of linear systems with uncertainties [70, 71]. Therefore, the expected maximum singular values of the matrices can be used as the upper bounds for the stochastic stability of the system (4.10).

4.5 Simulations

In this section, a two-area power system model is used to evaluate the effects of CR networks on the system performance. For stochastic sojourn time cases, both uniform and geometric p.d.f sojourn time processes are simulated to evaluate their influences to the dynamic performance of the power system. The two processes are firstly evaluated under two different initial frequency changes resulted from load changes. Then, they are investigated under two different tie-line power situations. For the arbitrary sojourn time case, the largest sojourn time interval below which the asymptotical stability can be guaranteed is calculated. For the stochastic sojourn time case, the expected maximum singular values are calculated for the sojourn times of CR networks follow a uniform probability distribution. All the numerical simulations are run in Matlab R2012a in a computer with 2.66GHz CPU and 8.00GB RAM. In this study, 100MVA is chosen as the base unit for per unit (pu) calculations.

Figure 4.5: Two-area power system

The two-area power system is shown in Fig 4.5 and its parameters are shown in Appendix C. Its state space model is given as follows.

$$\dot{\mathbf{x}} = \mathbf{A}_c \mathbf{x} + \mathbf{B}_c \mathbf{u} \quad (4.24)$$

where

where

$$\mathbf{x} = \begin{bmatrix} \Delta P_{tie} & \Delta f_1 & \Delta P_{m1} & \Delta P_{v1} & \Delta f_2 & \Delta P_{m2} & \Delta P_{v2} \end{bmatrix}^T; \mathbf{u} = \begin{bmatrix} \Delta P_{c1} & \Delta P_{c2} \end{bmatrix}^T;$$

$$\mathbf{A}_c = \begin{bmatrix} 0 & 0.545 & 0 & 0 & -0.545 & 0 & 0 \\ -5 & -0.07 & 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & -2.5 & 2.5 & 0 & 0 & 0 \\ 0 & -5.21 & 0 & -12.5 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & -0.05 & 6 & 0 \\ 0 & 0 & 0 & 0 & 0 & -2.78 & 2.78 \\ 0 & 0 & 0 & 0 & -6.94 & 0 & -16.67 \end{bmatrix};$$

$$\mathbf{B}_c = \begin{bmatrix} 0 & 0 & 0 & 12.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 16.67 \end{bmatrix}^T.$$

A Linear Quadratic Regulator (LQR) is designed for this power system $\mathbf{u} = \mathbf{K}\mathbf{x}$, the control gains are

$$\mathbf{K} = \begin{bmatrix} -0.1915 & 0.4640 & 1.1086 & 0.4379 & -0.1445 & -0.3362 & -0.0417 \\ -3.4763 & -0.6687 & -0.5064 & -0.0590 & 0.9898 & 1.6769 & 0.4275 \end{bmatrix} \quad (4.25)$$

Firstly, the effects of a CR network with uniform p.d.f. sojourn times on the power system performance are evaluated. The following mean square error (MSE) of the state of the power system is used as the metric of its dynamic performance:

$$MSE(k) = \frac{1}{N} \sum_{i=1}^N (\mathbf{x}(k) - \mathbf{x}_0(k))^T (\mathbf{x}(k) - \mathbf{x}_0(k)) \quad (4.26)$$

where, $\mathbf{x}_0(k)$ is the original power system state at k th time instant without any disturbances, and $\mathbf{x}(k)$ is the system state when a CR network is used, and N denotes

how many times the simulations run. Here, the simulations run 500 times and the time horizon of each simulation is 5 seconds. In order to evaluate different load changes and tie-line power flows in the power system, four different initial conditions are considered:

- Case 1: $\Delta f_1(0) = 1.5Hz$ in Area 1 and $\Delta f_2(0) = 0.5Hz$ in Area 2;
- Case 2: $\Delta f_1(0) = 2Hz$ in Area 1 and $\Delta f_2(0) = 1Hz$ in Area 2;
- Case 3: $\Delta P_{tie}^{12}(0) = 0.5(pu)$;
- Case 4: $\Delta P_{tie}^{12}(0) = 1(pu)$.

The MSEs of the states of the power system with random sojourn times which follow uniform p.d.f for the four cases are shown from Fig 4.6 to Fig 4.9. By comparing these Fig 4.6 and Fig 4.7, it can be seen that the system performance becomes much worse when the load changes in two areas are bigger. Also, for both cases, the system performance is the worst over the CR network with the biggest τ_{max} . When tie line power are considered, the comparison between the results of Fig 4.8 and Fig 4.9 shows that the system performance is worse when the larger tie-line power are transferring between area 1 and area 2. Moreover, for these two tie-line power cases, the system performance is the worst over the CR network with the biggest τ_{max} . According to these results, with a given maximum mean square error that a power system can endure, the maximum sojourn time that a CR network should not be exceeded can be estimated when the CR network is designed for a smart grid.

Then, the effects of a CR network with geometric p.d.f. sojourn times on the power system performance are evaluated. The MSEs of the states of the power system with random sojourn times which follow geometric p.d.f for the four cases are shown from Fig 4.10 to Fig 4.13, while the parameter p denotes the success probability of the geometric p.d.f. When load changes are considered, the comparison between the

Figure 4.6: Mean square errors of the power system states with uniform p.d.f sojourn times in Case 1

Figure 4.7: Mean square errors of the power system states with uniform p.d.f sojourn times in Case 2

Figure 4.8: Mean square errors of the power system states with uniform p.d.f sojourn times in Case 3

Figure 4.9: Mean square errors of the power system states with uniform p.d.f sojourn times in Case 4

Figure 4.10: Mean square errors of the power system states with geometric p.d.f sojourn times in Case 1

results of Fig 4.10 and Fig 4.11 tells that the system performance becomes much worse when the load changes in two areas of the power system are bigger. Also, it can be seen from the two figures that the system performance is the worst over the CR network with the smallest success probability of the geometric p.d.f. ($p = 0.4$). When tie line power changes are taken into accounts, by comparing Fig 4.12 and Fig 4.13, it is shown that the system performance is worse when the larger tie-line power are transferring between area 1 and area 2. Furthermore, for these two tie-line power cases, the system performance is the worst over the CR network with the smallest success probability of the geometric p.d.f. ($p = 0.4$). According to these results, with a given maximum mean square error that a power system can endure, the smallest successful transmission rate that a CR network should be reached can be estimated when the CR network is designed for a smart grid.

Figure 4.11: Mean square errors of the power system states with geometric p.d.f sojourn times in Case 2

Figure 4.12: Mean square errors of the power system states with geometric p.d.f sojourn times in Case 3

Figure 4.13: Mean square errors of the power system states with geometric p.d.f sojourn times in Case 4

Furthermore, the maximum sojourn time is calculated for the arbitrary but bounded sojourn time case according to Theorem 4.4.1. Maximum eigenvalues with different sampling periods are listed in Table 4.1. From this table, we can obtain the maximum sojourn times below which the asymptotical stability of the power system are guaranteed with different sampling periods, by checking the first time when maximum eigenvalues are outside unity circle which are indicated as bolded and colored numbers in the table.

Finally, we consider a stochastic sojourn time case. The stochastic sojourn times are assumed to follow the uniform p.d.f within $[\tau_{min}, \tau_{max}]$. This kind of sojourn times has been used to model the sojourn times in CR networks [60]. The relationships between the expected maximum singular values and the maximum sojourn time intervals with different sampling periods have been shown in Table 4.2 and Table 4.3. These tables are able to give suggestions on how to design the CR networks to guarantee

Table 4.1: The maximum eigenvalues of the matrices $\lambda(\Psi(\tau))$ with different sampling periods T_s

τ (time steps)	$\lambda(\Psi(\tau))$ ($T_s = 0.05s$)	$\lambda(\Psi(\tau))$ ($T_s = 0.1s$)	$\lambda(\Psi(\tau))$ ($T_s = 0.5s$)	$\lambda(\Psi(\tau))$ ($T_s = 1s$)
1	$0.9092 + 0.1409i$	$0.8252 + 0.2636i$	$-0.0860 + 0.7328i$	$-0.5639 + 0.1830i$
2	$0.7998 + 0.2558i$	$0.5905 + 0.4278i$	$-0.4829 + 0.1912i$	$0.2758 + 0.2706i$
3	$0.6754 + 0.2961i$	-0.6043	$0.3125 + 0.3354i$	$-0.0851 + 0.2006i$
4	-1.3261	-0.9937	$0.2788 + 0.3278i$	$0.0219 + 0.1312i$
5	-2.0714	-1.8570	$-0.2343 + 0.2897i$	$0.0334 + 0.0996i$
6	-2.6570	-2.7057	0.3935	-0.0790
7	-3.6432	-3.3791	0.4433	$0.0328 + 0.0325i$
8	-4.7127	-3.9666	0.5127	-0.0488
9	-5.8693	-4.4563	0.5803	0.0364
10	-7.0743	-4.8474	0.6420	0.0783
11	-8.3116	-5.1475	0.7023	0.0256
12	-9.5671	-5.3701	0.7640	-0.1077
13	-10.8281	-5.5323	0.8264	0.0127
14	-12.0836	-5.6525	0.8887	-0.1372
15	-13.3242	-5.7484	0.9507	-0.1519
16	-14.5420	-5.8357	1.0127	-0.1666

the stochastic stability of the LFC of smart grids, according to the corresponding relationships between the maximum sojourn time interval and the expected maximum singular value.

4.6 Summary

In this chapter, we have studied the stability of the LFC of smart grids for which cognitive radio (CR) networks are used as the communication and networking infrastructure. By modeling a CR network as an On-Off switch with sojourn times, a new switched power system model has been proposed for the LFC of a smart grid. The stability of the LFC of the smart grid has been studied for two main types of CR networks: 1) the sojourn times are arbitrary but bounded, and 2) the sojourn times follow an independent and identical distribution (i.i.d) process. For the first type of

Table 4.2: The maximum singular values $\sigma_{max}(\Psi(\tau))$ with the maximum sojourn times τ_{max} under sampling period T_s

τ_{max} time steps	$\sigma_{max}(\Psi(\tau))$ $h = 0.05$	$\sigma_{max}(\Psi(\tau))$ $h = 0.1$	$\sigma_{max}(\Psi(\tau))$ $h = 0.5$	$\sigma_{max}(\Psi(\tau))$ $h = 1$
1	1.7391	2.1950	2.7718	1.2238
2	11.7573	9.6373	2.6534	1.3902
3	15.2699	12.1562	2.7059	1.2699
4	17.2216	13.5203	2.5066	1.2856
5	18.5933	14.4820	2.4528	1.2717
6	19.7057	15.2893	2.4636	1.2775
7	20.6924	16.0455	2.4849	1.2872
8	21.6170	16.7984	2.5049	1.2983
9	22.5131	17.5686	2.5339	1.3148
10	23.4002	18.3613	2.5719	1.3307

Table 4.3: The maximum singular values $\sigma_{max}(\Upsilon(\tau))$ with the maximum sojourn times τ_{max} under sampling period T_s

τ_{max} time steps	$\sigma_{max}(\Upsilon(\tau))$ $h = 0.05$	$\sigma_{max}(\Upsilon(\tau))$ $h = 0.1$	$\sigma_{max}(\Upsilon(\tau))$ $h = 0.5$	$\sigma_{max}(\Upsilon(\tau))$ $h = 1$
1	1.7391	2.1950	2.7718	1.2238
2	1.9304	2.3592	2.0105	0.9436
3	2.0618	2.4618	1.8759	0.7941
4	2.1604	2.5110	1.5547	0.6828
5	2.2368	2.5116	1.4447	0.5965
6	2.2953	2.4707	1.2699	0.5270
7	2.3380	2.3975	1.1759	0.4701
8	2.3663	2.3022	1.0582	0.4227
9	2.3814	2.1949	0.9824	0.3828
10	2.3844	2.0856	0.8987	0.3490

CR networks, sufficient conditions have been derived for ensuring the asymptotical stability of the LFC of the smart grid. For the later one, sufficient conditions have been found to guarantee the mean-square stability of the LFC of the smart grid. Simulation results show how the conflict between PU and SU traffics affects the dynamic performance of the smart grid. They also show that the degraded dynamic performance and these developed sufficient conditions can be used to estimate the maximum sojourn time in the design of CR networks in smart grids.

Chapter 5

Denial-of-Service Attacks on Load Frequency Control in Largely Interconnected Power Grids

5.1 Introduction

As another reason that results in communication failures in smart grids, the impact of the denial-of-service (DoS) attack on the load frequency control (LFC) in a largely interconnected power grid is studied in this chapter. In particular, we consider DoS attacks on the communication channels in the sensing loop through which measurements telemetered in remote terminal units (RTUs) are sent to control centers. It can be noted that adversaries may make the power system unstable by properly designing their DoS attack sequences. Simulation studies are conducted to evaluate the effect of DoS attacks on the dynamic performance of the power system.

The rest of this chapter is organized as follows. In Section 5.2, the DoS attack issues in smart grids are introduced. In Section 5.3, the power system with DoS attacks is modeled as a switched system. In Section 5.4, the existence of DoS attacks that can make the power system unstable is proved. In Section 5.5, a two-area power

system model is used to evaluate the effect of DoS attacks on the power system. Finally, conclusions are made in Section 5.6.

5.2 Denial-of-Service (DOS) Attacks in Smart Grids

While open communication infrastructures are embedded into smart grids to support vast amounts of data exchange, they make smart grids more vulnerable to cyber attacks. The importance of securing current and future power grids has attracted more and more attentions from both the academia and industry communities. In [72], the authors pointed out that replacing proprietary network by open communication standards exposes process control and supervisory control and data acquisition (SCADA) systems to cyber security risks. A class of false data attacks on state estimation in power SCADA system, bypassing the bad data detection, were firstly presented in [73]. In [74], adversaries were assumed to only know the perturbed model of power systems when they are designing false data attacks against state estimations. In [75], the smallest set of adversary-controlled meters was identified to perform an unobservable attacks.

Although these works are very promising, they considered only static state estimation in power systems without noticing the impact of attacks on the dynamics of power systems. Regarding cyber attacks on SCADA control systems, a lot of challenges were identified by A. A. Cardenas et al in [74, 76]. In [77], Y. Mo et al. studied false data attacks on a control system equipped with a Kalman filter. As one of the few automatic control systems in the control center of a power system, the LFC under cyber attacks is considered in Viking projects conducted in [78, 79]. They performed the analysis of the impacts of cyber attacks on control centers in a power system, by

Figure 5.1: Two-area load frequency control (LFC) under DoS attacks

using reachability methods. However, they only considered the scenario that control center is attacked and controlled by adversaries. In fact, it is harder to attack the control center than to compromise the communication channels in the sensing loop of a power system. The sensing loop could be either for traditional SCADA systems or wide-area measurement systems (WAMSs).

To launch a DoS attack on the communication channels, the adversaries can jam the communication channels, attack networking protocols, and flood the network traffic etc. [80,81]. If attacked, measurement packets sent from sensors through this channel will be lost. Thus, the existence of DoS attacks may destabilize power systems.

5.3 Modeling of A Largely Interconnected Power System with DoS Attacks

In this section, the classical model of a LFC [8,33] is extended to include DoS attacks existing in sensing channels of the multi-area interconnected power system, shown

in Fig 5.1. In Fig 5.1, the telemetered measurements for RTUs are sent back to the control center of the LFC through communication channels either wired or wireless networks. The adversaries can launch DoS attacks by jamming the communication channels or flooding network traffics to cause congestions in networks. As the telemetered measurements are lost, the control center cannot update its control commands in time and the dynamic performance of the power system may be influenced. For LFC studies, all the generators in each area are represented equivalently by one single machine.

The model of the LFC in the area i was described in the previous chapter and omitted here. For the whole multi-area power system, a linear time invariant(LTI) interconnected model is given by:

$$\dot{\mathbf{x}}(t) = \mathbf{A}_c \mathbf{x}(t) + \mathbf{B}_c \mathbf{u}(t) \quad (5.1)$$

where

$$\mathbf{x} = \begin{bmatrix} x_1 & x_2 & \cdots & x_N \end{bmatrix}^T; \mathbf{u} = \begin{bmatrix} u_1 & u_2 & \cdots & u_N \end{bmatrix}^T;$$

$$\mathbf{A}_c = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1N} \\ A_{21} & A_{22} & \cdots & A_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ A_{N1} & A_{N2} & \cdots & A_N \end{bmatrix}; \mathbf{B}_c = \text{diag} \left\{ B_1 \quad B_2 \quad \cdots \quad B_N \right\}^T;$$

Due to the DoS attack and the attack sequence are inherently in a discrete-time fashion, the following discrete-time model of the power system is considered:

$$\mathbf{x}(k+1) = \mathbf{A} \mathbf{x}(k) + \mathbf{B} \mathbf{u}(k) \quad (5.2)$$

where, $\mathbf{A} = e^{\mathbf{A}_c h}$, $\mathbf{B} = \int_0^h e^{\mathbf{A}_c \tau} \mathbf{B}_c d\tau$, h is the sampling period.

Figure 5.2: The model of the power system under DoS attacks

We consider the following optimal state feedback controller with the gain matrix $\mathbf{K}$

$$\mathbf{u}(k) = -\mathbf{K}\mathbf{x}(k) \quad (5.3)$$

for the power system.

When DoS attacks are considered, the adversary attacks the communication channels, by preventing the sensed measurements in RTUs to be transmitted successfully to the control center. We can model a DoS attack as a switching on/off event of the state $\mathbf{x}(k)$ as shown in Fig 5.2. We denote the equivalent controller by

$$\mathbf{u}(k) = -\mathbf{K}\tilde{\mathbf{x}}(k). \quad (5.4)$$

Since we consider the controller equipped with zero-order-hold (ZOH), the DoS attack on $\mathbf{x}(k)$ can be modeled as follows.

$$\begin{cases} \tilde{\mathbf{x}}(k) = \mathbf{x}(k) & \text{if, } S_1; \\ \tilde{\mathbf{x}}(k) = \tilde{\mathbf{x}}(k-1) & \text{if, } S_2 \end{cases} \quad (5.5)$$

Define the augmented state $\mathbf{z}(k) = [\mathbf{x}^T(k), \tilde{\mathbf{x}}^T(k-1)]^T$. By integrating the (5.4)

into (5.2), we get the closed-loop form with the augmented state:

$$\mathbf{z}(k+1) = \Phi_{\sigma_i} \mathbf{z}(k) \quad (5.6)$$

where σ_i is the switch position variable, $\sigma_i = 1$ for position S_1 , $\sigma_i = 2$ for position S_2 ,

$$\Phi_1 = \begin{bmatrix} \mathbf{A} - \mathbf{BK} & \mathbf{0} \\ \mathbf{I} & \mathbf{0} \end{bmatrix}; \Phi_2 = \begin{bmatrix} \mathbf{A} & -\mathbf{BK} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}.$$

In practice, DoS attacks can be performed by intentionally changing the switch position for a random time interval $[t_{si}, t_{fi})$, where t_{si} and t_{fi} are the DoS attack starting and finishing time instants, respectively. For example, in a time interval $[k, k+30)$, the switch position may be in S_1 during the time interval $[k, k+10]$, and be in S_2 during $(k+11, k+30)$.

5.4 Existence of Successful DoS Attacks in the Smart Grid

In this section, it will be shown that DoS attacks can make the power system unstable by carefully designing the sequential attacking time intervals of DoS attacks. The power system with DoS attacks has been modeled as a linear switched system in the previous section. As it is known, the stability of a switched system has been extensively addressed, such as [82, 83]. On the one hand, the whole system which comprises of several unstable subsystems can be stable by properly designing switching strategy among these subsystems. On the other hand, it can be also unstable, by improperly switching among several stable subsystems. From the adversaries' point of view, they may be able to make the whole power system unstable by choosing proper switching strategies.

At first, we will show the necessary and sufficient conditions for the stability of a linear switched system.

Theorem 5.4.1. [83] *A linear switched system $x(k+1) = \Phi_{\sigma_i}x(k)$ where $\Phi_{\sigma_i} \in \{\Phi_1, \Phi_2, \dots, \Phi_N\}$, is asymptotically stable under arbitrary switching if and only if there exists a finite integer n such that*

$$\|\Phi_{i_1}\Phi_{i_2}\cdots\Phi_{i_n}\| < 1 \quad (5.7)$$

for all n -tuple $\Phi_{i_j} \in \{\Phi_1, \Phi_2, \dots, \Phi_N\}$, where $j = 1, 2, \dots, n$, $\{i_1, i_2, \dots, i_n\}$ is the switching rule.

According to the above Theorem 5.4.1, it may be possible for adversaries to find switching rules to make the power system unstable as long as these switching rules make $\|\Phi_{i_1}\Phi_{i_2}\cdots\Phi_{i_n}\| \geq 1$ happen. In fact, we can equivalently see the switched system (5.6) as an average system

$$\Phi_\alpha = \alpha\Phi_1 + (1-\alpha)\Phi_2 \quad (5.8)$$

where $0 < \alpha < 1$.

Then, we can get the following theorem to show there might exist some switching DoS attacks make the power system (5.6) unstable.

Theorem 5.4.2. *The linear switched system (5.6) where $\Phi_{\sigma_i} \in \{\Phi_1, \Phi_2\}$, is unstable, if there exists a constant $0 < \alpha < 1$ such that the average system $\Phi_\alpha = \alpha\Phi_1 + (1-\alpha)\Phi_2$ has an eigenvalue with its magnitude outside the unity circle.*

Proof. The time interval $[t_s, t_f]$, defining $\eta = t_f - t_s$, is considered for the linear switched system (5.6) where $\Phi_{\sigma_i} \in \{\Phi_1, \Phi_2\}$. We assume, without attacks, the linear switched system (5.6) stays at Φ_1 for $\alpha\eta$ seconds. Then, the adversary starts the DoS

attacks. That means the system (5.6) stays at Φ_2 for $(1 - \alpha)\eta$ seconds. The state of the system (5.6) at time instant t_f will be

$$\mathbf{x}(t_f) = e^{\Phi_1 \alpha \eta} e^{\Phi_2 (1 - \alpha) \eta} \mathbf{x}(t_s) \quad (5.9)$$

Let $\Phi(t_f) = e^{\Phi_1 \alpha \eta} e^{\Phi_2 (1 - \alpha) \eta}$. The system (5.6) is unstable, if $\Phi(t_f)$ has eigenvalues which are outside the unity circle. For some commutable and Hurwitz matrices Φ_1 and Φ_2 ,

$$\Phi(t_f) = e^{\Phi_1 \alpha \eta} e^{\Phi_2 (1 - \alpha) \eta} = e^{\Phi_1 \alpha \eta + \Phi_2 (1 - \alpha) \eta} = e^{(\Phi_1 \alpha + \Phi_2 (1 - \alpha)) \eta} \quad (5.10)$$

Thus, the system (5.6) is unstable, if its equivalent average system matrix $\Phi_1 \alpha + \Phi_2 (1 - \alpha)$ has eigenvalues with magnitudes outside the unity circle. $\square$

5.5 Simulations

In this section, a two-area power system model shown in Fig 5.1 is used to evaluate the impacts of DoS attacks on power systems. The generators in each area are modeled as a single equivalent generator. Matlab/Simulink R2012a is chosen as the simulation environment. In this chapter, we consider DoS attacks existing in communication channels of the sensing loop of the power system. We use 100 MVA as the base unit for per unit (pu) calculations. All the parameters of the two-area power system are shown as follows:

$$T_{ch1,2} = 0.08s, T_{g1,2} = 0.3s, R_{1,2} = 2.4Hz/pu, D_{1,2} = 0.0084pu/Hz \\ M_{1,2} = 0.1667, T_{12} = 0.08678.$$

The original linear quadratic optimal controller is $\mathbf{u} = -\mathbf{K}\mathbf{x}$. By using the command *dlqr* in Matlab R2012a and setting $Q = 100 * \text{diag}([1111111111]), R = 100 * \text{diag}([11])$, the controller gain $\mathbf{K}$ can be obtained.

Firstly, according to Theorem 5.4.2 and its proof, the root locus of $\det(\lambda I - \Phi_\alpha) = 0$

Figure 5.3: The root locus of the average two-area power system (Arrows indicate α decreasing)

, where $\Phi_\alpha = \alpha\Phi_1 + (1 - \alpha)\Phi_2$, is shown in Fig 5.3 by increasing $\alpha \in [0.1, 1)$. As it is illustrated in Fig 5.3, the system becomes unstable as $\alpha \leq 0.4$.

Then, simulations are conducted to evaluate the system performance when both area 1 and area 2 are under DoS attacks. We will see how the dynamics change according to different DoS attacks launching time, indexing by $0 < \alpha \leq 1$. The time duration is set to be 1 second. Four cases are considered in this chapter:

- Case 1: $\alpha = 1$, the power system operates normally;
- Case 2: $\alpha = 0.8$, the power system operates under DoS attacks activated at $T = 0.8s$;
- Case 3: $\alpha = 0.4$, the power system operates under DoS attacks activated at $T = 0.4s$;
- Case 4: $\alpha = 0.3$, the power system operates under DoS attacks activated at $T = 0.3s$.

The dynamics of the two-area power system are shown in Fig 5.4 and Fig 5.5. These

Figure 5.4: The dynamics of area 1 under different DoS attacks initial times

figures illustrate the effects of the proposed DoS attacks on the two-area dynamic power system. It can be observed that DoS attacks affect the dynamics of the power system seriously when $\alpha \leq 0.4s$ which coincide with the root locus analysis. Thus, the adversary would like to launch DoS attacks as early as possible. The DoS attacks might not work anymore if they start late such as the cases when $\alpha = 0.8s$ in these two figures.

5.6 Summary

This chapter considers the problem that how DoS attacks in the cyber layer of smart grids can affect the dynamic performance of physical power systems. The power system under DoS attacks is modeled as a linear switched system, by formulating DoS attacks as a switch (on/off) action on sensing channels. We identify the existence of

Figure 5.5: The dynamics of area 2 under different DoS attacks initial times

DoS attacks that can destabilize the power system, by using switched system theories. In simulation studies, a two-area LFC power system model has been built to evaluate the effect of DoS attacks with different attack-launching instants. It shows that DoS attacks can affect the dynamic performance of the power system badly if they are launched early before the dynamics of the power system converge. Its dynamics are weakly influenced when adversaries enable DoS attacks after the dynamics of the power system converge.

Chapter 6

Modeling and Distributed Gain Scheduling Strategy for Load Frequency Control with Communication Failures in Largely Interconnected Power Grids

6.1 Introduction

From analysis results presented in the previous two chapters, it can be found that it is critical to design advanced control methods to improve the robustness of smart grid control to communication failures. In this chapter, a distributed gain scheduling LFC strategy is proposed to compensate for the degraded performance due to communication failures. A four-area LFC power system model is used to verify the effectiveness of the proposed method.

The rest of this chapter is organized as follows. In Section 6.2, the general structure of the proposed distributed gain scheduling approach is introduced. In Section 6.3, a new power system model is introduced to integrate the changes of communication topologies into the physical dynamics. In Section 6.4, the stability analysis of this new power system is conducted. The distributed gain scheduling algorithm is described

in Section 6.5. In Section 6.6, simulations are conducted by using a four-area power system model under six communication topologies. Finally, Section 6.7 concludes this chapter with some remarks.

Figure 6.1: Centralized control scheme

Figure 6.2: Distributed control scheme

Figure 6.3: The proposed distributed control algorithm

6.2 General Structure of The Proposed Distributed Gain Scheduling Strategy

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 6.2) work better than their centralized counterparts (see Fig 6.1) [2, 48, 84]. For distributed control strategies, the entire power system can be divided into multiple interconnected areas [28, 35, 85] or micro-grids with distributed generations (DGs) [2, 86, 87]. 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 amounts of information exchanged in a real-time power system, high-speed open communication infrastructures are urgently required to be implemented in large-scale power systems [51, 88]. In [85], GridStat, a prototype of a new communication framework, is proposed for delivering real-time information and operational commands in power systems. For substation automation, local area

networks (LANs) are introduced in communications for intelligent electronic devices (IEDs) within substations under the communication standard IEC 61850, while wide area networks (WANs) are used for data exchange among substations [54, 89, 90].

In this chapter, a new distributed control method is proposed for the LFC of a smart grid to counteract the communication failure effect. A two-layer structure is introduced and a global communication topology detector (CTD) is used to check communication topologies in a real-time fashion and distribute the communication topology information to each area control center (ACC). With the knowledge of its local communication topology changes, each ACC calculates its optimal local and inter-connected feedback gain matrices accordingly. The proposed distributed control scheme is illustrated in Fig 6.3.

6.3 Modeling of A Multi-area Interconnected Power System with Communication Failures

The frequency control of a power system is fundamental in determining the way in which the frequency will change when load changes happen [91, 92].

We assume there are N interconnected areas in the power system. We write the discrete-time state-space model of the above dynamics for the LFC in area i as follows:

$$x_i(k+1) = A_i x_i(k) + B_i u_i(k) + \sum_{j=1, j \neq i}^N A_{ij} x_j(k) + F_i \Delta P_{L_i}(k), i \in \{1, 2, \dots, N\} \quad (6.1)$$

where $x_i = \begin{bmatrix} \Delta f_i & \Delta P_{m_i} & \Delta P_{v_i} & \Delta P_{tie}^{ij} \end{bmatrix}^T$; $u_i = \Delta P_{c_i}$;

$$\begin{aligned}
A_i &= \begin{bmatrix} -\frac{D_i}{M_i} & \frac{1}{M_i} & 0 & -\frac{1}{M_i} \\ 0 & -\frac{1}{T_{ch_i}} & \frac{1}{T_{ch_i}} & 0 \\ -\frac{1}{R_i T_{g_i}} & 0 & -\frac{1}{T_{g_i}} & 0 \\ -\sum_{j=1, j \neq i}^N T_{ij} & 0 & 0 & 0 \end{bmatrix}; A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ T_{ij} & 0 & 0 & 0 \end{bmatrix}; \\
B_i &= \begin{bmatrix} 0 & 0 & \frac{1}{T_{g_i}} & 0 \end{bmatrix}^T; F_i = \begin{bmatrix} -\frac{1}{M_i} & 0 & 0 & 0 \end{bmatrix}^T.
\end{aligned}$$

In the distributed control of the power system, each area controller needs not only its own states, but also the states of its neighbors. By assuming the communication infrastructures are completely reliable, the distributed controller for i th area can be:

$$u_i(k) = -K_i x_i(k) - \sum_{j=1, j \neq i}^N K_{ij} x_j(k), i \in \{1, 2, \dots, N\} \quad (6.2)$$

where K_i, K_{ij} are constant feedback gains matrices.

For u_i in the i th ACC, other areas' states x_j are accessible through the communication infrastructures. However, random communication failures happen in communication links. They will cause communication topology changes. Therefore, it is more practical to take communication topology changes into consideration when we design the distributed control for the LFC in a smart grid. The structure disturbances of u_i resulted from communication topology changes are modeled by the following time-varying communication matrix.

Definition. 6.3.1 Communication matrix: The communication matrix of S is a binary matrix $L(k) = [l_{ij}(k)]_{n \times n}$ have the elements $l_{ij}(k) = 0$ or 1. Since x_i is a local state in the i th ACC, $l_{ii}(k) = 1$ is always true. That means $L(k)$'s diagonal elements

are all ones.

$$L(k) = \begin{bmatrix} 1 & l_{12}(k) & \cdots & l_{1n}(k) \\ l_{21}(k) & 1 & \cdots & l_{2n}(k) \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1}(k) & l_{n2}(k) & \cdots & 1 \end{bmatrix} \quad (6.3)$$

Now the dynamics of the large power system including communication topology effects are written as

$$x_i(k+1) = A_i x_i(k) + B_i u_i(k) + \sum_{j=1, j \neq i}^N l_{ij}(k) A_{ij} x_j(k) + F_i \Delta P_{L_i}(k), i \in \{1, 2, \dots, N\} \quad (6.4)$$

Also, the state feedback distributed controllers including the effects of communication topologies are

$$u_i(k) = -K_i x_i(k) - \sum_{j=1, j \neq i}^N l_{ij}(k) K_{ij} x_j(k), i \in \{1, 2, \dots, N\} \quad (6.5)$$

where K_i, K_{ij} are constant feedback gains matrices. Plugging these controllers into the dynamics of the large power system, we get the closed-loop form as follows.

$$x_i(k+1) = \hat{A}_i x_i(k) + \sum_{j=1, j \neq i}^N l_{ij}(k) \hat{A}_{ij} x_j(k) + F_i \Delta P_{L_i}(k), i \in \{1, 2, \dots, N\} \quad (6.6)$$

where $\hat{A}_i = A_i - B_i K_i, \hat{A}_{ij} = A_{ij} - B_i K_{ij}$.

6.4 Stability Analysis of The Multi-area Interconnected Power System with Communication Failures

In this section, we give sufficient conditions to keep the multi-area interconnected power system with communication topology changes (its dynamic model is (6.6)) globally asymptotically stable.

In order to analyze the stability of the power system (6.6), we firstly recall the theorem of M – matrix.

Lemma 6.4.1. [93] *There exists a positive diagonal matrix D such that $DW + W^T D$ is positive definite if and only if W is an M – matrix; that is the leading principal minors of W are positive:*

$$\det \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1N} \\ w_{21} & w_{22} & \cdots & w_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ w_{N2} & w_{12} & \cdots & w_{NN} \end{bmatrix} > 0,$$

In [94] and [93], both Siljak and Khalil analyzed the stability issues of nonlinear interconnected systems by a Lyanunov function method. A similar Lyanpunov method is also used for the stability analysis of the multi-area interconnected power system (6.6).

Theorem 6.4.2. *A linear system (6.6) is globally asymptotically stable if the following test matrix $W = [w_{ij}]_{N \times N}$ is an M – matrix.*

$$w_{ij} = \begin{cases} \lambda_m(H_i - G_i) - 2l_{ij}\lambda_M(H_i)\lambda_M^{1/2}(\hat{A}_i^T \hat{A}_i), & i = j \\ -2l_{ij}\lambda_M(H_i)\lambda_M^{1/2}(\hat{A}_{ij}^T \hat{A}_{ij}), & i \neq j \end{cases} \quad (6.7)$$

where G_i, H_i are symmetric positive definite matrices satisfy the Lyapunov matrix equations $\hat{A}_i H_i \hat{A}_i - H_i = -G_i$, and $\lambda_m(\star)$ and $\lambda_M(\star)$ are the minimum and maximum eigenvalues of the corresponding matrices respectively.

Proof. The linear system (6.6) is an interconnection of N subsystems

$$x_i(k+1) = \hat{A}_i x_i(k), i \in \{1, 2, \dots, N\} \quad (6.8)$$

Denote interconnection terms as functions $I_i(x(k)) = \sum_{j=1, j \neq i}^N l_{ij} \hat{A}_{ij} x_j(k)$, where $x = [x_1^T, x_2^T, \dots, x_N^T]^T$.

Let us build the following function

$$V(x(k)) = \sum_{i=1}^N d_i V_i(x_i(k)) \quad (6.9)$$

as a composite Lyapunov function of the linear system (6.6), where $d_i > 0$ for all $i \in \{1, 2, \dots, N\}$.

For each subsystem $i \in \{1, 2, \dots, N\}$, we choose a quadratic Lyapunov function

$$V_i(x_i(k)) = x_i(k)^T H_i x_i(k) \quad (6.10)$$

where H_i is a symmetric positive definite matrix. H_i satisfies a Lyapunov matrix equation $\hat{A}_i H_i \hat{A}_i - H_i = -G_i$, where G_i is a symmetric positive definite matrix.

Each subsystem is stable, if the following inequalities hold.

$$\lambda_m(H_i)\|x_i(k)\|^2 \leq V_i(x_i(k)) \leq \lambda_M(H_i)\|x_i(k)\|^2, i \in \{1, 2, \dots, N\} \quad (6.11)$$

where, $\lambda_m(H_i)$ and $\lambda_M(H_i)$ are the minimum and maximum eigenvalues of H_i respectively. And,

$$\Delta V_i(x_i(k)) = V_i(x_i(k+1)) - V_i(x_i(k)) \leq -\lambda_m(G_i)\|x_i(k)\|^2, i \in \{1, 2, \dots, N\} \quad (6.12)$$

where, $\lambda_m(G_i)$ is the minimum eigenvalue of G_i respectively.

Define a comparison function $\phi_i \in \mathcal{K}$ for each $i \in \{1, 2, \dots, N\}$. We suppose the interconnection terms $I_i(x(k)) = \sum_{j=1, j \neq i}^N l_{ij} \hat{A}_{ij} x_j(k)$ satisfy the following inequalities

$$\|I_i(x(k))\| \leq \sum_{j=1, j \neq i}^N l_{ij} \xi_{ij} \phi_j(\|x_j(k)\|), i \in \{1, 2, \dots, N\} \quad (6.13)$$

where $\xi_{ij} \geq 0$. The derivative of $V(x(k)) = \sum_{i=1}^N d_i V_i(x_i(k))$ along the trajectories of the multi-area interconnected power system (6.6) satisfies the inequality

$$\begin{aligned} \Delta V(x(k)) &= V(x(k+1)) - V(x(k)) \\ &\leq \sum_{i=1}^N d_i [-\eta_i \phi_i^2(\|x_i(k)\|) + l_{ij} \xi_{ij} \phi_i(\|x_i(k)\|) \phi_j(\|x_j(k)\|)] \\ &\leq -1/2 \phi^T(\|x(k)\|) (DW + W^T D) \phi(\|x(k)\|) \end{aligned} \quad (6.14)$$

where $\phi(\|x(k)\|) = [\phi_1(\|x_1(k)\|), \phi_2(\|x_2(k)\|), \dots, \phi_N(\|x_N(k)\|)]^T$, $D = \text{diag}\{d_1, d_2, \dots, d_N\}$, $\eta_i > 0$. Define $\xi_{ij} = \lambda_M^{1/2}(\hat{A}_{ij}^T \hat{A}_{ij})$. From the inequalities (6.11) and (6.12), we choose $\phi_i(x_i(k)) = \|x_i(k)\|$. Thus, we get a W matrix whose

elements are defined by

$$w_{ij} = \begin{cases} \lambda_m(H_i - G_i) - 2l_{ij}\lambda_M(H_i)\lambda_M^{1/2}(\hat{A}_i^T \hat{A}_i), & i = j \\ -2l_{ij}\lambda_M(H_i)\lambda_M^{1/2}(\hat{A}_{ij}^T \hat{A}_{ij}), & i \neq j \end{cases} \quad (6.15)$$

If W is M -matrix, according to the Theorem 6.4.2, the inequality $DW + W^T D > 0$ holds. Then, $\Delta V(x(k)) < 0$ holds for all $x \neq 0$. So, the interconnected system is uniformly asymptotically stable. $\square$

6.5 Distributed Gain Scheduling Strategy for The LFC in A Smart Grid

In this chapter, our goal is to develop a distributed gain scheduling method for the LFC of a smart grid to compensate for the degraded dynamic performances caused by communication topology changes. As shown in Fig 6.3, a global communication topology detector (CTD) is used by installing some network topology softwares (*Remark 6.5.1*). Then, it distributes the communication topology to each ACC by sending the i th row vector information R_i of the communication matrix to the i th ACC. After knowing its local neighbors, the i th ACC calculates corresponding optimal local and inter-connective gain matrices $K_i(\infty)$ and K_{ij}^* to reduce the effects of the corresponding inter-connective terms.

Firstly, we assume that each pair (A_i, B_i) as defined in equation (6.1) is controllable. Thus, we can always choose the feedback gains K_i to place the eigenvalues of $\hat{A}_i$ at the desired locations in root loci. Linear quadratic regulators (LQR) are designed for each (A_i, B_i) . That is to find optimal state feedback controllers $u_i(k)$ for all $i \in \{1, 2, \dots, N\}$ to minimize the following cost functions during the time range

$[0, t_f]$:

$$J_i = x_i(t_f)^T S_i x_i(t_f) + \sum_{k=0}^{t_f-1} \{x_i(k)^T Q_i x_i(k) + u_i(k)^T R_i u_i(k)\}, i \in \{1, 2, \dots, N\} \quad (6.16)$$

where S_i , Q_i are semi-definite symmetric matrices, and R_i are positive definite symmetric matrix.

Based on the finite time horizon cost functions, LQR state feedback actions $u(k)$ are given by

$$u_i(k) = -K_i(k)x_i(k), i \in \{1, 2, \dots, N\} \quad (6.17)$$

where

$$K_i(k) = (R_i + B_i^T P_i(k) B_i)^{-1} B_i^T P_i(k) A_i, i \in \{1, 2, \dots, N\} \quad (6.18)$$

We solve the following algebraic Riccati equation (ARE) to get the positive definite matrices $P_i(k)$:

$$P_i(k) = Q_i + A_i^T (P_i(k+1) - P_i(k+1) B_i (R_i + B_i^T P_i(k+1) B_i)^{-1} B_i^T P_i(k+1)) A_i \quad (6.19)$$

with terminal conditions $P_i(t_f) = S_i$.

In order to guarantee the real-time performance of the power system and to improve the convergence rate of state variables, we choose the steady state feedback gain $K_i(\infty)$, instead of feedback gain sequences $K_i(t)$.

$$K_i(\infty) = (R_i + B_i^T P_i(\infty) B_i)^{-1} B_i^T P_i(\infty) A_i, i \in \{1, 2, \dots, N\} \quad (6.20)$$

We solve the following algebraic Riccati equation (ARE) to get the positive definite

matrices $P_i(\infty)$:

$$P_i(\infty) = Q_i + A_i^T (P_i(\infty) - P_i(\infty) B_i (R_i + B_i^T P_i(\infty) B_i)^{-1} B_i^T P_i(\infty)) A_i, i \in \{1, 2, \dots, N\} \quad (6.21)$$

Because $P_i(\infty)$ and $K_i(\infty)$ are constant in the steady state, there is no need to compute the feedback gains recursively. It reduces the computation load without influencing convergence performances.

To conduct the stability analysis for the power system, we need to find a test matrix $\tilde{W}$ to check whether it is an M -matrix, according to the Theorem 6.4.2. In order to get a simple test matrix $\tilde{W}$, We transform $\hat{A}_i$ into diagonal form Λ_i by a linear nonsingular transformation

$$x_i(k) = T_i \tilde{x}_i(k), i \in \{1, 2, \dots, N\} \quad (6.22)$$

where, $T_i = [t_{i1}, t_{i2}, \dots, t_{in}]$, t_{ik} is the k th right eigenvector of $\hat{A}_i$ corresponding to the k th eigenvalue $\lambda_{ik} = -\sigma_k^i \pm j\omega_k^i$ or $\lambda_{ik} = -\sigma_k^i$, $k \in \{1, 2, \dots, n\}$

The diagonal formed system is written as

$$\tilde{x}_i(k+1) = \Lambda_i \tilde{x}_i(k) + \sum_{j=1, j \neq i}^N \Delta_{ij} \tilde{x}_j(k), i \in \{1, 2, \dots, N\} \quad (6.23)$$

where $\Lambda_i = T_i^{-1} \hat{A}_i T_i$, $\Delta_{ij} = T_i^{-1} \hat{A}_{ij} T_j$.

We define a quadratic Lyapunov function as follows,

$$V_i(\tilde{x}_i(k)) = \tilde{x}_i(k)^T \tilde{H}_i \tilde{x}_i(k), i \in \{1, 2, \dots, N\} \quad (6.24)$$

where $\tilde{H}_i$ is the solution of the Lyapunov matrix equation

$$\Lambda_i^T \tilde{H}_i \Lambda_i = \tilde{H}_i - \tilde{G}_i \quad (6.25)$$

where, let $\tilde{H}_i = I$, $\tilde{G}_i = \text{diag}\{1 - \sigma_1^i, \dots, 1 - \sigma_n^i\}$.

Then, the test matrix $\tilde{W} = [w_{ij}]_{N \times N}$ is defined as

$$w_{ij} = \begin{cases} \sigma_M^i - 2l_{ij}\lambda_M^{1/2}(\Delta_{ii}^T \Delta_{ii}), & i = j \\ -2l_{ij}\lambda_M^{1/2}(\Delta_{ij}^T \Delta_{ij}), & i \neq j \end{cases} \quad (6.26)$$

The diagonal formed system is stable if $\tilde{W}$ is an M -matrix. The original system is stable if the diagonal formed system is stable.

Also, we select the optimal K_{ij}^* when the element of communication matrix $l_{ij} = 1$ by using the diagonal formed system.

To perform the distributed gain scheduling algorithm for each area controller ACC, it only needs to know the i th row of the communication matrix. Thus, it becomes simpler than solving it in the centralized method.

When $l_{ij} = 1$, we choose the optimal $\tilde{K}_{ij}^*$ by solving the following optimization problem.

$$\zeta_{ij}^* = \min\{||\Delta_{ij} - \tilde{B}_i \tilde{K}_{ij}||\} \quad (6.27)$$

where $\Delta_{ij} = T_i^{-1} \hat{A}_{ij} T_j$, $\tilde{B}_i = T_i^{-1} B_i$, $\tilde{K}_{ij} = K_{ij} T_j$.

After calculating each optimal $\tilde{K}_{ij}^*$, we get the optimal K_{ij}^* by

$$K_{ij}^* = \tilde{K}_{ij}^* T_j^{-1} \quad (6.28)$$

Assuming the initial communication topology is known to the CTD, the dynamic gain scheduling algorithm in each ACC is summarized as in Algorithm 1.

Algorithm 1 Dynamic gain scheduling procedure

-
- 1: **For** each given time period b
 - 2: The global CTD checks the current communication topology and forms it in the communication matrix formula $L = [R_1^T, R_2^T, \dots, R_n^T]^T$.
 - 3: It distributes ith row vector R_i^T to the corresponding local ACC.
 - 4: Each ACC receives its row vector and calculates its system matrices $(A_i^{T_i}, B_i^{T_i})$, where T_i denotes the ith communication topology.
 - 5: Each ACC calculates its local LQR gain $K_i(\infty)$ and the optimal inter-connective gains K_{ij}^* according to the minimum optimization formula for each $l_{ij} = 1$.
 - 6: **end** .
-

Remark 6.5.1 In practice, a variety of software products already exist to automatically detect the real-time communication topology using Virtual Routers and Routing Protocol Listening techniques, such as HP Network Node Manager i, OpManager, and OPNET's NetMapper etc.. By implementing these software applications, real-time communication topology information can be obtained by the CTD and sent the information to every ACC in each area in smart grids, as shown in Fig 6.3.

6.6 Simulations

In this section, a four-area power system model (see Fig 6.3) is used to evaluate the proposed control method. The mean square error (MSE) of the state vector $x_i = \begin{bmatrix} \Delta f_i & \Delta P_{m_i} & \Delta P_{v_i} & \Delta P_{tie}^{ij} \end{bmatrix}^T$ in each area $i \in \{1, 2, 3, 4\}$ is chosen as the dynamic performance metric for the four-area power system. The generators in each area are modeled as a single equivalent generator. The simulations are run in the Matlab R2012a environment. All the parameters of the four-area power system are given in Appendix D. In this study, 100 MVA is the base unit for per unit (pu) calculations. All the power system models are sampled by sampling period $T = 0.01s$.

Each simulation lasts for 12s. The initial frequency deviations for all the four area are $0.5Hz$.

Firstly, the impacts of communication failures on the dynamic performances of the four-area power system are analyzed. 6 communication topologies (see Fig 6.4) are chosen. Fig 6.4(a) is the ideal communication topology of the fully connected distributed controller for the power system. The dynamic performance of this communication topology is used as the reference when we calculate the MSEs of the state vector x_i in each area $i \in \{1, 2, 3, 4\}$. Fig 6.4(b-f) are 5 imperfect communication topologies which are caused by communication failures among the four areas in the power system. The five imperfect communication topologies are triggered by the following scheduling illustrated in Fig 6.5. In Fig 6.5, mode 1-5 represent the imperfect communication topologies shown in Fig 6.4(b-f), correspondingly. With comparison to the fully connected communication topology (see Fig 6.4(a)), the MSEs of the state vector x_i in area $i \in \{1, 2, 3, 4\}$ under the 5 imperfect communication topologies (see Fig 6.4(b-f)) are shown from Fig 6.6 to Fig 6.9. As illustrated in these figures, the distributed controllers for the four-area power are sensitive to communication topology changes. Also, as indicted in these results, the dynamic performance of the distributed controller for each area greatly depends on how well it can communicate with its neighbor areas. For instance, as it can be seen from Fig 6.7, the maximal and sub-maximal peak mean square errors of the state vector x_2 appear when it are under the topologies of Fig 6.4(e) and Fig 6.4(f). The reason for these results is the distributed controller in area 2 under the topologies of Fig 6.4(e) and Fig 6.4(f) lacks the inter-area state information.

To improve the robustness of the distributed controller to communication topology changes, we design then the distributed gain scheduling strategy as described in previous sections. The five imperfect communication topologies (see Fig 6.4(b-f)) are triggered by the same schedule as shown above (see Fig 6.5). The MSEs of the state

Figure 6.4: Six communication topologies

Figure 6.5: The scheduling scheme of the 5 imperfect communication topology modes

Figure 6.6: Dynamic response of Area 1

Figure 6.7: Dynamic response of Area 2

Figure 6.8: Dynamic response of Area 3

Figure 6.9: Dynamic response of Area 4

Figure 6.10: Dynamic responses of 4 areas under the distributed gain scheduling strategy

vector x_i in area $i \in \{1, 2, 3, 4\}$ are shown in Fig 6.10. As it can be noticed from Fig 6.10, the MSEs in the four areas are greatly reduced. These results illustrate the proposed strategy can enhance the robustness of the LFC.

6.7 Summary

In this chapter, the modeling and distributed control problems for a smart grid with communication failures are addressed. The change of communication topologies in the smart grid is modeled as a time-varying communication topology matrix. This communication topology matrix enables to build a closed-loop power system model, integrating the dynamic communication topology into the dynamics of physical power systems. The stability analysis of the closed-loop power system is conducted. A distributed gain scheduling strategy for the LFC is proposed to compensate for the

degraded performances of the smart grid. Simulation results of a four-area power system under six communication topologies have confirmed that the proposed approach is able to maintain low mean-square errors for the power system with communication failures.

Chapter 7

Conclusions

In this chapter, we draw conclusions and discuss several possible topics for the future research.

7.1 Thesis Conclusions

- 1. The effect of communication delays on the LFC in an islanded multi-DG microgrid is studied. As communication delays are taken into account, a small-signal model based method is applied to determine a delay margin below which the microgrid can maintain stable. By performing a thorough theoretical analysis, relationships between secondary frequency control gains and delay margins are identified. Simulations results of this multi-DG microgrid system have verified that communication delays can badly affect the stability of the microgrid and illustrated the correctness of the proposed small-signal analysis results for the microgrid.
- 2. Based on the small-signal model of the microgrid formulated in the previous chapter, a gain scheduling approach is proposed to compensate the communication delay effect on the LFC performance of the microgrid. This approach consists of both offline stability analysis and online gain schedule. In the offline

stability analysis, feasible gain sets corresponding to different communication delays are found based on the root locus of the small-signal model of the microgrid. Relationships between these gains and the degraded performance indexed by the average quadratic state error are also identified by series of simulations. In the online gain schedule, via the GPS service supplied by PMUs and gain schedulers, each local controller can calculate current time delays and then schedule the corresponding controller gains corresponding to the current time delay. Studies of an islanded microgrid with 4 inverter-based DGs have shown the proposed gain scheduling method can greatly improve the dynamic performance of the microgrid, with comparison to a fixed gain secondary frequency controller.

- 3. For largely interconnected power systems, a CR network is considered as the source of communication failures. By modeling the CR network as a On-Off switch with sojourn times, a novel switched power system model is proposed for the LFC of an interconnected power system. To study the stability of the power system, two main types of CR networks are considered, including the sojourn times that are arbitrary but bounded and that follow independent and identical distribution (i.i.d). The sufficient conditions are obtained for the stability of the power system with these two kinds of CR networks, respectively. Simulation studies show that the obtained results are very useful to the design of CR networks in order to guarantee the stochastic stability of the power systems.
- 4. The DoS attack is considered as another reason that results in communication failures for the largely interconnected power systems. The state-space model of a power system under DoS attacks is formulated as a switched system. Based on switched system theories, the existence of DoS attacks that may cause the dynamics of a power system unstable is proved. A two-area power system is

used to conduct case studies.

- 5. A distributed gain scheduling strategy is proposed to compensate the potential degradation of the performance of the LFC caused by communication failures in largely interconnected power systems. This strategy has a two-layer structure. In its cyber layer, a global communication topology detector (CTD) is used to check communication topologies in a real-time fashion and distribute the communication topology information to each area control center (ACC) in the power systems. With the knowledge of its local communication topology changes, in the physical layer of this structure, each ACC calculates its optimal local and inter-connected feedback gain matrices accordingly. A four-area smart grid model is used to verify the effectiveness of the proposed method. Simulation results show that the proposed distributed gain scheduling approach is capable to improve the robustness of the smart grid to communication topology changes caused by communication failures.

7.2 Possible Directions for Future Research

The following are possible topics for the future research.

- 1. The effects of communication delays on the performance of an islanded microgrid are analyzed in Chapter 2. In fact, the communication delays result from complicated networking actions in a communication system. Therefore, it would be interesting to analyze the effects of the factors of the networking layer of the communication system on the microgrid performance, including TCP/IP protocols and UDP protocols.
- 2. The stability of a largely interconnected power system under denial of service (DoS) attacks has been investigated in Chapter 5. It would be very interesting to

investigate some networking defense mechanisms to act against the DoS attacker in the communication system through which measurements and control signals of the power system are transmitted. When we design these defense mechanisms in the communication system, the dynamic performance of the physical power system should also be taken into account.

- 3. In this thesis, the approaches for the compensations of communication delays and failures in smart grids are considered from the power system control aspect. In specific, these approaches are gain scheduling control algorithms. It would be interesting to consider reducing communication delays and failures from the aspect of the communication system design, including improving the networking protocols in the network layer of the communication system and queueing mechanisms in the physical layer of the communication system.

Appendix A

Microgrid Parameters

Table A.1: Distribution system parameters

Parameters	Value
S_{base}	10 (MVA)
V_{base1}	$120\sqrt{2}/\sqrt{3}$ (kV)
V_{base2}	$12.5\sqrt{2}/\sqrt{3}$ (kV)
V_{base3}	$208\sqrt{2}/\sqrt{3}$ (V)
R_S	0 (p.u.)
X_S	0 (p.u.)
R_T	0 (p.u.)
X_T	0.1 (p.u.)
R_f	0.0029 (p.u.)
X_f	0.0041 (p.u.)
R_t	0 (p.u.)
X_t	0.2 (p.u.)

Table A.2: Inverter parameters

Parameters	Value
K_{pPLL_i}	50
K_{iPLL_i}	500
K_{pi}	2.5
K_{ii}	500
L_S	1 (mH)
K_{ppi}	2.5
K_{ipi}	100
ω_0	377 (rad/s)
$Q_{ref1}, Q_{ref2}, Q_{ref3}, Q_{ref4}$	0 (p.u.)

Appendix B

Chebyshev's Differentiation Matrix

A $N + 1 \times N + 1$ dimension Chebyshev's differentiation matrix D_N is created as follows, according to [17].

Firstly, $N + 1$ Chebyshev's nodes have to be defined by normalizing the interpolation points on the interval $[-1, 1]$:

$$x_k = \cos\left(\frac{k\pi}{N}\right), k = 0, \dots, N. \quad (\text{B.1})$$

Then, the element (i, j) in the differentiation matrix D_N indexed from 0 to N is defined as the following:

$$D_{(i,j)} = \begin{cases} \frac{c_i(-1)^{i+j}}{c_j(x_i - x_j)}, & i \neq j \\ -\frac{1}{2} \frac{x_i}{1 - x_i^2}, & i = j \neq 1, N - 1 \\ \frac{2N^2 + 1}{6}, i = j = 0 \\ -\frac{2N^2 + 1}{6}, i = j = N \end{cases} \quad (\text{B.2})$$

where $c_0 = c_N = 2$ and $c_2 = \dots = c_{N-1} = 1$. In Chapter 3 of this thesis, D_2 is used

for calculations. It is

$$D_2 = \begin{bmatrix} \frac{3}{2} & -2 & \frac{1}{2} \\ \frac{1}{2} & 0 & -\frac{1}{2} \\ -\frac{1}{2} & 2 & -\frac{3}{2} \end{bmatrix}. \quad (\text{B.3})$$

Appendix C

Two-area Power System Parameters

The two-area power system parameters are shown as follows.

Table C.1: Two-area power system parameters

Area 1	Area 2
$T_{ch_1} = 0.4s$	$T_{ch_2} = 0.36s$
$T_{g_1} = 0.08s$	$T_{g_2} = 0.30s$
$R_1 = 2.4Hz/pu$	$R_2 = 2.4Hz/pu$
$D_1 = 0.014pu/Hz$	$D_2 = 0.0084pu/Hz$
$2H_1 = 0.2pu \cdot s$	$2H_2 = 0.1667pu \cdot s$
$T_{12} = 0.08678$	$T_{21} = 0.08678$

Appendix D

Four-area power system parameters

The four-area power system parameters are shown as follows.

Table D.1: Four-area power system parameters

Area 1,3	Area 2,4
$T_{ch_{1,3}} = 0.17s$	$T_{ch_{2,4}} = 0.2s$
$T_{g_{1,3}} = 0.4s$	$T_{g_{2,4}} = 0.35s$
$R_{1,3} = 0.0$	$R_{2,4} = 0.05$
$D_{1,3} = 1.5$	$D_{2,4} = 1.8$
$M_{1,3} = 12$	$M_{2,4} = 12$
$B_{1,3} = 41.5$	$B_{2,4} = 61.8$
$T_{ij} = 0.05$	$T_{ij} = 0.05$

Appendix E

Publications

The research presented in this thesis resulted in a number of refereed publications, both in journals and conference proceedings.

1. Shichao Liu, Peter X. Liu, and A. El Saddik, "Modeling and distributed gain scheduling strategy for load frequency control in smart grids with communication topology changes", *ISA Transactions*, vol. 53, no. 2, pp. 454-461, 2014
2. Shichao Liu, Peter X. Liu, and A. El Saddik, "A stochastic game approach to the security issue of networked control systems under jamming attacks", *Journal of The Franklin Institute*, Accepted, In Press, 2014
3. Shichao Liu, Peter X. Liu, and A. El Saddik, "Modeling and stability analysis of automatic generation control over cognitive radio networks in smart grids", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Accepted, In Press, 2014
4. Shichao Liu, Xiaoyu Wang, and Peter X. Liu, "Impact of communication delays on secondary frequency control in an islanded microgrid", *IEEE Transactions on Industrial Electronics*, under Minor Revision

5. Shichao Liu, Peter X. Liu, and A. El Saddik, "Modeling and stochastic control of networked control system with packet losses," 2011 IEEE Instrumentation and Measurement Technology Conference (I2MTC), China, 10-12 May 2011, pp. 1-5
6. Shichao Liu, Peter X. Liu, and A. El Saddik, "Modeling and dynamic gain scheduling for networked systems with bounded packet losses ", 2011 IEEE International Workshop on Measurements and Networking Proceedings, Italy, 2011, pp. 135-139.
7. Shichao Liu, Peter X. Liu, and A. El Saddik, "Load frequency control for wide area monitoring and control system (WAMC) in power system with open communication links," 2012 IEEE Power Engineering and Automation Conference (PEAM), China, 18-20 Sept. 2012, pp. 1-5
8. Shichao Liu, Peter X. Liu, and A. El Saddik, "Denial-of-Service (DoS) attacks on load frequency control in smart grids ", 2013 IEEE PES Innovative Smart Grid Technologies (ISGT), Washington D.C, America, 2013, pp. 1-6.
9. Shichao Liu, Peter X. Liu, and A. El Saddik, "A stochastic security game for Kalman filtering in networked control systems (NCSs) under Denial of Service (DoS) attacks (invited paper)", 2013 IFAC International Conference on Intelligent Control and Automation Science (ICONS 2013), Chengdu, China, 2013, pp. 1-6
10. Xinran Zhang, Shichao Liu, Wes Kwasnicki, Yu Cui, Xiaoyu Wang, Chao Lu, "Wide-area HVDC damping controller design in Alberta power grid", 2014 CIGRÉ Canada Conference, Toronto, Canada, September, 2014, to be presented

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