DECENTRALIZED COMMUNICATION AND CONTROL SYSTEMS FOR POWER SYSTEM OPERATION

By

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DECENTRALIZED COMMUNICATION AND CONTROL SYSTEMS

FOR POWER SYSTEM OPERATION

Abstract

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Due to the rapid increase of phasor measurement units (PMUs) installed in largely interconnected power systems, great opportunities have been opened for new applications to improve system stability and to enhance the operation of the grid. To take advantage of high sampling rate of these measurement data (30-120 samples per second) which data can illustrate great details about system dynamic performance, a high band-width, networked communication system is required. The specification for the next generation communication system that overlay the continental power grids are under intense discussion.

Although PMU based monitoring systems have been widely used, work on PMU based fast acting closed loop wide-area control systems which has stringent latency requirements is relatively rare. Since traditional communication links with centralized topology will not be able to meet the stringent latency requirements, a new communication topology that provides reasonable delay and makes both communication network and power infrastructures to collaborate strongly needs to be provided.

In this dissertation, a combined process for design and simulation of both communication network and power network has been presented with the objective of damping inter-area oscillations. This process is used to validate the adequacy of a communication system for a particular transmission grid. A method to determine the optimal location of data routing hubs so as to minimize the volume of communications is also proposed. The two-area benchmark system and IEEE 118 bus system is used to study the performance of communication system and the wide area power damping control system on both centralized and decentralized topologies, and the results are discussed. At the end of this dissertation, we show that the decentralized communication topology, involving data routing hubs, is better suited for control applications requiring fast control actions.

Keywords: PMU, Communication architecture, Wide area damping controller, Power system operation

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1. Introduction

1.1. Motivation

As the power system is operated closer to the margins, it becomes imperative to collect fast-sub-second measurement to enable fast action control application to improve the dynamic behavior of the grid and to take necessary control actions for reliable operation of the system. The network topology and its real-time operating state are required for successful analysis, operation and control of the grid. The topology defines the interconnection of the grid and the state of the system defines the operation points of the system.

It is an established observation that real-time sub-second measurements are necessary to gain insights about the dynamic behavior and to take fast automatic control actions in a modern power grid operated under stressful conditions [1]. PMU devices obtain synchronized measurements of voltage and current phasors as well as other digital and analog signals at rates of 30 to 120 measurements per second. It is also a common assumption that smart grid of the future is expected to have PMU data measured widely across the grid, which will introduce significant impact on how we design and operate system components.

Traditionally, the system operators observe, control, and manage generation and transmission system through Supervisory Control and data Acquisition (SCADA). SCADA with slow sample rate to minimize the space required to store the data. And the data transportation of SCADA is usually handled by point to point communication links. However PMUs now are generating much more measurements and the communication facilities needs to be upgraded to network of communication modes with high-capacity links to support such amount of throughput. The notion of centralized operation and control will no longer be scalable and decentralized topology will be more and more widely used. This new topology of SCADA-EMS system is proposed to bring high-level performance that is able to provide satisfactory quality of service (QoS). And it is supposed to deliver both PMU measurements and control signal in a faster way. Such information infrastructure should have the ability to meet strict latency requirements and can be achieved with reasonable cost [2].

With the advances made in ubiquitous computing systems, the notion of distributed data and distributed analytics becomes amenable. This provides us a powerful tool to design decentralized communication architecture for power system operation, in which large data is stored and processed at different locations and only necessary information requested by control actions or control devices is sent over long distance through communication network. This would decrease the total workload of the communication network when dealing with the same amount data, meaning that the average delay in the network can be shortened and an improved overall performance.

Several smart grid applications are already developed to exploit high throughput real-time data generated by PMUs. Most of this kind of application has a strict latency requirement in the range of 100 milliseconds to 5 seconds [3-4]. And the latency mentioned here refers to how much time it takes to transport PMU data package to the controller through a meshed communication network. The delay caused by PMU devices and within substation is not included. Therefore, among the other delays [5], communication delay consists of the major part of latency and needs to be minimized. The communication delays on the network are comprised of transmission delays, propagation delays, processing delays, and queuing delays [6]. Each of these four types of delay needs to be looked into to understand the complete behavior of the communication network on a given scenario.

During the process of proposing a decentralized architecture to minimize the time delay, we are trying to build an example which explains some basic but critical questions on how to manage the cooperation between power infrastructure and communication networks. The questions include - what should be the design process of such the new decentralized communications architecture? Given that the data and computations are going to be distributed, how to choose the best set of locations to store and process the data to achieve optimal performance? How to choose protocols for each layer and to decide how data is to be moved to the applications in an efficient way to meet the latency requirements? How to integrate the test results from both power side and communication side so that we can represent how these two networks are managed all together realistically?

In reference [5] a detailed survey has been conducted about various smart grid applications and their different latency and bandwidth. Latency is considered as a measure of time delay experienced in a communication system, which has important impact on lead-lag controllers using signals transmitted through networks. Whereas, bandwidth is the rate of data transfer in bits per second, that can be achieved by a communication resource. According to reference [7] all kinds of applications related to power system operation can be classified according to the increasing order of their latency requirement as follows: application about transient stability like low-frequency oscillation damping usually requires a delay less than 100 milliseconds, small signal stability application requires delay less than 1 second, state estimation also needs delays shorter than 1 second, voltage stability related applications can tolerate delay in the range of 1 to 5 seconds, some post-postmortem analysis of grid disturbances can still be functional with a delay over few minutes.

So we can tell that the latency requirements of different power applications vary in rather wide range. But to some application, the requirement is stringent. For example, we need transport a signal over several hundreds of miles and over several intermediate hubs and switches within 100 milliseconds for a wide-area damping controller [8]. And such stringent requirement also makes it very difficult for human operators to respond to problems pertaining to transient and small signal stability of a large-scale power grid.

Typically, the stability is achieved by local controllers operating with local information as input. However, due to large interconnections of power grids, disturbances in one region can spread to others. And a group of generators from one area can oscillate against the rest generators in the system. And sometimes local signals cannot provide controllability to such oscillation or dynamic modes [9]. Therefore, remote signals are required to improve the damping of such oscillation and increase system dynamic stability. Hence, wide area controllers, which rely on remote signals, become necessary.

1.2. Objective and findings

In this dissertation, we come up with process of design and simulation of both communication network and power network. Two tasks will be performed here: delay calculation and dynamic stability analysis. The delay calculation scheme will determine the time delay for the PMU measurements and control signal for certain power controller under both centralized and decentralized communication architecture. For this calculation, a detail model of communication scenario will be built. Proper protocols will be assigned to different layers to suit the requirements of power system operation. Size of packets sent from each substation is set based on IEEE 37.118 standard. We calculate delay under different bandwidth for both centralized and decentralized topology to determine the minimum bandwidth needed to meet the latency requirement of power application.

For the dynamic stability analysis, the current method is to observe the generator performance after disturbance through a time domain non-linear simulation to determine whether the system is stable. Based on results of small signal stability analysis (SSSA), we can select the unstable node related to poorly damped low frequency oscillation and design a wide-are damping controller (WADC) to improve the damping performance. The WADC is tested with different delay values based on the results of communication results to verify the relationship between the latency and the system stability. Therefore, we can tell which communication topology is the more suitable choice for power system.

Most of the testing conducted in this dissertation will be done on the IEEE-118 bus system [10] and Kundur’s two-area four-machine system [11]. These two systems are configured in a way to represent power systems with multiple control areas that are connected to each other by long distance tie-lines. Communication networks are designed for both test systems to show the integration of power hardware and communication infrastructures. The use of IEEE-118 bus system also proves that our design process and conclusions shown in this dissertation can be extended to larger systems with more complex system topologies.

1.3. Outline

This dissertation is consist of 5 chapters and is organized as follows. The motivation of the research topic in this dissertation, and the objectives we pursue are both described in Chapter 1.

A brief introduction of both centralized and decentralized communication architectures and various assumptions of communication network design are included in Chapter 2. We also propose a process which shows the outlines about how to setup both the power network and IT network to accomplish a close-loop wide are control with the help of communication network.

Chapter 3 focuses on the design and simulation of communication network. We use two-area system and IEEE 118 bus system as test bed to present how to build communication network to transport PMU measurements following the process shown in previous chapter. How to choose the best location for control center or data routing hubs, how to decide the protocol set and latency results with different bandwidth for both topologies are also included in this chapter. We can tell that decentralized topologies can provide less delay by using less network resources.

Then Chapter 4 describes the simulation of dynamics of power network with controller and presents the results. We use WADC as an example of power application with strict latency requirement. We demonstrate that the same controller can perform differently with different amount of time delay and too much delay will even turn a stable system into an unstable one. We also use power network simulation to determine the minimum bandwidth requirements for both topologies so that we can compare the network resources needed to support this application with different communication architectures. Case studies are conducted on the two area system and IEEE 118 bus system to valid our theory and design process.

A summary of the findings in this dissertation will be provided in Chapter 5.

2. Overview of Design Process for Both Communication and Power Network

2.1. Architectural considerations in design process

To propose a decentralized architecture for power system operation with the objective of minimizing time delay, five factors have to be taken into considerations.

2.1.1. Location of data

Both topology and state of the system are classified as data. The topology defines the interconnection between buses and is almost taken as constant over time. On the other hand, the states such as voltage and currents describe how power system changes dynamically over time due to unbalance between generators and loads. But since topology that defines the characteristic of the grid is considered as static data and it resides in the Control Center and do not need update very often, data refer to states of the power system.

Each substation stores the data measured at that location in a local database and makes this data available. This data is used for power applications which require different data rates [12]. The approach here is to keep the data distributed and close to the power network components from which the data is measured.

2.1.2. Location of applications

Based on advances in communication hardware and parallel computation, there is no need to centralize all the applications at one place. We are able to locate applications according to their own requirements. For example, the fast control applications related to transient stability can be located closer to the controllable equipment.

2.1.3. Movement of data

Since the data and applications are defined to be distributed, a communication infrastructure is needed which can identify a specific subset of data and transfer to the required application. The characteristics of such an infrastructure are described in [13]. A middle-ware system forms the heart of such an infrastructure, which can perform the functions of efficient routing of data packets while conforming to the quality of service (QoS) constraints. An architectural paradigm known as publish/subscribe is suitable for such a middle-ware. The sources of data need not be aware of the consumer of data. The sources simply publish their data to the middle-ware. The applications which require specific data will subscribe to the middle-ware. A list of all received subscriptions is maintained by the middle-ware. When the data is published the middle-ware notifies the receiving application and forwards the data.

2.1.4. Format for data and control commands:

The PMUs are being manufactured by multiple vendors and interoperability among equipment from different vendors is ensured by using standard formats. The standard C37.118 is used in practice for communication of PMU data [14]. In this standard, four types of packets are defined to include different communication situation of PMU devices. Detailed information about these four types are listed in the following.

1. Data frame: A data frame shall contain measured data. The real-time phasor data frame shall consist of binary data.

2. Configuration frame: A configuration frame is a machine-readable binary data set containing information and processing parameters for the PMU and the current real-time data set. Information of a configuration frame includes PMU capability

indicating measurements that the PMU is capable of and measurements currently being made and transmitted in the data frame. This may be only a subset of available data.

3. Header frame: This frame shall be human readable information about the PMU, the data sources, scaling, algorithms, filtering, or other related information.

4. Command frame: A PMU shall be able to receive commands from a control system and take appropriate actions.

Among the four frames that are defined in C37.118, the data frame is one that is sent out from the substation under normal conditions. The command frame defined in C37.118 can be used to send commands to the PMUs for controlling the associated power system equipment.

2.2. Centralized communication architecture

Figure 1 illustrates the typical communication architecture with a centralized control center (CC). This CC receives all the measurements from each substation (SS) located in different areas. The structure shown in Figure 1 represents the logical connection, whereas, the substations are interconnected to the control center through a physical network which can have meshed structure similar to the power network based on the assumption that our communication links are overlaid with transmission lines. The logical connection refers to a connection defined by only its source and destination, independent of the path between them. For most substations, there is no direct link to send data to control center. The data needs to be forwarded through various numbers of intermediate nodes on its path. And path is determined by routing algorithm.

The data received at CC is useful for system wide energy management applications such as, state estimation, operator visualization, security analysis, contingency studies, and voltage stability. The results of these studies would determine required control actions such as, switching of capacitor banks, and transformer taps. These control actions would have be implemented typically in the time scale of few seconds to minutes. Hence a centralized architecture is suitable for such applications.

Although this centralized architecture is simple, it may not be scalable for all applications, especially those that require fast control action to be taken within a few cycles. For example, wide area special protection schemes require fast breaker actions after a fault. For such cases, delivering data to CC that are far away from the measuring devices will leads to too much delay to support the application, which leads to ideas of developing a different communication architecture.

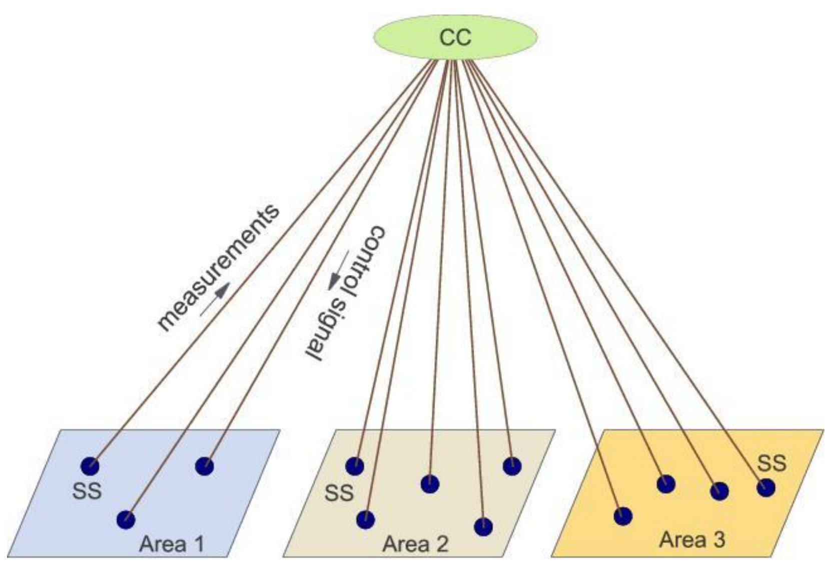

Figure 1. Centralized communication architecture

2.3. Decentralized communication architecture

As shown in Figure 2 a new layer of communication nodes which act as data routing hubs, is added between the substation and central control center. The main function of data routing hubs (or simply referred as hubs) is to receive the measurements from all the substations in the local area and route them to main control center and/or to substations with controllable devices.

The control algorithms themselves run in parallel at respective substations, whereas, the hubs only route the measurements as per their offline pre-defined configuration. The configuration itself is flexible and can be remotely changed time to time, by the main control center as per the changing state of power system. Hubs are also interconnected in a peer-to-peer fashion to exchange information across areas.

In this distributed architecture, due to shorter distance between sources and destination, we can expect that in the new architecture the total time between the substation sending measurements and receiving control signal is reduced and hence the applications which have more stringent latency requirements, such as transient stability and small signal stability can be well supported. Since there are also links between hubs and CC, we can send data measured from different areas at lower speed so that applications mentioned in centralized architecture are still supported and we can meet a wide range of latency requirements of applications.

Based on the above considerations we can tell that some of the applications needing lower latency should be decentralized. As a consequence of this decentralized or distributed approach a need arises for storing the data at various levels. Since, only a subset of data is communicated as per the requirement of the applications, effective data management strategies are needed to define the movement of the data across the various nodes of the network.

To address this need, an information architecture for power system operation based on distributed controls using a publish/subscribe communication scheme and distributed databases is described in Figure 3.

The key feature of the proposed architecture in Figure 3 is that there are distributed database at each level. Each substation stores the measured data locally. Applications that need real-time data for transient stability monitoring and control are not located in the control center but can be located on a computing node near the substations, identified as “control schemes” in Figure 3. The special protection schemes (SPS) being used in power systems are one example for such control schemes [15]. At this level the data can also be stored for future use in computations. The data and control frames, as described by the C37.118 standard, can be exchanged via publish/subscribe based middle-ware which manages the fiber optic communication network. The communication network can be physically laid along with the power system network.

The control center has its own set of applications and associated databases. While the focus is on optimizing the latency of time critical data, the data which is non-time critical can also be moved around with appropriate QoS attributes using the same communication network. The objective is to achieve a configuration of communication network which is most efficient and compatible with the operation of power system network in a decentralized way.

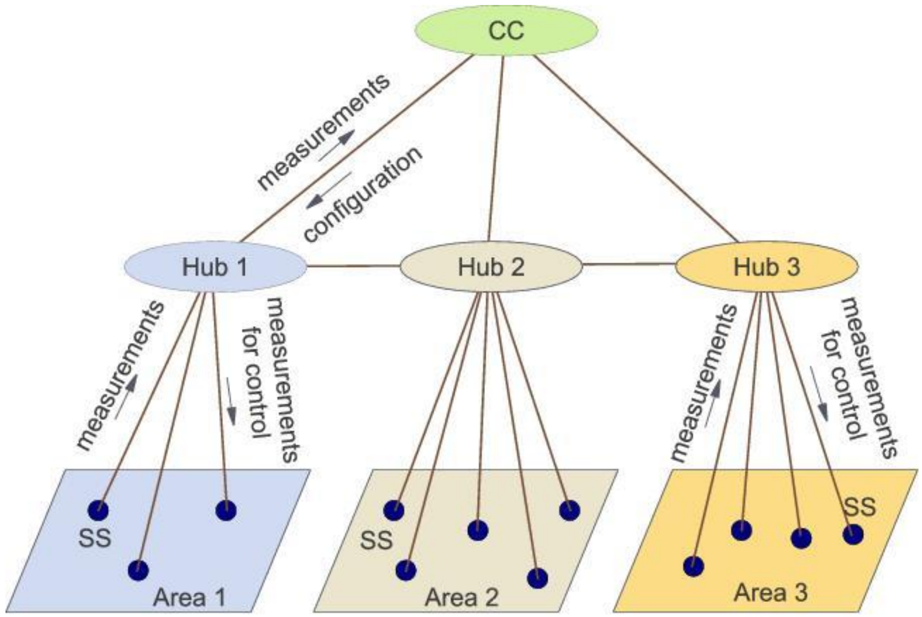

Figure 2. Decentralized communication architecture

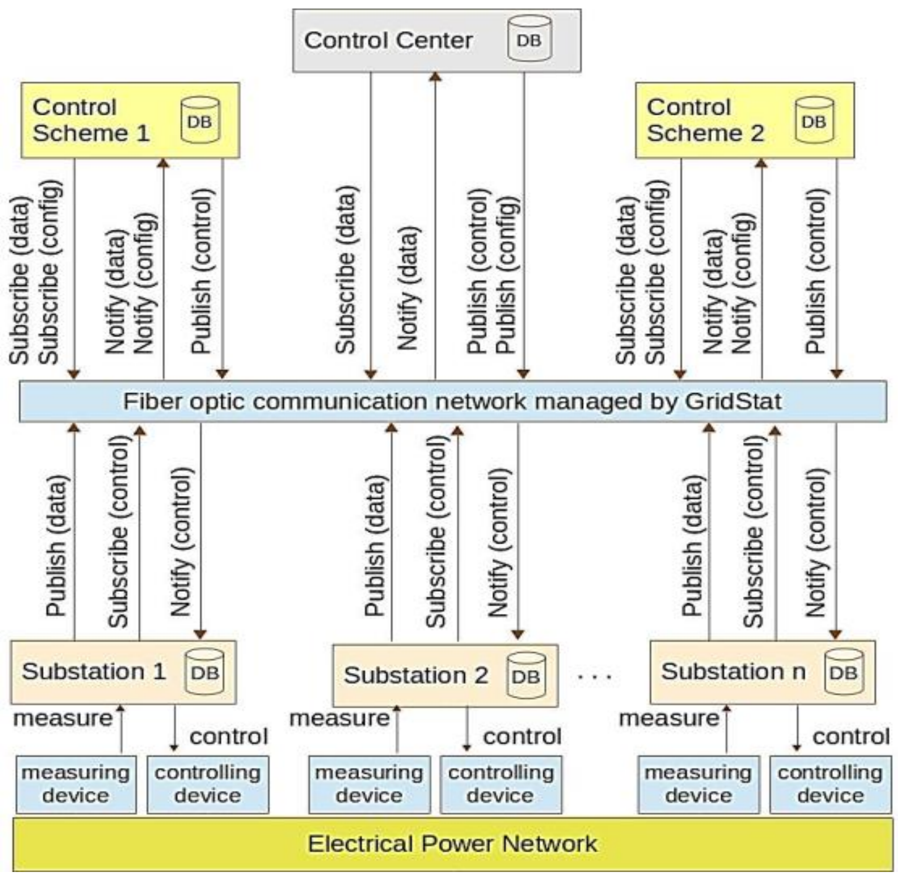

Figure 3. Distributed communications architecture for power system control

Development of such systems to provide the latency and other quality of service (QoS) requirements is one of the objectives of the North American synchrophasor initiative (NASPI) [16], [17] and some research initiatives like Gridstat [18], [19].

2.4. Management of middleware

As discussed in previous section, while the system becomes increasingly distributed an effective means of configuring the flows on the communication infrastructure is needed. In order to achieve this, the middleware should provide an interface which can be used to manage and configure the subscriptions from various applications. One of the major responsibilities of the middleware is to deliver the QoS requirements. These functions are achieved by middleware by separating the data plane and management plane. As an example, the functionality of GridStat [17] is shown in Figure 4.

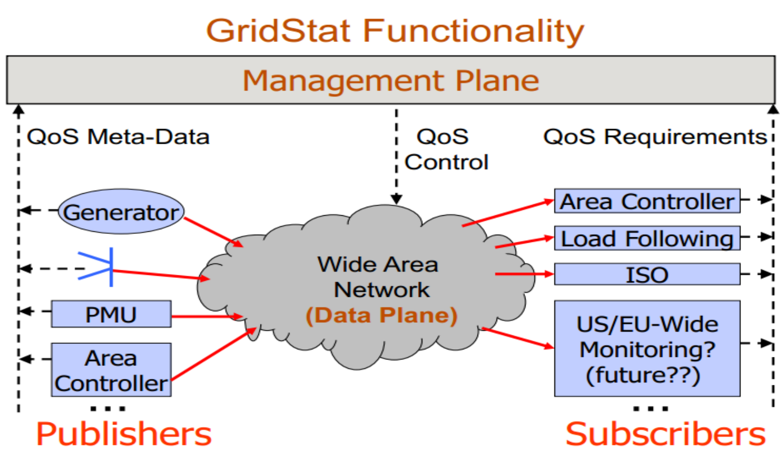

Figure 4. Basic middleware functionality of GridStat

As indicated in Figure 4, substations acting like publishers make their data on about generators parameters, PMU measurements and controller information available by sending them to computational nodes such as CC or hubs. Information are processed and stored at these locations. Then based on off-line settings CC or hubs send required signals to subscribers. During this process, management plane will supervise the network status, making sure the QoS requirements of all subscribers are met through QoS control method.

An important characteristic provided such middleware is that the publishers and subscribers of the data are independent from each other.

2.5. Design process

The flow chart of Figure 4 describes the proposed process for the design of communication architecture and control systems aiming to damp inter area oscillations for a large power system with three blocks.

In the pre-processing block we are interested in figuring out the detailed model of power system. Since the purpose of control system mentioned in this dissertation is to improve the damping performance of inter-area oscillations. Small signal analysis is carried out to for mode analysis. By calculating the ovservability and controllability of unstable inter area mode, the location of controller and the choice of remote signal are determined. Then we can use all these information to find out the parameters of wide area damping controller.

The second block focuses on the design and simulation of the communication network for both centralized and decentralized topologies. Our communication scenario assumes that each substation is considered as a communication node. Substations send their measurements to CC in centralized topology or local hub in decentralized topology at rate of 60 packets per second. Substations with controllable devices are referred as controllable substations, which receive control signals from either CC or hubs at the same rate of sending measurements. There are

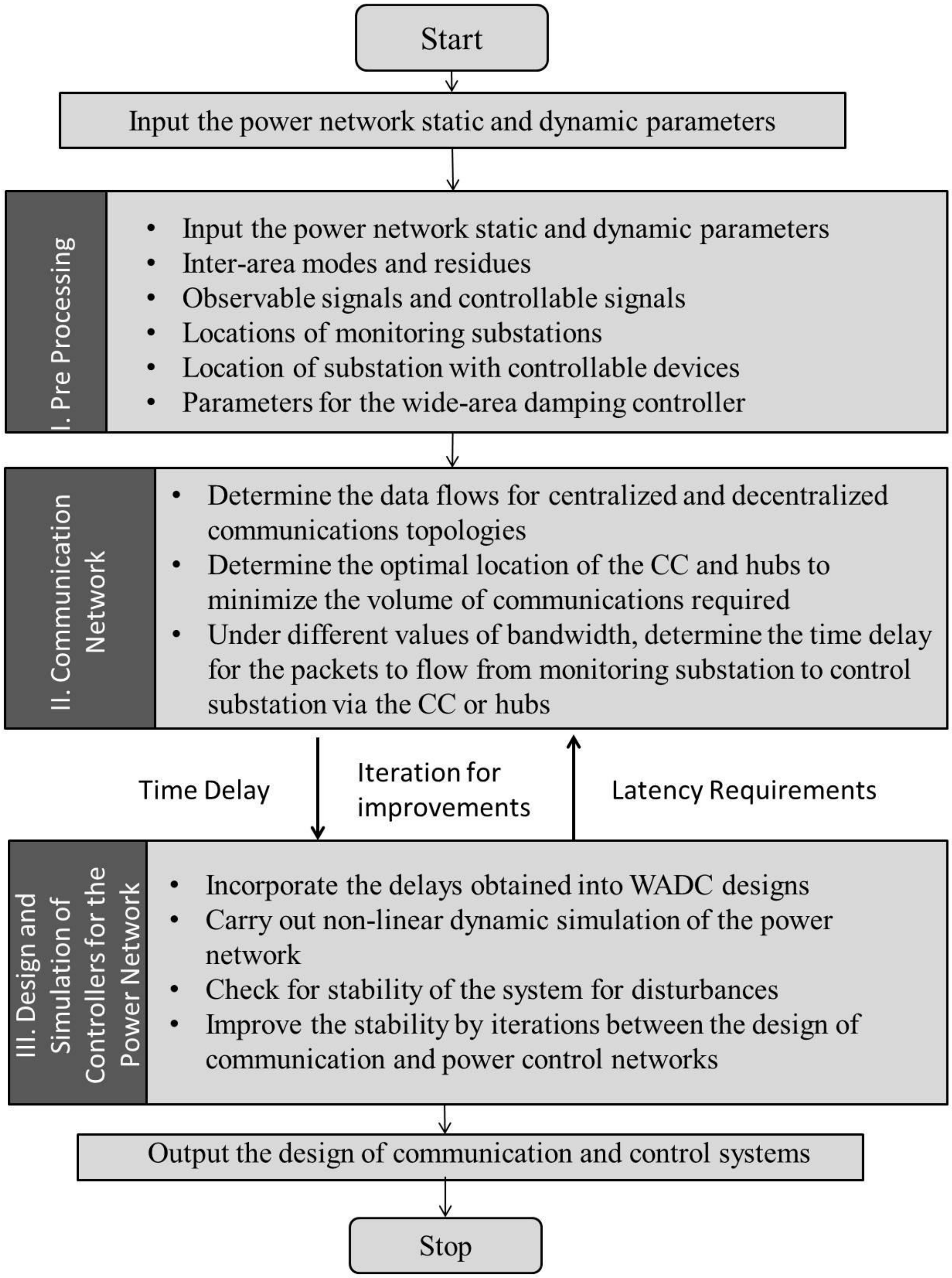

Figure 5. Process for design of communication architecture

communications between hubs which enable information exchange between areas without interfere of CC. Under such scenario and the assumption that optic fiber links are laid along with transmission lines, we can draw the conclusion that our communication and power network has almost identical topology.

The location of CC and hubs are chosen with the objective of minimizing the latency which means minimization of volume of communication. This choice is considered optimal for simulation purpose. How different locations of CC and hubs change the latency is discussed with more details in the following chapter.

The simulation also determines the time delay for communication network for various values of bandwidth with both centralized and decentralized topologies. We want to compare the performance and analysis which communication topology suits the need of applications with more strict latency requirements better. We also want to find the minimum bandwidth that can support the controller with reasonable time delay value. This information can be crucial when operators try to convert from one topology to another and when they are considering whether or not to upgrade their network.

The third block focuses on the non-linear time domain simulation of the power network incorporating the time delay in the WADC. We want to test the system stability with different time delay and to discuss more about the latency requirements of WADC.

This process of block II and block III can be iterated until a suitable overall solution for stability is achieved. The criterion for iterations is to ensure that the time delay is within the latency requirements with reasonable bandwidth. In the iterative process, we can use more investments to increase the number of hubs which means the system is even more decentralized and/or to install larger bandwidth fiber optic cables to increase the system capability.

2.6. Literature review

During the past few decades, engineers, scholars and consultants have put a lot of work on the study of inter-are oscillation and related control method. With the recent and rapid development on PMU devices and implement of wide area measurement system, more and more attention has been drawn to the area of controller using a remote signal to enhance the system stability like WADC. A large number of research papers have been published through conferences symposiums and journals. Also in industry, due to the fact of more interconnection between large grids are built or under construction, utilities and operators are putting more efforts on monitoring and damping out inter area oscillations. Poorly damped low frequency oscillations have been proved to be a serious concern of system stability by both monitoring results from power industry and research analysis. Along with WADC, other controllers that require high speed system wide signals are currently widely studied and used. With the help of PMU data at rate of 30-120 packets per second, all kinds of software package and applications now can run at faster rate. And it is general belief that our traditional communication network which is used to transport signal between SCADA and EMS once in a few minutes can no longer service the grid with high-stand performance required to process the large amount data generated by PMU located all over the system at such a high speed. A lot of discussion and study have been done on the topic of how to set up the communication network for the future power grid.

Moustafa and Kun conduct a general survey on communication requirements for PMU-based applications [5]. Data has been collected to record the current progress of developing power application using PMU signals with synchronized time stamp and their requirements on communication network. Transmission system operators' and scholars' opinions are included to show the latency requirement considered in the process of developing the software or control algorithm. The results are also compared to what has been defined by NASPI to encourage cooperation.

The survey shows that the general expectation of delay limits is basically similar among the operators and researchers from different organizations. And with the huge progress in some PMU-based application, more and more phasor devices have been planned to be installed. Therefore it is reasonable to assume in the near future we can obtain all measurements (voltages, currents and other system states) through PMUs.

Regarding the applications functions the latency requirements are varying from one to another. Some applications remain functional with a delay as long as a few minutes while other applications have more stringent latency requirement. The highest requirement reaches 100 ms. This survey provide a solid base to estimate the latency requirement for WADC which is mainly discussed in this dissertation.

More works are carried out with last five years to discuss the possibility to build a dedicate network for power system with large capacity to be able to handle the throughput of PMU measurements to replace currently-used satellite or wireless communication system. Various software and methods are proposed to simulate and validate the feasibility of such thought. Among those works, [20] illustrate some insights about what kind of communication network will suit the power system mostly. It presents some basic assumptions for setting up and simulating the communication network for grid operation. It also builds a detailed example on PMU-based communication scenario involved with special protection scenario (SPS) and provides a feasible way to simulate the performance of communication network.

Based on the simulation results, analysis about time delay, bandwidth and other evaluations like link usage are demonstrated. And from this analysis, we can tell the current development of high-bandwidth optic fibers is already sufficient to deliver the packet within the latency requirement. And among the total delay between sending a signal and receiving the signal, the queuing delay and transmission delay are limited and should not raise much concern when the communication capacity superior the workload of transporting data by a large degree. And for such case, processing delay within a communication node is important. To minimize the processing delay which is related to what data is processed, efficient routing, authentication check and data analysis method can be used. However, when our network resources are constrained, queuing delay will grow to the major part of the total delay value and results in high delay value.

[22] also indicates that for most static routing technique, about 20% of communication links are stay vacant and unused. Based on assumption that optic fibers use the same channel as the transmission lines do, a notable portion of network resources are allocated to unused links.

This raises a valuable question about how to perform the trade-off on how many links need to be built and how to allocate the network resources among them.

Weiqing's proposes a method [23] to reduce the calculation stress on certain nodes by using distributed computation technology to develop a distributed state estimator [24]. In this distributed method, multiples nodes are involved in the state estimation procedure which is used to be carried out on only one node. Distributed or decentralized application is considered as an efficient way to alleviate the computational burden to allocate the computation across the different nodes rather than to do the entire process at the control center.

Distribute state estimator (SE) provides us a useful example about how to reduce the data size and to accelerate the speed of computation. Both of these two achievements can help reduce the delay. Reduced data size leads to smaller traffic volume in the network to support the same application and improving the running time of the application will significantly decrease the processing time. The distributed SE utilizes a decentralization and centralization process. These two processes indicate the nature division of large power grid. The large system is divided into several control areas, thereby localizing PMU measurement.

Based on this distribution method, we have developed decentralized communication network. All the calculation is distributed to several data routing hubs. Each hub is responsible to handle the data measurement in its own area and communicate necessary information among them. The on top of hubs, control center will supervise the calculation by communicating with all hubs to gather all data across the whole grid but at lower data rates. In this design both aspects are covered. Faster calculation is done at hubs to reduce the delay and better support the application with higher latency requirement. At the same time the control center is responsible to store essential part of data needed for applications with lower data rate.

Besides works on communication architecture and delays, WADC and its latency requirement is also deeply studied by [25]. From the point of view of dynamic stability and controller performance, it is crucial to check out the maximal delay time, defined as a latency requirement, within which a power grid equipped with wide-area controller can keep stable [26]. Moreover, since system with WADC can be represented by a linear system modeled, Lyapunov stability theory can be applied to the grid with closed-loop model [27]-[28]. This means that we can study more details about the latency requirement through a theoretical method and we can analysis which parameters affect the value of such requirements. Theses information is helpful during the process of WADC design. With the linearized mode, detailed information about difference between constant time delay and time-varying delay is also studied.

By investigating the dynamic stability of power system with WADC, defining delay-dependent stability criterion and linearized model, we can see how delayed signal change the stability index of the system. [25] also confirm the survey results about common latency requirement of application related dynamic stability analysis. And this requirement changes according to the pattern of delay, such as the upper limit of the changing rate and the gain of the controller. And all these factors must be taken into consideration when the parameters of WADC are determined.

Based on the information listed above, we can see a lot of discussion on the topic of what future communication network should be like to support WAMS and a lot of study and calculation on stability issue about delay related WADC. However, only limited work has been done to link the communication network and power network together to mimic the real world collaboration between the two different layers of infrastructure. And how to use decentralization technique to reduce the stress of communication network and the delay introduced by communication flows is not well studied neither.

In this dissertation, we are trying to carry previous study one step further and link communication network and power network even more tightly. We intend to propose a design process for both communication and power control system, and figure out the details about how network design affects the system stability through latency.

We also intend to use simulated delay results other than assumption to test the performance of WADC, so that we will know whether system is stable or not given a realistic delay value. Also by performing this, we can conclude the relationship between network resources such as bandwidth and system stability. This gives us the minimum bandwidth value to help keeping our grid in a stable condition. And this information is useful for system operators and utilities when they want to set up a new communication network or upgrade their current one. They will be able to come a reasonable decision to achieve the demanded performance with minimum investment.

Finally we proposed a decentralized communication topology in which the computation burden of control center is divided into data routing hubs. This division will result in less traffic volume in the system because in decentralized topology, data can be process closer to where it is measured. And the fact that the same amount of calculation is now done by three computation node other than one improves the efficiency and reduces the processing time. This decentralized topology will allow us to introduce less delay to the signal with even less bandwidth, which makes it a considerable boost to the overall performance of our communication network to deliver all PMU measurements to where data is stored and processed.

2.7. Test bed systems

Kundur's two area system is used as one of the test bed systems. This system is commonly used to test WADC performance and verify system's safety margin on communication delay. This system is also a possible choice to build a small size communication area to test out design process mentioned above.

The IEEE-118 bus system is adopted as another test bed system for simulations to investigate decentralized communication and control systems for power system operations. 118 bus system has 3 control areas, which make it a very good example on display the differences between centralized and decentralized communication architecture.

3. Design and Simulation of Communication Architecture

3.1. Assumptions of communication scenario

In order to build a communication scenario that not only suits the data transporting need of real power network, but also is easy to be simulated by software package, several assumptions are made. These assumptions cover from how to generate a new network based on power system topology information, how to select topology set for different layers and how to set up the application that can mimic the PMU communication in real world.

Based following assumptions, we are able to illustrate one of the possible communication scenarios of both two area system and IEEE 118 bus system. Different scenarios can be utilized to study different protocols, PMU sampling rates and communication network. The scenarios presented in this dissertation are considered realistic on the future communication systems for the power grid. [5, 29-31]

Assumption 1: Substations are the base unit that participate the communication which is presented as a node. Buses connected through transformers are located in the same substations. Buses connected through transmission lines are located in different substations. CC and hubs are not included in any substations. Each of them is connected to certain substation through only one direct link.

Assumption 2: All communication links are overlaid with power lines. This leads to similar topologies between two networks.

Assumption 3: All communication links share the same bandwidth.

Assumption 4: There is only one CC for centralized topology of both test systems. And for decentralized topology, each control area has its own data routing hubs. Control areas are determined by long distance transmission lines.

Assumption 5: The routing algorithm used by our simulation software is the shortest route (number of hops) and is considered as static routing. Therefore, some links might stay unused.

Assumption 6: The delay caused by PMU devices and communication within substations are considered negligible. Hence, only delay between substations and control centers are calculated.

Assumption 7: The sample rate is set to be 60 samples per sec for all communication flows.

Assumption 8: We assume that the power grid is operated under steady state, which means that only data frames are sent from substations and since there are no spikes in data the communication is uniform.

Assumption 9: Among four parts of communication delay, the processing delay (usually considered between 10 to 100 microseconds) are set to be zero at all levels of communication. The propagation delay is also neglected because the signals are traveling at the speed of light.

3.2. Choice of protocol stack

In this dissertation, we are trying to design a mew communication topology with the target of minimizing time delay for those time sensitive applications. For such applications, designers usually prefer User Datagram Protocol other than Transmission Control Protocol (TCP). This is because when latency is the prior consideration, dropping the packets instead of waiting for or re-transporting the delayed packets, which may be unrealistic for real-time system like power network [32].

UPD is a faster solution than TCP because the following reasons. Firstly, we have no error checking. Secondly, there is no ordering of messages and no tracking connections, etc. UDP is a smaller transport layer designed on top of IP than TCP. Besides UDP has light weight header (8 bytes) and there is no need setup prior transmission connections and handshake since UDP is a connectionless protocol.

UDP also has its shortcomings. The most outstanding one is that UDP is an unreliable choice. When a UDP packet is sent, it cannot be known if the packet will reach the destination. But what we propose here is a dedicated network used only by power infrastructures. It is not connect to Internet and provide no public access. For such network, we assume that the chance of losing packets is so low that the fact the UDP cannot guarantee the delivery of data is not a serious concern.

Using UDP also provide us some advantage on the security aspect. Because with point-to-point protocol like UDP also means that for confidentiality we can use encryption technology such as SHA-256 [33] which takes negligible time to encrypt the data.

From the assumption mentioned above, we can tell that our communication network is time invariant since PMUs are sending out a stream of data frames on the constant rate. That makes constant bit rate (CBR) a good choice to carry the continuously generated data frames at the application layer.

The maximum transmission unit (MTU) size of the link layer is set to be 1500 bytes. This helps in the design of application level software to receive a complete C37.118 packet and not a broken one.

For link layers, both optical fibers and broadband over power line (BPL) are suitable solution. But we use optical fibers for all links just for uniformity. The full protocol stack is listed in Table I.

TABLE I. Protocol layers for communication

Layer	Protocol
Application	CBR
Transportation	UDP
Network	IP
Data	Ethernet
Link	Ethernet (Optical fiber)

3.3. Optimal locations for CC and hubs

Since, it is assumed that the communication network will be overlaid over the power network both will have a similar topology. And substations are considered as nodes in the network. The only things that are missing are the location of CC and hubs before we can determine our communication topology.

However the data routing hubs can be connected to any substation in the area. And factors that impact these decisions in real life such as geography are too complex to include in this dissertation. We will decide where to locate such computation nodes based on the consideration of total traffic volume and time delay.

Different locations of hubs will result in different amount of traffic volume. Since different locations leads to different path for all communication flows and different number of intermediate hops. And since the major part of delay is queue delay, the more intermediate hops on a path the longer delay we expect to observe from the network. Thus the notion of optimal hub location arises which would result in minimum amount of communications.

3.3.1. Choice of metric: MegaBit-Hops

In order to define a criterion to evaluate traffic volume and to decide the optimal location of CC and hubs, a metric is introduced in Equation (3.1), namely Mega-bit-hop.

$$Mbh_c = \sum_{i=1}^{N} (h_i * p_i) \qquad (3.1)$$

where, c is the location of CC in centralized topology or location of hub in a control area of decentralized topology, i represents the flow ID, N is the total number of flows including flows that carry measurements and flows that carry control signal, h_i is the number of hops taken by the packets on i^{th} flow and p_i is the packet size of i^{th} flow in the unit of Mega bits. As mentioned in the assumption, the propagation delay is assumed to be negligible as the information flows at speed of light, whereas, major part of time delay occurs when the packets are enqued and dequed at the intermediate nodes.

3.3.2. Packet size

Each substation sends all its measured data to the control center, hence the packet size depends on the number of feeders connecting to the substation. Each of such flow from substation to control center can be assigned a flow ID. Thus the packet size pi for each flow, is calculated based on the number of feeders and the data frame format defined by IEEE C37.118 standard for each substation. We assume that each feeder has one PMU that measures 6 phasors, namely 3 phase voltages and 3 phase currents. Each PMU has 9 digital channels and 9 analog channels [6]. The size of each part is listed in Table II [34].

TABLE II. Data frame format of C37.118

No.	Field	Size (bytes)	Comment
1	SYNC	2	Sync byte followed by frame type and version number
2	FRAMESIZE	2	Number of bytes in frame
3	IDCODE	2	PMU/DC ID number
4	SOC	4	Time stamp
5	FRACSEC	4	Fraction of second and time quality
6	STAT	2	Bitmapped flags
7	PHASORS	4 or 8 * PHASOR	Phasor estimates
8	FREQ	2/4	Frequency
9	DFREQ	2/4	Rate of change of frequency
10	ANALOG	2 or 4 * ANNMR	Analog data
11	DIGITAL	2 * DGNMR	Digital data
	Repeat 6-11		
12+	CHK	2	CRC-CCITT

3.3.3. Shortest path and number of hops

To calculate Mbh value, we need to decide the path that each flow takes to calculate the number of hops on that flow. The methodology used here is Floyd-Warshall algorithm [35].

Floyd-Warshall algorithm is a well-known algorithm of graph analysis. It is applied to find the shortest paths between two nodes in a weighted graph. A single execution of the algorithm will determine the distance (in our case, the number of hops) between all pairs of vertices, including paths from each substation to our CC or hubs. Based on this number, we can calculate the Mbh value as indicated in Equation

(3.1) for a certain choice of location. Then we compare all possible locations and define our optimal solution as the one that produce minimum Mbh value.

With this optimal solution, we now have our complete topology of communication network. The algorithm is applied again for this topology. And based on intermediate results generated from Floyd-Warshall algorithm, a method is created to reconstruct the actual path between any two endpoints. After comparing the path results here with the simulation results, we confirm that the simulation software uses the same routing algorithm. The idea of this algorithm is to compare all possible paths through the graph between each pair of nodes. The complexity is $\Theta(|V|^3)$, which is remarkable considering the number of edges in the system and the number of possible solutions that are tested. Even though, the algorithm takes too much time for system with thousands of node such as power system to run in real time.

The communication network can be considered as a connected graph where the nodes represent substations and links represent the communication lines. Each flow is between substation node and the chosen control center node or a hub node. Since, IP based communication is used, the path taken by each flow is the shortest path in terms of links used from the sending node to the receiving node.

In networking, the hop count represents the total number of links a given packet passes through between the source and destination nodes. The more the number of hops the greater is the transmission delay incurred.

3.3.4. Communication delay and the number of hops

We explain further the relationship between the average communication delay in a system and Mbh value.

Firstly, we conducted a theoretical derivation. From Equation (3.1), we know that Mbh values equal the summation of the product of packet size and number of hops. And for different locations, the packet size of each flow remains constant. Then we can say that if the average number of hops in the system increases the Mbh increases. We are also aware of that there is positive relationship between the number of hops and time delay. Combining these two connections together, we come to the conclusion that the higher Mbh value is, the longer delay is in the system. This verify that by finding the locations which leads to minimum Mbh value, we construct a topology with minimum traffic volume and shortest latency.

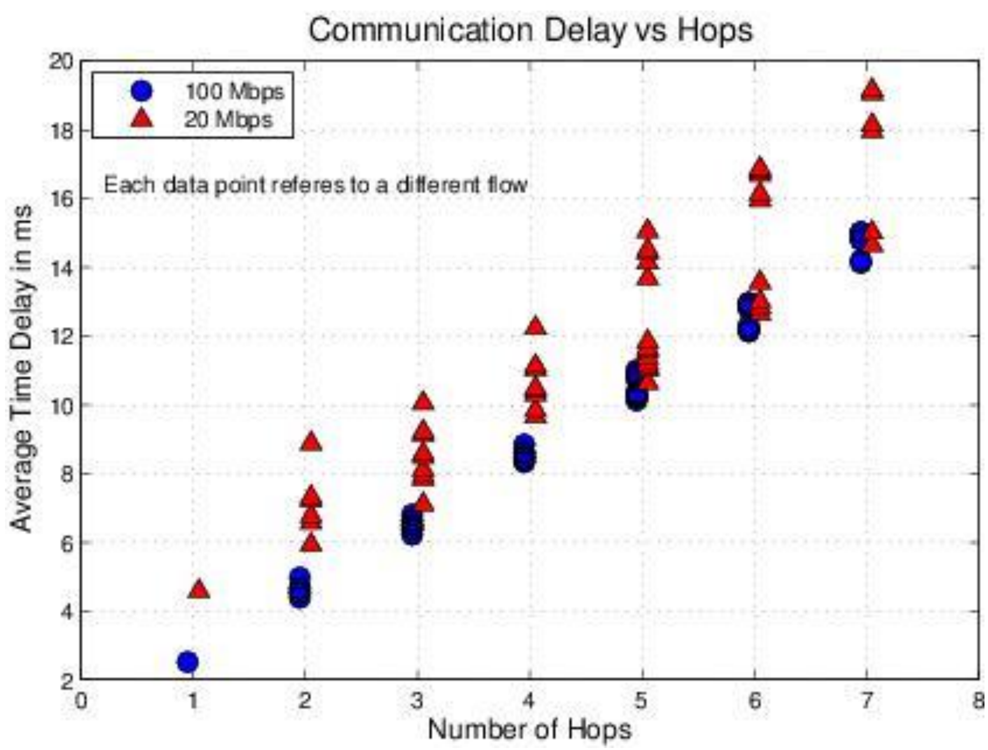

Figure 6. Relationship between communication delay and number of hops for various flows with different link capacities

Besides the theoretical analysis, a simulation is also carried out on IEEE 118 bus system. Each substation is modeled to send its data to the central control center which is connected to one of the substations. The communication links are modeled as two cases, assuming high and low capacities of 100 Mbps and 20 Mbps respectively. The simulations tell the delays and number of hops for each links. These results are plotted in Figure 6 to show the relationship between number of hops and time delays.

From this study, following observations can be made. Firstly, the communication delay varies linearly with number of hops, indicating that minimizing the hops results in minimizing the communication delay. Hence, the Mbh value is an appropriate metric to quantify the volume and delay for a given topology. Secondly, in the case where the link itself is overloaded due to lower capacity, an additional delay is experienced on account of buffering of the packets on the queues at the intermediate nodes. This buffering delay is not captured vary accurately in the Mbh metric hence, it should be ensured that the link bandwidths are sufficiently high.

Since, the Floyd's algorithm only calculates the shortest path, the communication network is also simulated as well to confirm the path and to determine the time delays for each flow. It is verified, that the shortest path found by Floyd's algorithm is same as that of simulation for all flows, as long as the communication network is not overloaded. Floyd's algorithm is convenient for solving multiple scenarios in a single program loop, whereas, software simulation also calculates the delays in communication.

We have proved that our optimal location will leads to least traffic volume and average delay. However, we need to clarify that the optimal location does not necessarily lead to shortest delay on each link individually.

3.4. Simulation environment

The software used to simulate communication network is Network Simulator 3 (NS-3) [36-37]. It is a C++ based discrete-event network simulator designed for Internet systems. NS-3 is primarily used for research about communication network.

As other discrete event simulation tools, NS-3 models the operation of a communication system as discrete sequence of events in time. Each event occurs at a particular instant in time and leads to a set of change in state of the systems. And between consecutive events, all system states are assumed to stay unchanged. Based on this assumption, the simulation can directly proceed in time from one event to the next.

In NS-3, discrete events contain subjects such as generating and sending a packet to lower layers, enque and deque process and receiving action of packets. And system states consist of status of each flow, each link and each packet like time stamp information. The states are calculated based on linear equations used to describe the communication network.

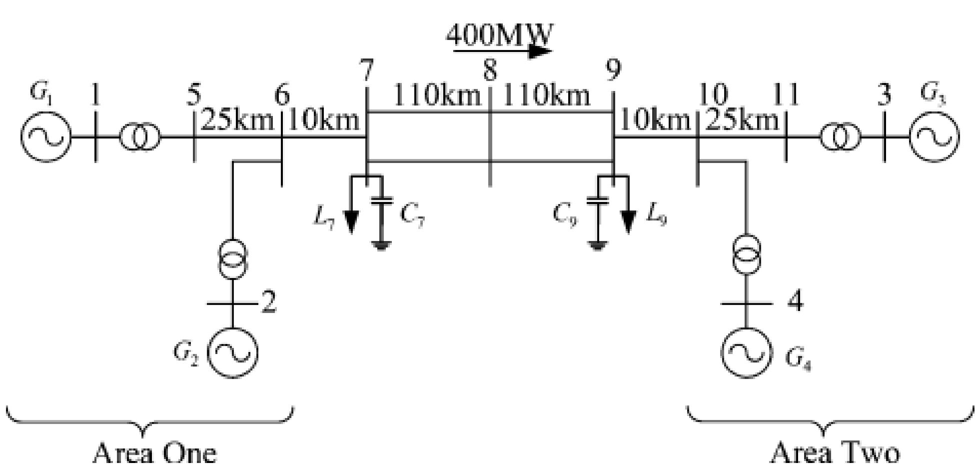

Figure 7. Two-area four-machine system

3.5. Simulation results of two area system

Our first test bed system is a two-area four-machine grid [11]. Its constructor is shown in Figure 7 and its parameters are listed in Kundur's book. This grid is widely used in research related to low frequency oscillation and wide-area damping control. Thus we can use it as example to illustrate our design process of communication network and control systems of power system operation.

We start by deriving a communication scenario according the branch information. In the scenario, buses are located in different substations and one CC is connected to the optimal location. Since the system only consists of 11 buses, there is no need to decentralizing the control and computation process.

After derivation, we have created a communication network of 8 nodes as shown in Figure 8. Node 1 to Node 7 represents seven substations that are connect through transmission lines and communication links. Node 8 represents the control center which will receive all measurements and send out control signals. The corresponding relationship between substations and buses is listed in TABLE III. The topology of the derived communication link is shown in Figure 8.

TABLE III. Substation connection for two-area system

Sub Number	Facilities included
1	Gen 1, bus 1, bus 5
2	Gen 2, bus 2, bus 6
3	bus 7
4	bus 8
5	bus 9
6	Gen 4, bus 4, bus 10
7	Gen 3, bus 3, bus 11
8(attached to sub 2)	Control Center

Since the transmission line between substation 3, 4 and 5 are over 100 miles. We model the communication links between these substation with fiber optic and repeaters.

Compared to communication network application used in local data transport, distance between source and destination plays a much important role in our wide-area communication scenario. Since we build all links with fiber optic cables for a possible length of several hundred kilometers, problem such as attenuation has to be considered.

We assume that for this long-distance fiber optics, there are repeaters every ten kilometers. Repeaters share the same queue size as the substation nodes. The only difference is that repeaters send no new packages into the system.

In the simulation, each substation sends its data to CC with a sample rate of 60 samples per sec, which is simulated by using CBR application. All links in the system have the same bandwidth, varying from 10 Mbps to 4 Mbps. The simulation results of 10 Mbps case is listed in TABLE IV.

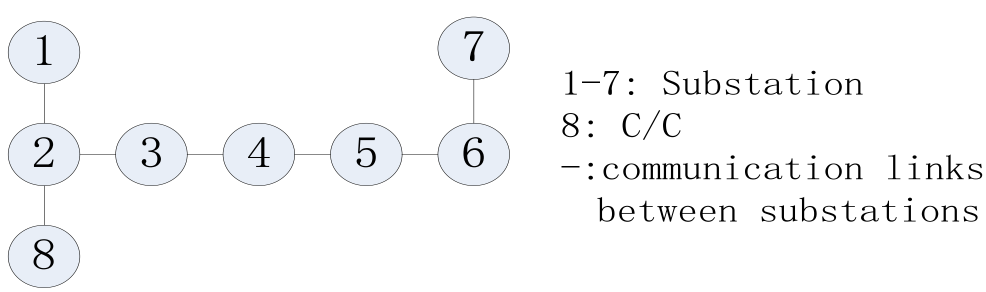

Figure 8. Substation connection

TABLE IV. Communication simulation results of 10 Mbps case

Source sub number	Average time delay/s	Forwarded time
1	0.011296	3
2	0.002824	0
7	0.07907197	27
6	0.07059998	24
3	0.005648	1
4	0.03671199	12
5	0.06777598	23

TABLE IV shows how this communication scenario works from a big picture. We can tell the amount of time delay varies form 2.824ms to 79.1ms for different communication links. The bandwidth we use is 10 Mbps, which is relative high value compared to the scale of the grid, but not a very high capacity regarding the material of optical fibers.

In this case, the bandwidth of 10 Mbps will guarantee that no package is dropped out of the queue and all packages are received at the end of simulation. This means that the delays on each packet are independent from previous packets. Therefore we can consider our delay as a constant value that does not change when the system is in a steady state. The third column in Table 2 represents how much time a data package is forwarded by hubs between source and destination.

The data in TABLE IV also shows a positive relationship between time delay and forwarded time, which proves our previous opinion. We can see the more substations the package goes through, the longer time delay is introduced. That is because in this model, the transportation delay and processing delay are both neglected, and each router involved will add certain amount of queue delay and transmission delay.

However, since routers close to the control center usually have more data flow and long delay, that relationship between forwarded time and time delay is not linear.

Among all the data shown in TABLE IV, we can determine the time delay of wide-area communication link, the link between substation 7 (providing the measurement of rotor speed) and substation 8 (control center).

In order to determine the minimum bandwidth which will meet the latency requirement, simulations based on different bandwidth have been carried out. The range of bandwidth varies from 10 Mbps to 4 Mbps, when congestion can been clearly observed. When we decrease the bandwidth to 3 Mbps, a steady condition has not been established at the end of simulation.

TABLE V shows the statistics about time delay over wide-area communication including the average and variance calculated by the delay of all received package.

TABLE V. Communication results for different bandwidth

Bandwidth	Average delay	Variance
10	0.07907	3.3E-32
9	0.08164	4.64E-32
8	0.08484	6.24E-32
7	0.08896	4.51E-32
6	0.094827	1.62E-8
5	0.10214	2.83E-32
4	0.116218	1.36E-7

We can tell when the bandwidth starts to decrease from 10 Mbps, the average delay start to go up slightly. However, when the bandwidth hit 3 Mbps, both the average value and variance go up dramatically as shown in Figure 9.

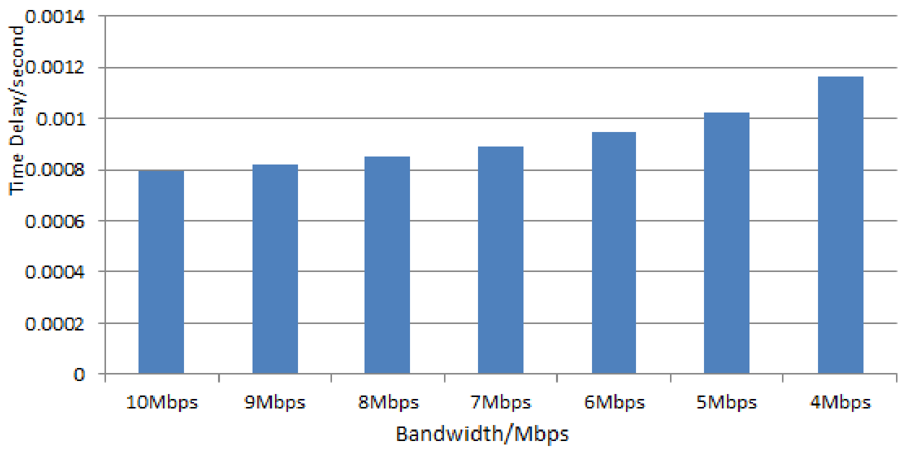

Figure 9. Time delay values at different bandwidth

3.6. Simulation results of IEEE 118 bus system

3.6.1. System description

This IEEE 18 bus test case that is shown in Figure 10 represents a portion of the American Electric Power System, which locates in the Midwestern US as of December, 1962. This system consists of 118 buses, 19 generators with non-zero active power output, 35 synchronous condensers, 177 lines, 9 transformers and 91 loads.

As indicated in Figure 10, IEEE 118 bus system has 3 control areas as indicated from reference [38]. Those control areas are determined by identifying those long distance transmission lines which have much larger impedance than that of shorter lines. And each control area has its own set of generators. The generators belonging to area 1 are at bus number 10, 12, 25, 26, and 31. Whereas for area 2, the generators are at bus 46, 49, 54, 59, 61, 65, 66, and 69. For are 3, bus 80, 87, 89, 100, 103 and 111 are buses with generations.

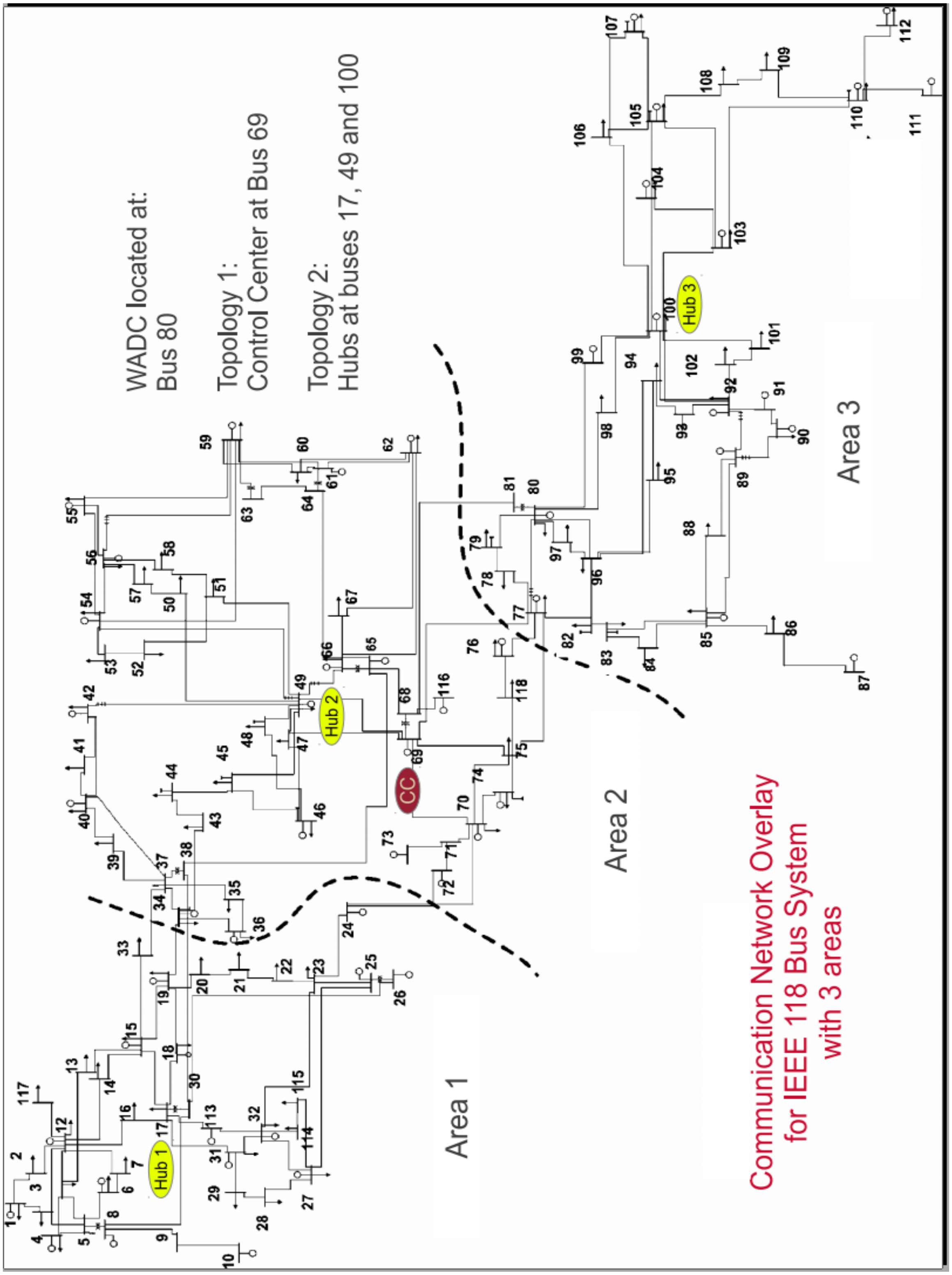

Figure 10. Communication Network Overlay for IEEE 118 Bus System with 3 areas. The single line diagram is from [39]

3.6.2. Communication scenarios

Based on previous assumptions, network reduction process is carried out to combine buses into substations. If two buses are connected to each other through transformers, they are defined to be located in the same substations. And each substation is taken as a communication node that send data frame of PMU packets at rate of 60 packets per second. To calculate the packet size, we assume that each feeder has one PMU device that measures 6 phasors, namely 3 voltage phasors and 3 current phasors. Each PMU has 9 digital channels and 9 analog channels. From such an assumption and IEEE C37.118 standard, it is determined that the packet size of PMU measurements vary from a minimum of 234 bytes to a maximum of 1440 bytes, with an average packet size of 409 bytes.

For IEEE 118 bus system, both centralized topology and decentralized topology are designed. For centralized topology, there is only one CC in the system, which receives measurements from substations at all three control areas. CC also sends out control signal to substation with generation (GSS) for control purpose. Since control signal should only contain necessary information, its packet size is set to be 200 bytes, less than the minimum size of measurements.

For decentralized topology, three data routing hubs are set up to receive data form its own area and send out control signal to local GSS. In this topology, only the communication between substations and hubs are taken into consideration. The communication between hubs and CC as shown in Figure 2 is not simulated. The reason for this is that there is no detail model for data processing within hubs and which subset data should be sent to CC cannot be determined. Hubs are connected to each through direct links, which enable them to exchange information across different areas.

3.6.3. Mbh value and optimal location for CC and hubs

The communication network that we design for IEEE 118 bus system has two kinds of nodes, substation and CC/hubs. The location and connection relationship of substations are generated from power network topology. The location of CC or hubs is determined by calculating the Mbh value and the optimal location is decided to minimize the time delay value.

Having defined a metric for volume of communications in Section 3.4, we proceed to determine the optimal location of CC for centralized topology and hubs for decentralized topology. Since in the process of deriving communication network from power network the buses are merged into a single communication node, the substation numbers are different than the nubs numbers. Assuming the location of CC at each of the substation, the Mbh is calculated using Floyd’s algorithm.

It is universally known from [40] that a criterion for delay dependent stability is that, at a given operating condition for every communication flows in the system, the communication delay between the source and destination nodes must stay in certain bound. A system is considered unstable if, for at least one delay over certain link is outside the boundary so that the performance of certain controller is significant changed. In this dissertation, since the only application involved is WADC, there is no concern about delay on other links.

A sample of results showing the path (intermediate hops) taken by individual data flows are shown in Table. I.

TABLE VI. Mbh results for IEEE 118 bus system

Flow ID	Topology 1 with 100 Mbps links (Centralized)				Topology 2 with 100 Mbps links (Distributed)			
	Path	Hop	Pkt size	Bit-hops	Path	Hops	Pkt'size	Bit-hops
1	1,3,5-8,17-30,37-38,65-66,68-69,CC	7	336	2352	1,3,5-8,17-30,31,hub1	5	336	1680
2	2,12,16,17-30,37-38,65-66,68-69,CC	7	336	2352	2,12,16,17-30,31,hub1	5	336	1680
3	3,5-8,17-30,37-38,65-66,68-69,CC	6	440	2640	3,5-8,17-30,31,hub1	4	440	1760
…	…	…	…	…	…	…	…	…
100	109,110,103,100,98,80-81, 68-69,CC	7	336	2352	109,110,103,100,hub3	4	336	1344
…	…	…	…	…	…	…	…	…
160	CC,68-69,65-66,37-38,17-30,113	5	200	1000	hub3,100,103,110	3	200	600
…	Total Mega-bit-hops (Mbh) =	275.68			Total Mega-bit-hops (Mbh) =			199.97

In Table I, the path column shows the route taken by each packet as a result of Floyd's algorithm. The hops column count the number of intermediate hops that forward data on a particular flow. The pkt' size column indicates how much data is included in the C37.118 packet. Bit-hops column shows how much traffic is carried by that flow.

In this sample, we assume the location for CC of centralized topology is bus 69 and the locations for the hub of decentralized topology are buses 31, 49 and 100. Those bus numbers connected by a dash mean that they are located in the same substation. Therefore, they are counted only as one hop. By comparing the Mbh value of both topologies, we can tell that for most flows, decentralizing the network will reduce the Bit-hop value, which means the delay on that flow is decreased. For example, by decentralizing the network the traffic flow between bus 1 and CC/hubs decrease from 2352 Bit-hops to 1680 Bit-hops by 28.6%. And the total Mbh value for the system goes down from 275.68 Mbh to 199.97 Mbh, reduced by 27.5%. These prove that by using hubs to process and store data in a more locally method, the traffic volume in the network becomes smaller significantly.

The same process is conducted for all possible locations and the results are sorted in the increasing value of Mbh to determine the optimal location of control center and hubs. The best 10 locations along with the volume of communication are plotted in Figure 11.

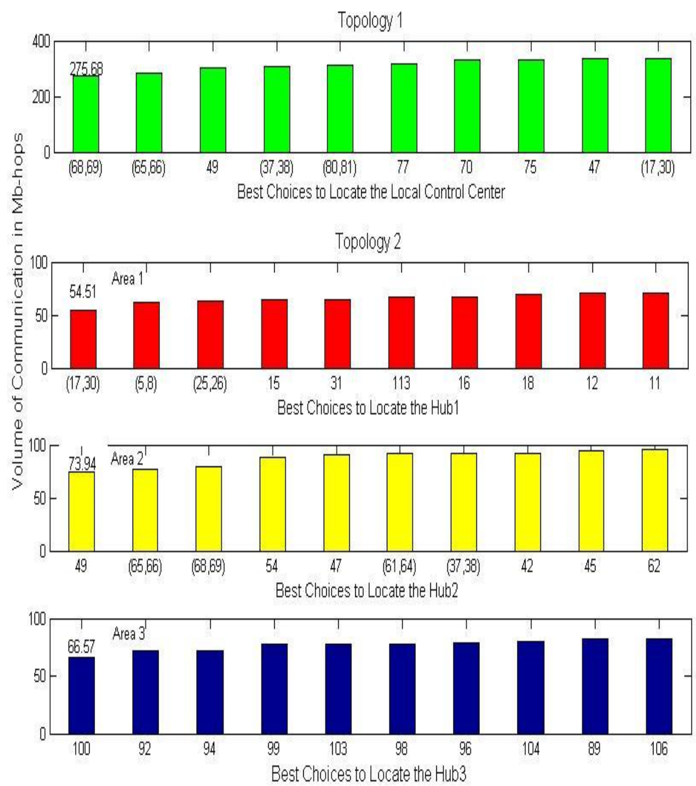

Figure 11. Optimal location of control center for centralized topology and data routing hubs for decentralized topology

It can be observed, that for the case of centralized topology, the best location for CC is at bus 69 (substation 61), resulting in total Mbh-275.68. Whereas for the decentralized topology the best locations for three hubs are bus numbers 17, 49 and 100 (which translates to substation 16, 45, and 91) resulting in Mbh values of 54.5, 73.9 and 66.6, respectively, with the total adding up to 195. The optimal locations are not exactly the same as what we assumed in previous sample. Figure 11 also indicates that for both topologies, the Mbh value does not vary a lot for the top 3 or 4 choices, which gives us some degree of flexibility on choosing where to install our storage and computation nodes.

It should also be noted that, by moving from centralized topology to decentralized topology the volume of communication reduced by 29.3%. With these location settings, we now have a design that brings the shortest average delay over the whole communication network under operating conditions of present power network. In the following section, the time delay over one communication link is calculated to test whether our design can support the delay-sensitive WADC.

3.6.4. Communication simulation results of centralized topology

Having determined the volume of communication with optimal location for CC, the next step is to determine the communication delay in the system. For determining the delay, a simulation on NS-3 has been carried out for centralized communication topology for different bandwidth. The sum of transmission delay and queuing delay are calculated based on simulation of NS-3. Processing delay and propagation delay are neglected.

Table VII shows the time delay on the flows related to WADC. Measurements including remote signal are sent from bus 10 to CC and control signals are sent from CC to bus 89, where WADC is installed. The system is configured in this way, because the small signal analysis (discussed later) of the system identified that the observable state is in bus 10 (substation 9) and controllable state is in bus 89 (substation 80) for damping a particular inter-area oscillatory mode. Judged by number of hops on these two flows, such configuration will generate one of largest delay s in the system. The obtained values of communication delay will be later used in simulation of WADC in Section 4.

TABLE VII. Calculation of delay in centralized topology

Bandwidth (Mbps)	Time Delay (ms)			% Increase
	Bus10-CC	CC-Bus89	Total	
100	14.1	12.8	26.9	0.0
60	14.2	13.3	27.5	2.3
50	14.3	13.6	27.8	3.4
40	14.8	14.0	28.8	6.9
30	17.5	14.6	32.1	19.3
25	39.8	15.2	54.9	104.0
20	178.5	16.0	194.4	622.2

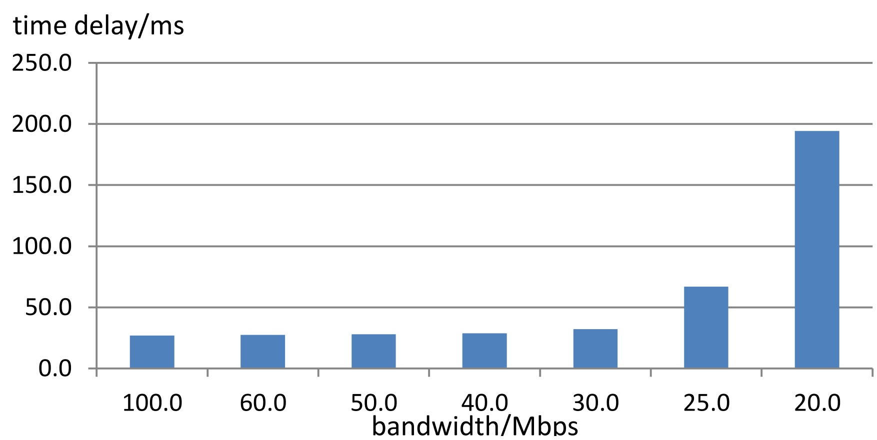

Figure 12. Bandwidth and time delay for centralized topology

From the results shown in Table VII and Figure 12, we can tell the delay of delivering a signal to WADC is relatively small and within the latency requirement when the bandwidth is adequate. And when we start to decrease the bandwidth from 100 Mbps, the delay grows slowly at first. For example, if we move 10% of 100 Mbps bandwidth, delay increase from 26.9 ms to 27.5 ms, by 2.3%. And we believe such amount of change will not affect the performance of power related controller.

Simulation results also indicate that our current design of communication network can support WADC with latency requirements of 100 ms with bandwidth larger than 25 Mbps, which introduces 54.9 ms into the signal. Therefore, even 75% of original bandwidth is cut, the communication network performance is still within the limit.

However, when provided with bandwidth of 20 Mpbs, the delay on the control signal is almost 200 ms, which is far beyond the latency requirement of WADC. By analyzing the increasing percentage, we can draw the conclusion that the delay increase slowly at first. But when the bandwidth is less than certain threshold, we can expect a sudden burst in delay value.

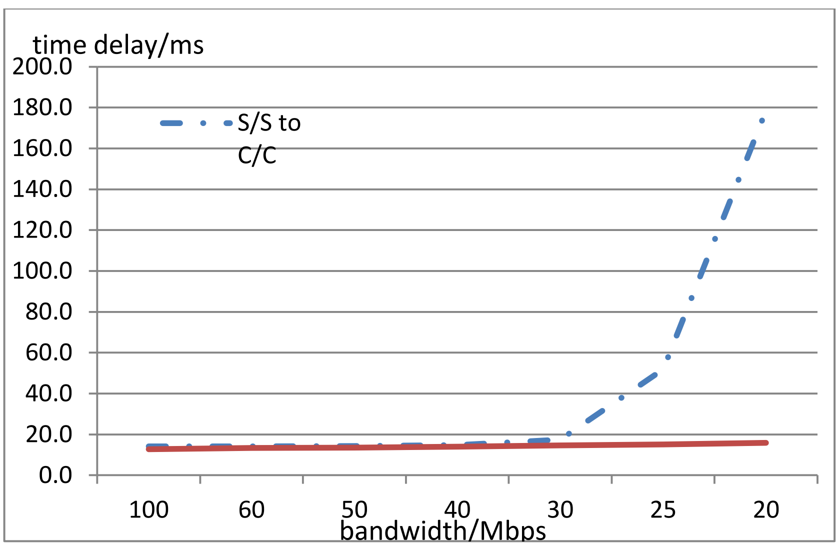

Figure 13. Delay on measurement and delay on control signal

Figure 13 shows how the two part of delay change with bandwidth separately. From the results shown above, we can tell that with adequate bandwidth, there is not much difference on the delay of measurements and delay of control signal, since they are taking the same path. When the bandwidth is decreasing, the growth speed of the two parts of delay varies in large degree. We can tell that the delay on control signal (from CC to bus 89) remains almost the same value when we reduce bandwidth from 100 Mbps to 20 Mbps while the delay on measurements (from bus 10 to CC) increased by 1200%. The reason for such a huge difference is that the packet size of control signal is less than half of the average packet size of measurements and they are transmitted through the system in different directions.

3.6.5. Communication simulation results of decentralized topology

The same NS-3 simulation procedure is carried out for decentralized topology, in which each substation sends its measurements to local hubs and hubs send control signals to local GSS. Since our remote signal for WADC comes from a different control area, a flow is built between hubs to send signal from one area to another. The simulation results are summarized in TABLE VIII.

TABLE VIII. Calculation of delay in decentralized topology

BW Mbps	Time Delay (ms)				% Inc
	B10-hub1	hub1-hub3	hub3-B89	Total	
100	8.07	2.02	6.13	16.22	0.00
60	8.12	2.03	6.21	16.37	0.91
50	8.15	2.04	6.26	16.44	1.36
40	8.18	2.05	6.32	16.55	2.04
30	8.25	2.06	6.43	16.74	3.18
25	8.31	2.07	6.52	16.90	4.16
20	8.88	2.09	6.64	17.62	8.63
10	12.79	2.18	7.29	22.26	37.26
5	193.26	2.37	8.58	204.20	1158.9

TABLE VIII shows that the delay related to WADC input signal consist three parts, delay on measurement, delay on inter-area signal transmission and delay on control signal. Since the delay on inter-area signal transmission happens on one direct link, it is shorter than the delay on the other two parts. The total delay value under 100 Mbps bandwidth is 16.22 ms, which is significantly less than 26.9 ms, the delay value under the same bandwidth for centralized topology. And the latency keeps less than 17 ms when the bandwidth is larger than 25 Mbps. Using 100 ms as latency requirement of normal wide-area controller, we can set our minimal bandwidth requirement as 10 Mbps. Considering the amount of bandwidth that is support by commonly used optical fibers, 10 Mbps is quite loose constraint. And this proves that our design of decentralized communication network does not have a high standard on bandwidth.

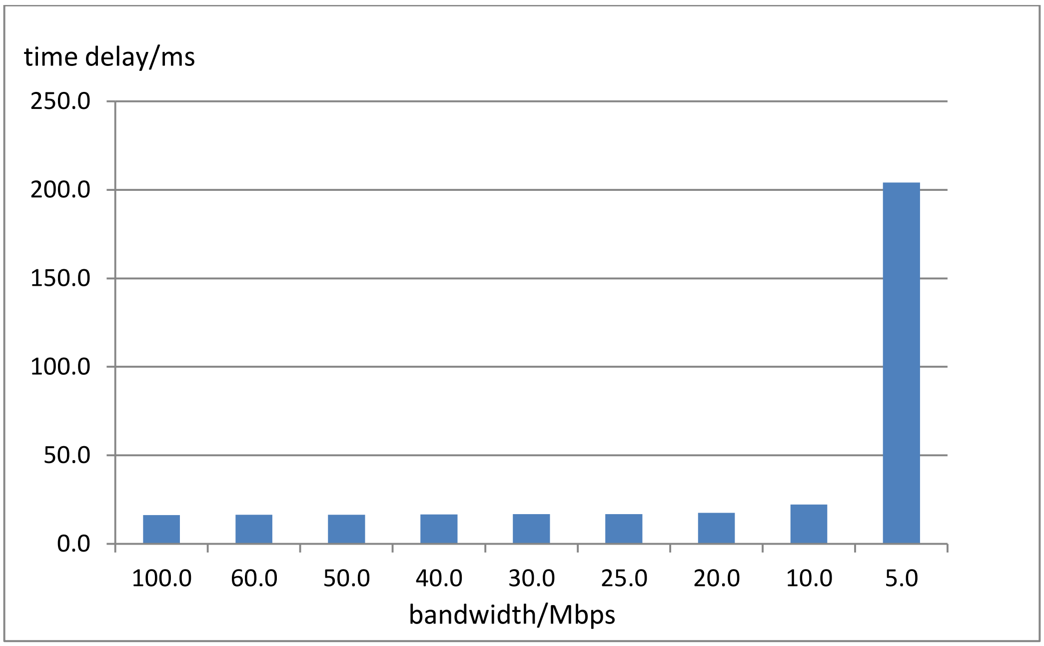

Figure 14. Delay for decentralized topology

From the results shown in Table VIII and Figure 13, we can confirm the conclusion that the delay of delivering a signal to WADC is relatively small and within the latency requirement when the bandwidth is adequate drawn from centralized topology. And when we start to decrease the bandwidth from 100 Mbps, the delay grows slowly at first. For example, if we move 40% of 100 Mbps bandwidth, delay increase from 16.22 ms to 16.37 ms, by 0.9%. And we believe such amount of change is negligible and makes no difference on controller performance.

Simulation results also tell us that our design of decentralized communication network can support WADC with latency requirements of 100 ms with bandwidth larger than 10 Mbps, which introduces 22.26 ms into the signal. Therefore, even 90% of original bandwidth is constrained, the communication network can still limit its delay in a tolerable area. And it should be noticed that the bandwidth requirement of decentralized topology (10 Mbps) is much smaller than that of centralized topology (25 Mbps).

However, when provided with bandwidth of 5 Mpbs, the delay on the control signal is more 200 ms, which is larger than the upper limit of our latency requirements. By analyzing the increasing percentage, we draw the same conclusion that when we decrease the bandwidth, there will be a bust on delay at certain point. Before that, the delay increase only in small amount.

3.6.6. Communication simulation results of decentralized topology with non-optimal locations for hubs

To validate our previous statements about how location of CC or hubs will change the traffic volume of communication network and therefore the time delay and how number of hops will affect the delay value. Simulations are done for a case about decentralized communication topology with locations different from the optimal choice mentioned above and different set of remote signal and controller location.

As calculated in Section 3.6.3, the optimal locations of hubs for decentralized communication topology are bus numbers 17, 49 and 100 (which translates to substation 16, 45, and 91). To make a difference, we move one of these three hubs to a different. For example, we relocate hub 1 from bus number 17 to bus number 31. Thus, the locations of hubs for non-optimal case are bus number 31, bus number 49 and bus number 100. And in this case, we customize the location of WADC to be substation 102 and remote control signal to be from substation 1.

The rest settings of communication scenario remain the same as the optimal location case. This means three hubs are set to handle the data which is measurement in local area. In this case, substations only send PMU data to and receive control data from its local hub, which will reduce the stress of transporting large amount of data and is supposed to reduce the average delay compared to the centralized topology.

Other than communication links between substations and local hubs, data transmission among data routing hubs are also simulated in this case. We assume that local hubs only share indispensable information with each other with same sending rate (60 packets/s) and packet size (200 bytes) as the parameters of control data. Considering that communication between local hubs should not share the same physical middleware with links between substations and local center. A communication wire is built between hub 1 and hub 3. The NS-3 simulation results of simulation are summarized in TABLE IX, including the total delay over communication link and the delay over three parts of data transporting procedure.

TABLE IX. Calculation of delay in decentralized topology with non-optimal location

Bandwidth (Mbps)	Time delay between S/S 1 and L/C 1(msec)	Time delay between L/C 1 and L/C 3 (msec)	Time delay between L/C 3 and S/S 102(msec)	Total time delay (msec)	Increased % compared to 100Mbps case (%)

100	10.2	2.0	8.4	20.6	0.0
60	10.3	2.0	8.6	21.0	1.9
50	10.4	2.0	8.7	21.2	2.8
40	10.5	2.0	8.9	21.4	4.2
30	10.6	2.1	9.2	21.9	6.5
25	10.8	2.1	9.5	22.3	8.4
20	11.1	2.1	9.8	23.1	12.0
10	16.2	2.2	11.7	30.1	46.3
5	200.8	2.4	15.4	218.5	961.9

From the results of time delay between substation and its local center, we can tell that new topology helps lower our bandwidth requirement. In this case, we can meet the time delay limit with a bandwidth as low as 10Mbps, which is a great progress compared to results in centralized topology.

It also shows that the distributed network introduce shorter delay with the same network environment. For example, in 50Mbps scenario centralized topology introduces a delay of 30.6ms into the system while decentralized topology introduces a delay of 21.2ms. The delay on measurement data and control data decrease due to the design of local control center, and the delay caused by data exchange between local centers is even smaller because of the link we add between local center 1 and local center 3. Table VI shows that the number of hops is reduced generally due to the distributed topology.

3.6.7. Comparison between centralized and decentralized topologies

Based on NS-3 simulation results for both centralized topology and decentralized topology, it can be concluded that the decentralized topology results in less volume of communication (occurring in real-time) and also less amount of time delay.

From the calculation of packet size and Floy'd algorithm, decentralizing CC into three data routing hubs leads a shrink in traffic volume about 70 Mbh, which account for about 25% of the total traffic for centralized communication. This means that by simply add three computation nodes into the system the throughput of communication network becomes much less stressful. This also means that the same system can now be able to handle more data at a faster speed.

From the NS-3 simulation results, we can tell that by decentralizing, the amount of delay on a particular flow related to WADC is reduced considerably. For 100 Mbps case, the delay is reduced from 26.9 ms to 16. 22 ms. The reduction percentage is about 40%. And for 60 Mbps case the delay decrease from 27.5 ms to 16.37 ms. For 25 Mbps case, in which the minimum bandwidth is used for centralized topology, the delay goes down from 54.9 ms to 16.9 ms, which means for the minimum required bandwidth for centralized topology, we can reduce the delay by roughly 70%. This is a huge change, considering there is no extra investment needs to upgrade the whole network with larger bandwidth links.

The other improvement of decentralization is on the minimum bandwidth requirement to meet a latency requirement of 100 ms. For centralized topology, we need at least 2 Mbps to support the WADC. While for decentralized topology, we only need bandwidth to be larger than 10 Mbps. It should be noted that the delay for 25 Mbps case of centralized topology is 54.9 ms and the delay for 10 Mbps case of decentralized topology is 22.26 ms. This suggests that our new design of communication network can guarantee less time delay with even less network resources.

Based on the discussions, we can say that the reduction in volume of communication can be attributed to the decentralized localization of data in real-time.

And the reduction in delay can be attributed to the reduction in length of communication path, due direct peer-to-peer communication between neighboring hubs, instead of transfer of the monitoring data all the way to the central CC and subsequent relay of control commands back from central CC to the control substation.

Based on simulation results of two communication topologies, it has been demonstrated that the distributed architecture has more advantages than the centralized one. Decentralized topology can achieve shorter time delays even with lower network bandwidth, there by reliable and suitable choice for wide-area damping controller spanning multiple control areas.

4. Wide-Area Control Systems

4.1. Introduction

Considering the development of long distance interconnection among power grids, the systems are now connected to each other more tightly. The scale of the grids becomes larger and more complex. Therefore, inter-area low frequency oscillation at 0.2 Hz to 1 Hz becomes a major stability consideration and more and more poorly damped oscillations have been observed. Traditionally, we use power system stabilizer (PSS), a controller utilizing local signals like rotor speed to perform a close loop control on the generator. Such controllers can be very functional with the local are modes, while their help on damping inter-are modes are limited because such modes are not usually observable/controllable from the local measurements.

With the rapid growth in the number of wide-area measurement systems (WAMS) installed in the grid, controllers that using remote measured signal is proposed to improve the damping performance of low frequency oscillation. WADC was firstly introduced in [41] as a two-level generation controller to improve the system stability. Robust methods are used to determine the parameters of WADC, such as a multi-agent H_∞ controller design method or a mixed H_2/ H_∞ method. In order to handle different operation points of power system and uncertainty in modeling, a method named as predictor-based H_∞ controller is also studied for compensation of delay in WADC.

Time delay or latency introduced by communication system during transmission of remote measurements is one of the key considerations influencing the whole stability index and damping ratio. Traditionally, the data is moved around through direct links built using satellite or wireless communication. But such communication carrier is increasingly unable to meet the latency demand of the more and more stressful power systems.

To be able to handle the large amount data generated by WAMS, communication network instead of direct links are more and more commonly used in industry. Hi bandwidth fiber optics links are built using the existing path of transmission lines. Such network is used only by power facilities and provides no public access. This is considered to be a popular solution to provide power grid a fast and safe communication links with reasonable costs.

From the point of view of damping oscillation and control purpose, it is crucial to determine the maximal latency over the network, defined as safety margin [], for power controllers such as WADC to make sure the controller stay functional as designed. During the design process, some of these controllers do not include the impact of time delay and they considered delay as part of system uncertainties which is processed by robust control method. Furthermore, the safety margin of delay was not calculated and the robustness of controller against latency is tested by simulations. The concept of safety margin is useful for guiding the design of the wide-area controller in a real grid.

4.2. Power system model

When studying power system dynamic performance, the grid including power generator, transmission lines, transformers and loads can be represented with a linearized model. The system is linearized around the equilibrium point so that the changing part will have a linear relationship with input the system states. After linearization, a set of differential-algebraic equations (DAEs) is developed to describe system response with small disturbance and to help with mode analysis as well as WADC design. The DAEs for a power system with only local controllers can be written into the following form:

$$\begin{cases} \dot{x_1}(t) = A_1 x_1(t) + B_1 u(t) \\ y(t) = C_1 x_1(t) \end{cases} \qquad (4.1)$$

where x_1, y and u are the vector of state variables such as generator rotor speed and angles, output variables and control variables. A_1 is the state matrix, B_1 the input matrix and C_1 the output matrix.

Furthermore, controller with remote signals is also added as part of input to the traditional exciter, which structure is shown in Figure 15. The input of this extra controller is a system-wide state variable. The commonly used signal includes tie-line real power signal and rotor speed signal measured from one of the remote generators. The exact location of remote signal is calculated based on observability and controllability. The output of WADC, along with the output of PSS, is considered as an input of the automatic voltage regulator (AVR) to control the excitation and terminal voltage of generator.

This new contracture of controller improves the power system performance and stability by regulation the generator field voltage E_f. Adding another feedback helps improve the observability and controllability concerning certain poorly damping mode.

Despite using a remote signal as input, WADC is designed as a linear damping controller as well as PSS. It can be represented as

$$\begin{cases} \dot{x}_2(t) = A_2 x_2(t) + B_2 u_2(t) \\ y_2(t) = C_2 x_2(t) + D_2 u_2(t) \end{cases} \tag{4.2}$$

where x_2 is the vector of state variables of the controller, y_2 the vector of defined output variables, u_2 the vector of control variables, A_2 the state matrix, B_2 the input matrix and C_2 the output matrix of the control system.

The entire power system, including both local and remote controller in its excitation part, as well as taking time delay into consider, can be linearized to a close-loop control system model as shown in Figure 16. From the figure, we can tell the input of WADC is connected to the signal we extract from conventional power system model. The block in the middle represent the time delay (denoted as d(t)) caused by data transfer. Although this delay may seem to be constant in the following NS-3 simulation results, we still consider it as a function of time throughout this paper. Therefore, the connection shown in Figure 16 could be represented as shown in Equation (4.3).

$$\begin{cases} \mathrm{u}_2(\mathrm{t}) = \mathrm{y}(\mathrm{t} - \mathrm{d}(\mathrm{t})) \\ \mathrm{u}(\mathrm{t}) = \mathrm{y}_2(\mathrm{t}) \end{cases} \tag{4.3}$$

Combine Equations (4.1) – (4.3), and eliminate the control variables like u(t) and u_2(t). We can determine a set of linear equations about system output and system states when delay is included in the remote signal used for WADC, as described in Equation (4.4):

$$\dot{x}(t) = Ax(t) + A_d x(t - d(t)) \qquad (4.4)$$

where $x = [x_1,x_2]^T$, $A = \begin{vmatrix} A_1 & B_1C_1 \\ 0 & A_2 \end{vmatrix}$, $A_d = \begin{vmatrix} B_1D_2C_1 & 0 \\ B_2C_1 & 0 \end{vmatrix}$.

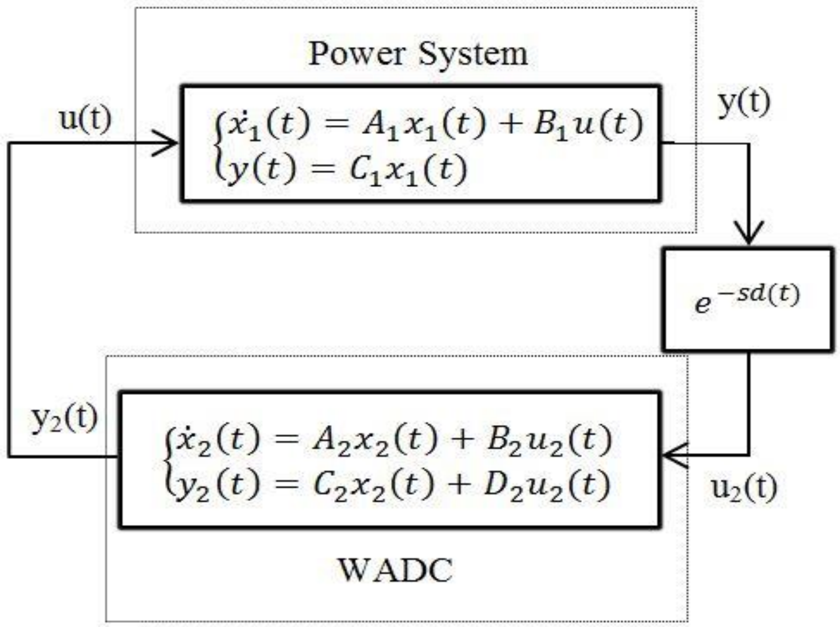

Figure 15. Close-loop system model

4.3. Latency requirement of WADC

Time delay or latency is always key factor that will affect a delay-dependent system in different ways, since delay that exceeds its limit will leads to violation on the stability of the whole control system. The study of delay-dependent linear system is discussed in [25]. In the closed-loop model described in Equation (4.4), asymptotic stability of the system can be achieved with time delay (d(t)) within certain limit for all time, where d(t) represents the time delay as a function of time and the upper limit is a certain time delay value considered as a latency requirement. The system will turn to an unstable condition with delays outside the limit at any time. The latency requirement is one major evaluation to specify the stability of power system with a delay-dependent wide-area controller.

Several methods have been proposed to calculate the margin, based on Lyapunov theory. Each method comes up with different details about conservativeness [42-43]. Though the stability conditions are just sufficient conditions, Lyapunov theory based methods are still considered as efficient tools to determine the stability of systems with time-varying or constant delay.

Among these methods mentioned above, the free-weighting matrices method presented in [27] provides less conservativeness. This method also provides sufficient condition for stability of system of Equation (4.4) for a given upper bound of changing rate of time delay. But its results cannot be used to determine the latency requirement directly. Two ways can be used to calculate the delay based on the theory of free-weighting matrices method and linear matrix inequality (LMI) theory. One way is to apply the function to check the existence of the upper limit of latency based on LMI constraints. For a given upper changing rate, if we manually increase the upper limit of delay and check the feasibility, the requirement can be found by first value that comes without any feasibility. The other way needs to convert the original problem to a standard generalized eigenvalue minimization problem. By solving the equivalent problem, the latency requirement can be found.

From the calculation procedure of latency requirement, we discover several factors that will affect how much delay a linear system. The first factor is the gain of WADC. It is observed that decrease of the gain value of the WADC will lower the latency requirement, which means the smaller the gain is, the more delay the system can cope with. However, this value will also change the damping ratio. It has been proved that larger gain leads to faster damping for the oscillation. Therefore, there must a tradeoff between the damping performance and latency requirement.

The other factor that affects the latency requirement is the upper limit of changing rate of delay. If the delay value (d(t)) changes faster with time, the system becomes easier to lose its stability due the delay. Based on this conclusion, we can tell power system has high latency standard towards time-varying delay than constant delay. Since in this dissertation, we assume all delays that we have in the communication network are constant delay which will not change with time, the latency requirement discussed here may not be valid for systems that have time-varying delay.

One example of calculation of latency requirement of two-area system is shown in [25].

4.4. Simulation results of two-area system

Having determined the communication delays, the next step is to design a WADC for the above 4 machine system. The system shown in Fig. 10 consists of two fully symmetrical areas connected together by two 230 kV lines of 220 km length. Identical speed regulators are further assumed to be installed at all locations, in addition to fast static exciters with a 200 gain. The load is represented as constant impedances and split between the areas in such a way that area 1 is exporting 400MW to area 2. To damp the local mode, conventional PSS using $\Delta\omega$ as an input (ω is the local generator speed) is installed on all plants, which structure is shown in Fig. 10.

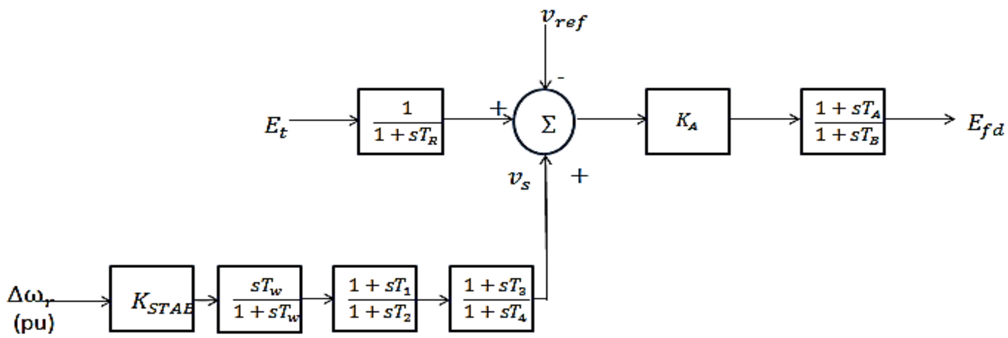

Figure 16. Control block of excitation system

WADC is added to the exciter at G1 as in Fig. 11. The input signal is the changing part of differential speed signal between the remote generator and the local generator. The transfer function of the controller is calculated based on residues compensation [25]. The parameters are as follows:

$$H_{PSS}(s) = 30\frac{10s}{1+10s}\left(\frac{1+0.05s}{1+0.03S}\right)\left(\frac{1+3.0s}{1+5.4s}\right) \tag{4.5}$$

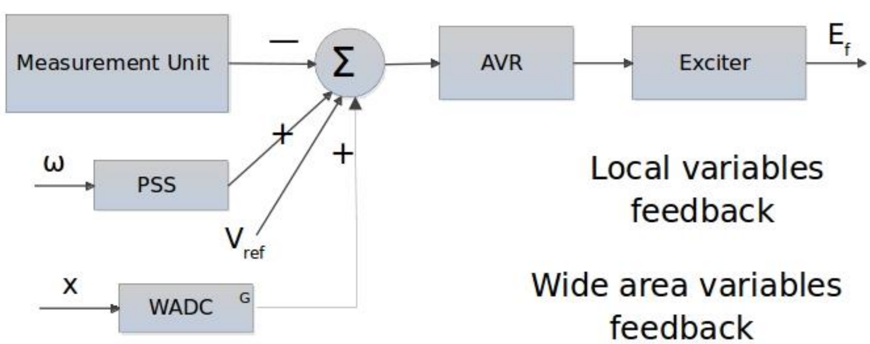

Figure 17. Excitation system with WADC

In the above figure a time delay as per the assumed bandwidth is introduced in the WADC input signal. To test the dynamic stability in this system, a 5%-magnitude pulse is used, applied at the voltage reference of the exciter at G1 for 12 cycles.

During the Simulink simulation, the input of the damping controller is delayed by a certain time, calculated by the NS-3 results shown Section 3. Relative rotor angles are plotted to determine the stability of the system. The rotor angle of generator 4 (M4) is used as reference value. Figure 19 shows the results with 10 Mbps bandwidth (a time delay of 79 milliseconds), whereas Figure 20 shows the results with 3 Mbps (a time delay of 210 milliseconds).

From the results we can see the oscillation of rotor angles after the disturbance. With a bandwidth of 10 Mbps, this oscillation is damped out by WADC at the end of simulation. However in the 3Mbps case, that oscillation makes the whole system unstable. The amplitude of oscillation keeps growing with time. So we can say that if the network condition is not good enough, the time delay introduced by remote-data transport can completely change the stability of a power system.

So far we have only studied centralized communication architectures. It is observed that, when the system size becomes larger, the data from far away substations have to take many hops before reaching the central control center. This results in latencies well beyond our target of keeping latencies below 100 msec.

To address this problem, design of distributed architecture is presented in the section 5, using the concept of mutually interconnected local control centers. The overall latencies are shown to be lesser even when using lower bandwidth links.

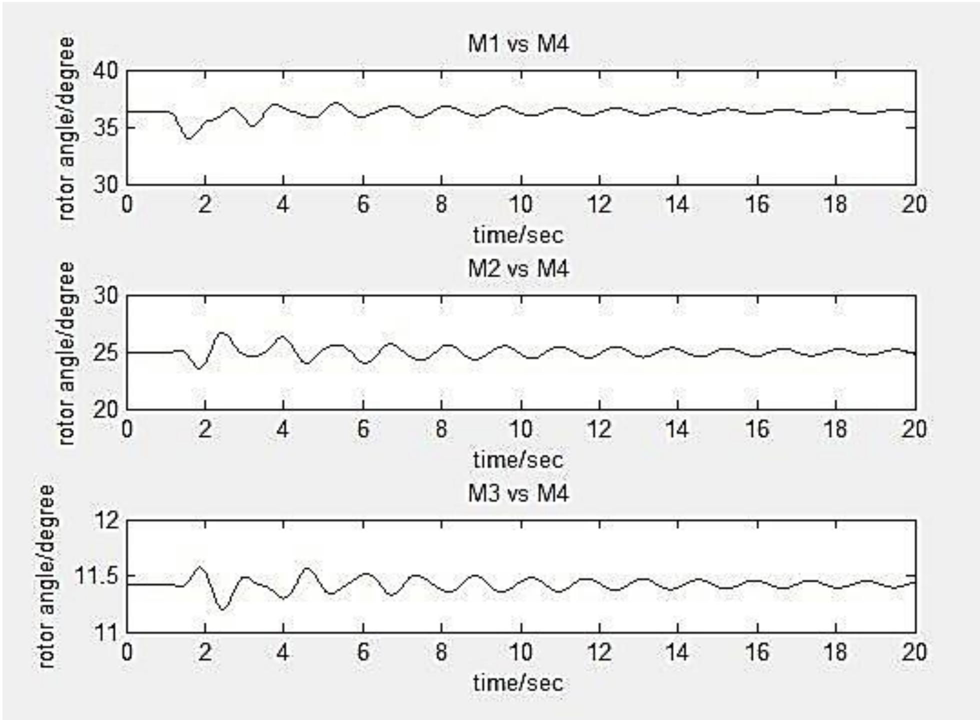

Figure 18. System performance with 10 Mbps. The system is stable

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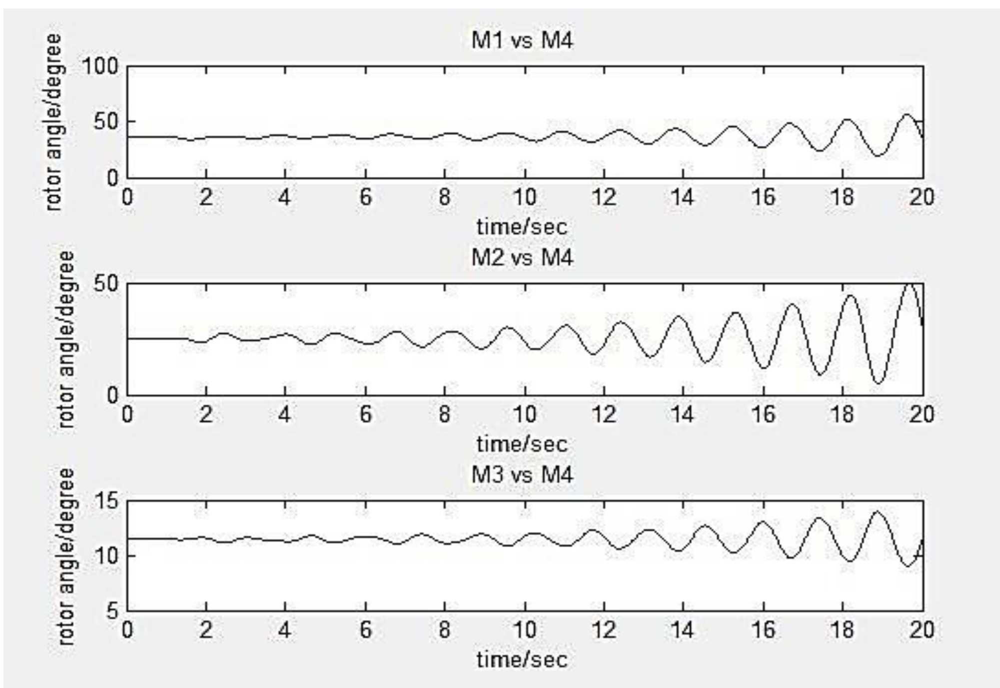

Figure 19. System performance with 3 Mbps. The system is unstable

4.5. Simulation results of IEEE 118 bus system

For the purpose of demonstration about the relationship between time delay in a wide-area control system and dynamic stability, time-domain non-linear TSAT simulations are carried out using IEEE 118 bus system. Generator performance is observed by plotting the relative rotor angle after small disturbance on the generation side. After presenting generator and control models, small signal stability analysis, WADC design process and simulation scenarios, the simulation results will be introduced and analyzed.

4.5.1. System description

As discussed above, the dynamic performance of the proposed WADC is tested on the IEEE 118 bus system, which is large and complex enough to observe the effects introduced by communication network which will occur in a real grid. The static system data are gathered from Figure 10 and [10]. IEEE 118 bus system consists of 19 generators and 99 loads. The system used in this dissertation is slightly modified to insert some necessary information regarding dynamic simulation. In order to assign proper voltage levels to generators and transmission lines, we consider that generators are medium-voltage buses with idea step-up transformers imbedded. The nominal voltages range from 6.9 kV to 24 kV based on their output. Also the high voltage transmission system is considered to run at 400 kV.

All 19 generators are represented by a detailed two-axis mode, in which parameters of both direct axis and quadrature axis are used to descript the generator dynamic performance. Since there are no existing dynamic parameters for the generators in IEEE 118 bus system, typical values taken from [44] were used for the simulation. The generators are categorized based on the least nominal power that can support the generation listed in power flow data. MVA ratings, nominal voltage and a few parameters missing in [44] are listed in TABLE X.

TABLE X. Generator parameters

Generator No.	S_r (MVA)	V_r (kV)	H (s)	K_d (MV/Hz)
10	512	24	2.63	0
12	100	13.8	4.99	0
25	270	18	4.13	0
26	384	24	2.62	0
31	9	6.9	2.61	0
46	35	13.8	7.26	0
49	250	18	6.41	0
54	65.8	13.8	2.67	0
59	192	18	3.3	0
61	192	18	3.3	0
65	448	22	2.66	0
66	448	22	2.66	0
69	590	22	2.32	0
80	590	22	2.32	0
87	9	6.9	2.61	0
89	835	20	2.64	0
100	270	18	4.13	0
103	52.2	13.8	4.98	0
111	52.2	13.8	4.98	0

From Table X, we can see that the rated output of 19 generators vary from 9 MVA to 512 MVA while their rated voltage level vary from 6.9 kV to 24 kV. As mentioned before, all plants are connected 400 kV transmission system through idea step-up transforms, which have no impedance and have no effects on the system. And to be able evaluate the performance of purely damping controller, the damping of generators (K_D) are set to 0.

All generators are modeled by classical two-axis model. They are also equipped with automatic voltage regulator (AVR) as shown in Figure 21. The simplified AVR model is showed on how the excitation field is controlled. VT represents the voltage magnitude at the output side of the plant. Vset is the setpoint of voltage to provide desired power output. EFD represents the field voltage. All generators are also equipped with PSS which structure is shown in Figure 18.

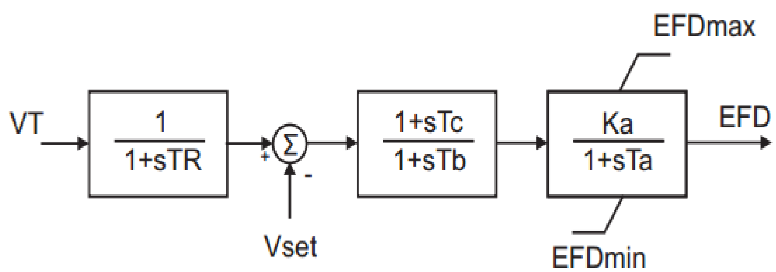

Figure 20. AVR block diagram

Generators take account of most dynamic performance in the system. The loads in IEEE 118 bus system are considered only as consistent impedance. The whole dynamic model is then loaded by SSAT, a small signal analysis tool to perform the mode analysis, and TSAT, a transient stability analysis tool to simulate the network in a non-linear time-domain method.

4.5.2. Small signal stability analysis

The small signal stability analysis (SSSA) results of IEEE 118 bus system with the dynamic model introduce in previous section are shown in TABLE XI. TABLE XI shows the real part and imaginary part of eigen value as well as the damping information about poorly damped modes. Four oscillations with damping ratio less than 10% are listed. Among them, two oscillations' damping ratios are quite close to the criterion while the other two are especially poorly damped.

TABLE XI. Small signal analysis results

Eigen Value		Frequency (Hz)	Damping Ratio	Mode Type
Real	Imaginary			
−0.277	±j7.26	1.15	3.81 %	13/19
−1.475	±j14.67	2.33	10 %	7/19
−1.113	±j11.71	1.86	9.47 %	7/19
−0.202	±j5.86	0.933	3.45 %	11/19

Mode type is also shown in TABLE XI. It is an index defined by SSAT software to describe the types of modes. The values listed under Mode Type column means how many speeds of generators in this mode shape are larger than a customized threshold over the total number of generators in the system. Using the mode type index of the oscillation with the worst damping ratio as an example, 11/19 means that out of the total 19 generators in IEEE 118 system, 11 generators' speeds are considered to significantly participate this mode. This also tells us that this mode is an inter-are mode. Mode type is useful tool to inspect the natural of a mode. It is more effective than inspecting mode shapes and participation factors.

4.5.3. WADC design process

An LMI approach to the mixed H2/H∞ output-feedback control with regional pole placement is applied to design a wide-area damping controller for inter-area oscillations. The designed controller should meet the requirements of robust stability, robust performance and acceptable transient response. Time-delays should be modeled in the controller synthesis problem so that the designed controller can handle time-delays. Sometimes the order of obtained controller needs to be reduced for easy implementation. In this case, the balanced model reduction is applied again.

The selection of appropriate stabilizing signals and locations of control sites is an important consideration in the design of wide-area damping control systems. For FACTS devices, the most often used input signals are line current, line active power and generator angular speed.

The remote stabilizing signals are often referred to as “global signals” to illustrate that they contain information about overall network dynamics as opposed to local control signals which lack adequate observability of some of the significant inter-area modes. The recent advances in WAMS technologies using PMUs make it possible to deliver synchronous phasors and control signals at a high speed (e.g., at a 60-Hz sample rate). It is also possible to deploy PMUs at strategic locations on the grid and obtain a coherent picture of the entire network in real time.

Methods developed to select feedback signals and control sites resulting in the maximum damping effects can be classified into two categories: controllability/observability analysis and damping torque analysis. Controllability/observability analysis is derived from modal control theory of linear time-invariant system [45-46]. With this method, measures of modal controllability and observability are calculated to resolve problems of the best control sites and the selection of the stabilizing signals for PSS and FACTS devices [46-48]. Damping torque analysis [49] gives more physical meanings to the criteria of selection of control sites and stabilizing signals. But, as pointed out in [50], residue analysis is equivalent to damping torque analysis.

As described in the previous section, the WADC uses the measurement from SS9 bus 10 and the controller is installed at SS80bus 89. In order to test the performance of PSS and WADC the damping coefficients of all the machines are the machines themselves is set to zero.

Thus, all the damping has to be provided by the controllers. Conventional PSS using Δω as an input (ω is the local generator speed) is installed on all plants to damp local modes. WADC is added in the form of an additional input to the exciter at generator SS80bus 89. The design of controller is shown in Fig. 8. The input signal is the changing part of differential speed signal between the local generator and the remote generator Δ(ω89−ω10). The transfer function of the controller is calculated based on residues compensation [19]. The parameters are as follows:

$$\mathrm{H(s)} = 26\left(\frac{10s}{1+10s}\right)\left(\frac{1+0.503s}{1+0.0288s}\right) \qquad (4.6)$$

4.5.4. Simulation scenario 1

Based on the dynamic model of generators and the design of WADC, IEEE 118 bus is simulated in TSAT to evaluate the system stability under different delay value. All 19 generators’ dynamic performances are observed recorded. The active power output of each plant is plotted to illustrate the system stability in intuitive way.

Firstly, the simulation delay value of centralized topology is used to assess the stability when all computation and processing are taking place at the only CC. Then the system is divided into three control areas and delay based on decentralized communication topology is simulated into WADC to determine the system stability.

TABLE XII. System and control area information

Parameters	Topology 1: Centralized	Topology 2: Distributed		
		Area-1	Area-2	Area-3
Buses	118	37	45	36
Substations (SS)	109	34	40	35
Control Centers (CC)	1	0	1	0
Data Routing Hubs	0	1	1	1
Generator SS (GSS)	52	16	19	17
Communication Links	161	50	59	52

TABLE XII shows the static information about the whole system and three different control areas. From TABLE XII, we can see that Area 2, which is located in the middle of the IEEE 118 bus system, has the most buses and generation substations. The CC of centralized topology is also included in Area 2. But the differences among 3 areas are relatively small, which suggests that all 3 areas should be considered equally when assigning computation capability of 3 hubs.

TABLE XIII shows the coherence of generators. From previous analysis, we know that the generators are coherent into three groups according to their dynamic performance.

TABLE XIII. Generator coherence

	Generator Buses
Group 1	46, 49, 80, 89
Group 2	66, 87, 100, 103, 111
Group 3	10, 12, 25, 26, 31, 54, 59, 61, 65, 69

To test the stability and observe generators' respond to slightly unbalance situation, the disturbance scenario considered in this simulation of dynamic behavior is a step change of automatic voltage regulator (AVR) set point by 0.05 pu at generator at bus 10 (SS 9) for duration of 0.2 sec (12 cycles).

As we expect, tit is observed in the simulations, that a higher value of controller gain (larger than 26 in Equation 4.6) will result in faster damping and higher damping ratio, but also requires stricter limit on allowable time delay. Reference [20] has investigated the delay-dependent stability of power system equipped with wide-area damping controller. Our findings are in agreement with [20] which have concluded that - a significant increment of the delay margin can be resulted from a small decrement of the gain with a cost of degrading the damping performance a little bit. Thus, there is a trade-off between damping ratio and time delay margin.

Also, an interesting question arises, namely, whether it is prudent to design the entire communication system around minimizing the delay between bus 10 (SS 9) and bus 89 (SS 80) and what this design impact the delays on the other communication flows.

The answer to this question is that the decentralized communication system design process proposed in this dissertation is in fact flexible and the communication network can easily be re-configured depending on the topology and any particular needs of the system. The changes in the topology and the operating point may result in different set of observable and controllable modes which means different source of remote signal and different location of WADC.

And then we need to analysis the delay on different flow. This suggests that an outer loop of control should be added which re-calculates the observable and controllable locations for different mode analysis results. This information from outer loop control can be dynamically passed on to the hubs, which can accordingly route the measurements from most observable node, to the most controllable node, as per the availability of the controller. And since the locations of hubs are chosen to bring minimum average delay to the system, our design has the ability to handle a re-configuration on the change of observable and controllable modes.

Based on discussion above, a detailed simulation scenario is set up in TSAT for IEEE 118 bus system using WADC to damp out inter-area oscillations. This simulation would provide a good example on how a real-time data received over communication delay with a realistic delay is used to excite close-loop control applications such as WADC.

Different stability regarding the constraints on latency of the remote signal is also discussed. The objective of this study of demonstrating the effect of communication time delay on the performance of closed- loop WADC is achieved. The collaboration between power and communication is presented. And wide-are controller or fast-action required control application using system-wide information is considered another major application of the PMU data apart from the monitoring application.

4.5.5. Simulation scenario 2

The non-linear time domain simulation of the power network of IEEE 118 bus system is carried out for both centralized topology and decentralized topology incorporating the time delays obtained respectively from communication case results simulated by NS-3.

For the simulation of centralized topology, a case with 30 Mbps bandwidth having 32.1 msec delay is chosen which is the case with minimum bandwidth to support WADC with delay less than 100 msec. And for decentralized topology, a case with 20 Mbps bandwidth having 17.6 msec delay is chosen. These values are chosen from the results shown in Tables VIII and IX from Chapter 3.

The design of the controller has been described earlier in Chapter 4.5.3 and the disturbance is described in Chapter 4.5.4. After a TSAT simulation of 20 second, the active power output of generators are plotted to indicate the stability of the system.

The first simulation is carried on with IEEE 118 bus system without the equipment of WADC, which means that all damping is provided by local controllers such as exciter and PSS used in excitation system.

All 19 generators' behavior is listed. The system starts from a steady state until t=1.5 second. Then the disturbance discussed before is introduced to generator on bus 10 (SS 9).

Observing the performance after this disturbance, it is clearly that the system is unstable. Oscillations in the system are not well damped and the magnitude of some oscillation is growing larger and larger.

Figure 22 also indicate that all generators are contributing to the oscillation more or less which confirm our previous results of mode type from SSSA done by SSAT software.

By comparing the phase angle and peak value of, the generators in Area 3 are oscillating against generators in Area 1 and 2. Oscillations in Area 3 and that in Area 1 and 3 has 180 degree phase shift. This means that when generators in Area 1 and 2 reach their peak value of output, the generators in Area 3 reaches their minimal output values.

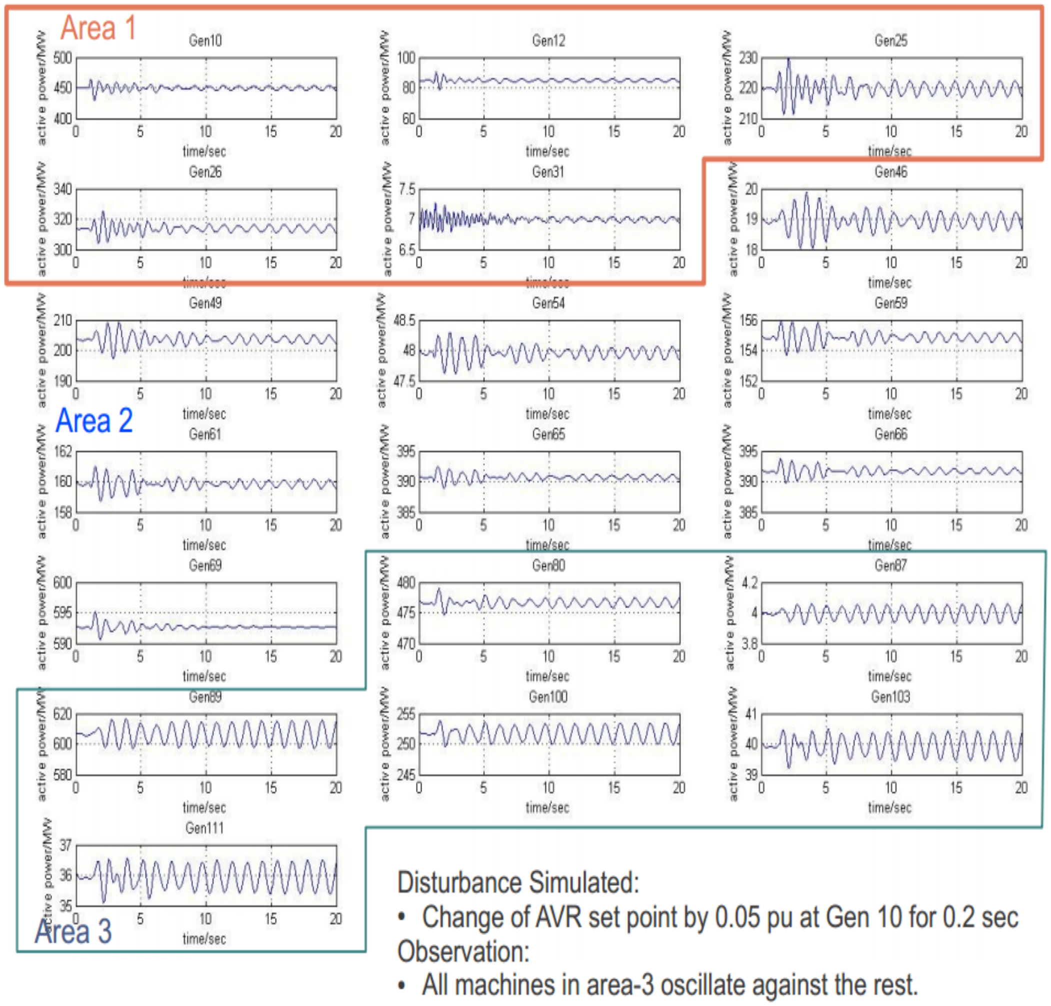

Figure 21. Active power output of all generators

The information shown in Figure 22 also validates our mode analysis in couple aspects. Firstly, the frequency of oscillation can be roughly calculated by using the cross point of the output value and the stating value. The results from time domain simulation and eigen value analysis agree with each other. Secondly, there are couple oscillations in the system dynamic performance. Some oscillations get damped out faster than others. The SSSA results also indicates there are two oscillation with damping ratio around 10% and other two with damping ratio of less 4%. We can tell that for the latter group oscillation, it is not damped out at the end of this 20 second simulation.

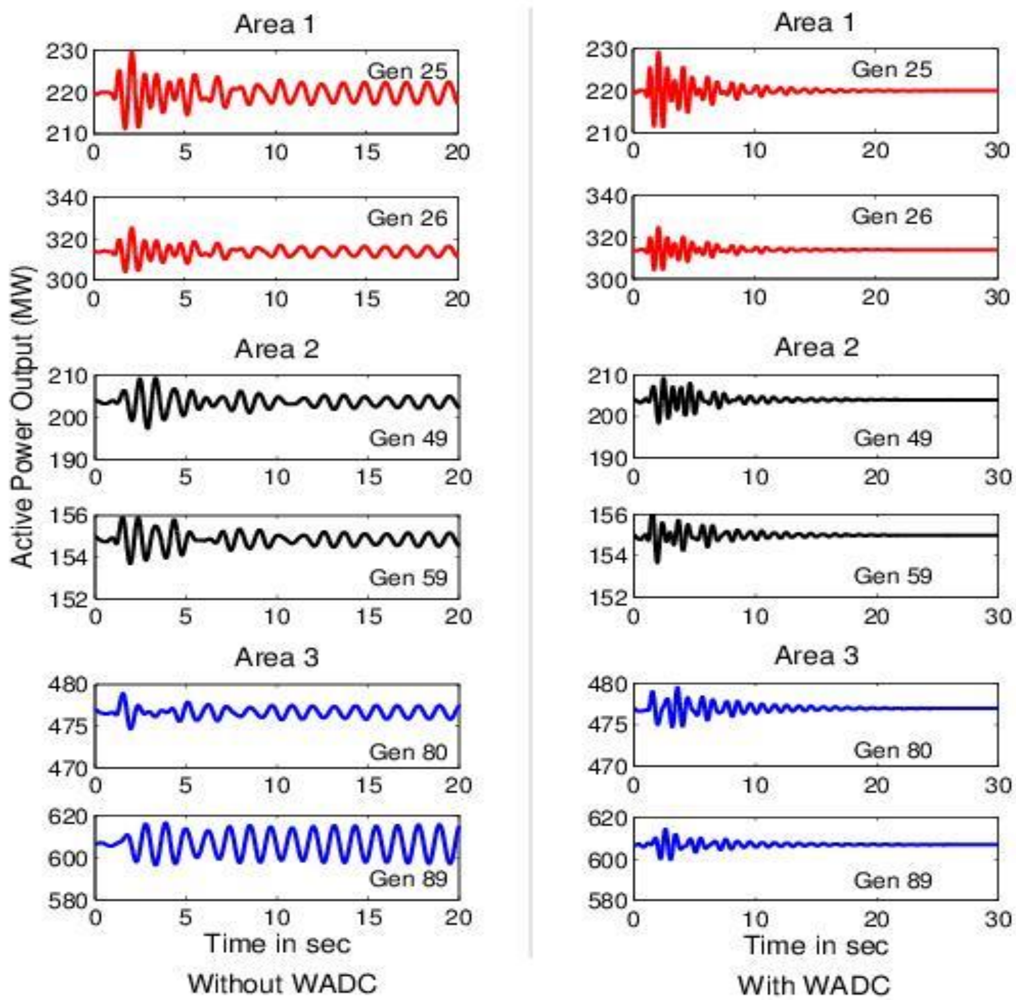

Figure 22. Dynamic response of generator for ideal WADC

The second simulation is carried out with IEEE 118 bus system equipped with a ideal WADC. An ideal WADC refers to a controller using a remote signal with no delay taking into consideration. The objective of this simulation is to test whether our design of WADC can properly improve the damping performance of the previously poorly damping oscillation.

To show the results of second simulation in a more clear way, 6 generators out of a total number 19 are selected to represent the system stability. 2 generators from each area with most obvious oscillation observed from Figure 22 are used. Generators at Bus 25 and 26 are taken from Area 1. Generator at Bus 59 and 59 are representing Area 2. And generators at Bus 80 and 89 are selected for Area 3. Results of both first simulation and second simulation are plotted in Figure 3 for these 6 generators.

Figure 23 shows how much difference WADC makes to system stability. The poorly damping oscillations shown in the left column of Figure 23 are now gone in the right column. And the system returns to a steady state at the end of simulation after disturbance. This proves that our design process of WADC is functional and our parameters are properly determined.

There is another observation needed to be mentioned. Since our WADC is design for the poorly damped mode, which damping ratio is 3.45%, it will not damp out every oscillation. Figure 23 indicated that the oscillations with better damping ratio (10% and 9.47%) still exit in the system. But due to the nature of these modes, the magnitudes of oscillations are negligible at t=20 second.

Second simulation provides a solid reference to compare the performance of WADC under different communication cases or idea case.

Fig. 10 presents the results of non-linear time domain simulation of power network. The plots in the first column show the dynamic response of two generators selected from each area for topology 1. Similarly, the plots in the second column represent the dynamic response for topology 2. To illustrate the effect of time delay on the controller performance the time delay has been successively increased and

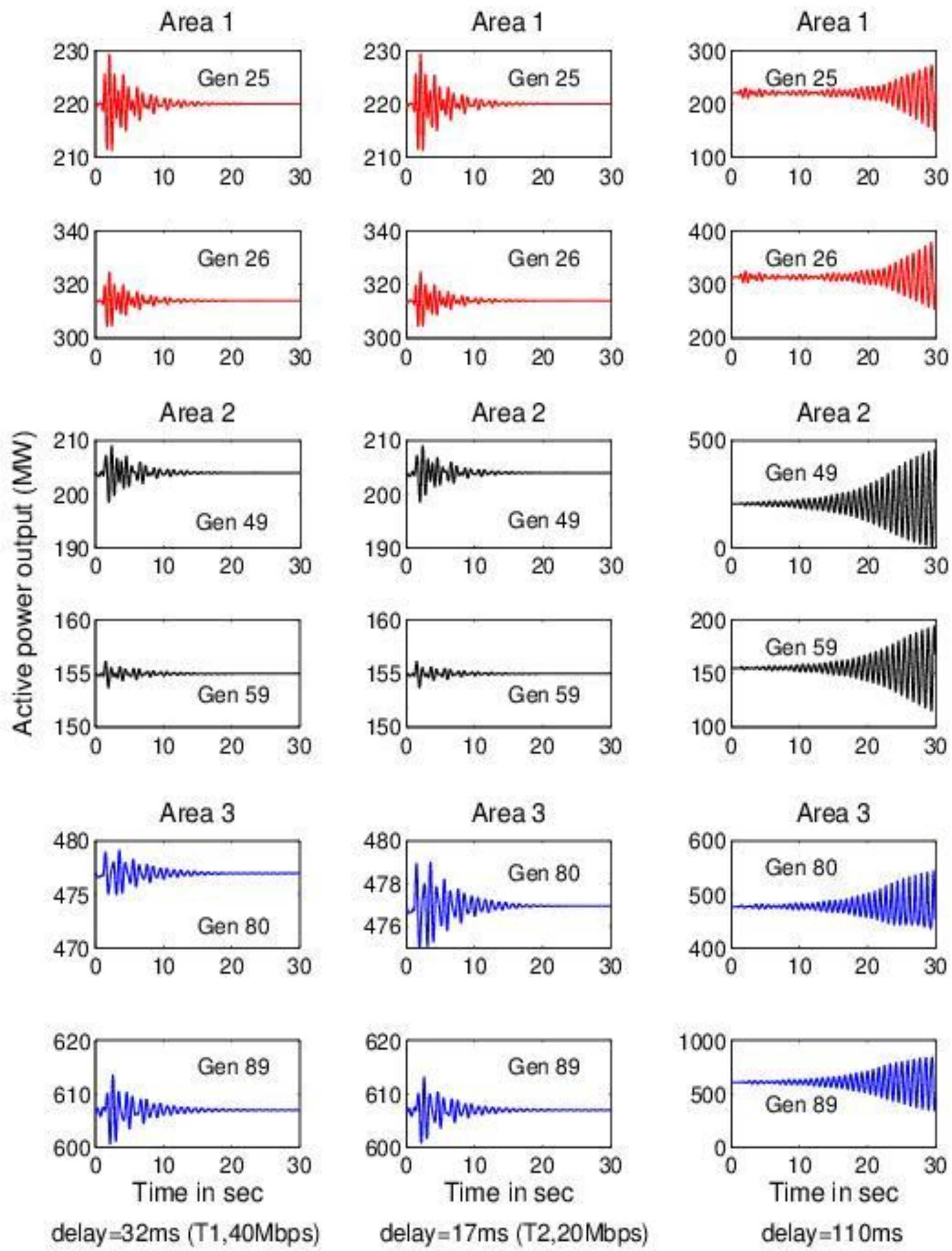

Figure 23. Dynamic response of generator for WADC with delays

it was observed that the WADC results in unstable system for a time delay more than 110 msec, as shown in the plots of the third column of the Fig. 10. Since for most cases the time delay of our communication network for both topologies is well less than the 110 msec latency requirement of the controller, it can be concluded that the WADC can successfully provide the required damping of the inter-area oscillations to stabilize the system.

4.6. Summary

This chapter gives a brand new voltage optimization method to save the operators lots of time so that they can make decision much faster after observing some bus operating at risk.

3 system dividing methods are presented in this chapter and their advantage and disadvantage are compared. It appears that Method 3 is the best option for the operators.

Several system dividing patterns are also compared in this chapter, and the conclusions is that in order to obtain an efficient system dividing method and take full advantage of the parallel optimization, care should be taken in deciding the number of zones. Based on that, 3 rules of system dividing are given as well.

Systems operating with some buses close to their phase angle instability point are also studied in this chapter. The simulation result shows that the methods are also suitable for the system angle stability problem.

Several different objective goals besides minimizing the system real power loss are discussed in this chapter as well. It is observed that the proposed optimization methods are suitable for various different objective functions and minimizing the system reactive power is the best objective goal for the operators.

The IEEE-118 bus system was first adopted as the test system to perform the efficiency and accuracy of the proposed voltage optimization methods and these studies were extended to a larger system, the IEEE-300 bus system. The successful approaches on those different test systems make us believe that this voltage optimization method can be widely used on real systems as well.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

In this dissertation, we first discuss the developing trend of wide-area power system controller towards decentralized energy applications and databases. With the trend that power grid are connected to each other more tightly and the increasing number of installed PMU devices and PMU measurements, phasor measurements becomes available with data rates as fast as 40-120 packets per second. Therefore the centralized operation and control system are no longer scalable. To provide better system performance and stability of power grids, a decentralized communication topology is presented.

This dissertation also addresses a process for design and simulation of both the communication network and power network to determine how communication infrastructure can serve power system in a most efficient way. This is a system specific study based on certain design assumptions. However the simulation methodology is general and useful for design of communication infrastructure for different power topologies. Propagation delay changes with network topology, whereas, queuing delay and transmission delays change with the communication bandwidth. Average link bandwidth needed for smart grid applications should be in range of 5-10 Mbps for communication within one control area and 25-75 Mbps for inter control center communications. Using meshed topology delays can be contained within the 100ms latency requirement satisfying all applications. Also with packets traversing just 8-10 hops processing delays at routers should not be a problem.

The effect of communication latency on the design of wide area damping controller is also demonstrated with an example. It is observed that if adequate bandwidth is not used for acquiring remote signals for closed loop control, the delays in getting the signals increase and the performance of the controller is deteriorated to an extent that the controller is no longer able to stabilize the system after a disturbance.

The architecture and the process described here are thus informative and may be used for design and estimating of parameters for a communication network for wide area control of a smart grid.

We have developed a method to determine the parameters and network topology to set up and simulate a communications system for a power grid starting from the power network configuration and the knowledge of the measurement data and the on-line applications. When designing the smart grid infrastructure for a particular power system, the assumptions should reflect the actual design parameters of the communication infrastructure. Such a simulation tool can be used to develop, design and test the performance of the communication system to determine the bandwidth and latency requirements. We believe that given the actual applications and their precise data requirements further improvements in the results can be obtained on a case to case basis. For example further reduction in bandwidth and latency is possible by using multicast routing and packet tagging. In another scenario we may not send all the traffic to the control center and SPSs can be used as the distributed data bases. Slower EMS applications running in control center can then source the required data from SPSs using middleware architecture like Gridstat. These improvements have to be made based on individual network needs.

For the case when the latencies are increasing beyond a feasible value, it is shown that a decentralized communication architecture with data routing hubs is a better choice.

The topology and the design process described in this dissertation aim towards development of a holistic approach for design of new decentralized and scalable architectures using distributed applications and distributed databases for wide area control of future smart grids.

We also provide a procedure to build a detailed dynamic model for large power system with limited information for research purpose. We present how to choose typical machine parameters based on their power flow data and how to add an excitation system that reflect the real controllers equipped on the power plants. It is also presented that how to determine the construction and parameters of wide area damping controller based small signal stability analysis and results of mode analysis. The design and chosen of parameters are validated in simulation to show that this damping controller can improve the system stability and enhance the damping performance of low-frequency inter-area oscillation.

This dissertation presented a process for combined design and simulation of communication and control systems for the IEEE 118 bus system with wide area damping controller (WADC) as a demonstration of power controller with high latency requirements. In the first step, WADC parameters have been determined which also models the time delay in communication. Then a procedure is proposed for optimal location of control center and data routing hubs to and bandwidths for centralized and decentralized topologies are determined through NS3 simulations.

These time delays are then incorporated into the WADC and a non-linear time domain simulation of the power network is carried out. We believe that other control signals or control algorithms can be tested similarly.

Based on simulation results of two communication topologies, it has been demonstrated that the distributed architecture has more advantages than the centralized one. Decentralized topology can achieve shorter time delays even with lower network bandwidth, there by reliable and suitable choice for wide-area damping controller spanning multiple control areas.

5.2. Future work

Further work to be done in this research project includes importing real PMU data into the control loop and introducing more realistic interaction between communication and power network. When simulating the power model with TSAT, all control signals are actually generated inside TSAT, and those signals and measurements are not transmitted through PMU data format. By using real PMU data, deeper understanding about the both network can be achieved. And communication flows with different data rates can also be carried out to include both application that requires high resolution data and applications that need slower information. To allocate different application with different subset of measurements will bring us a more detailed model on the communication network and we will have a network that can mimic what happens in real life in a better way.

We may also seek to add a more realistic interaction between communication and power network. Currently NS-3 simulation only calculates the system states based on a virtual power application and virtual data packets. And the packet delivery from communication network to actual power application is not available yet. With a more realistic interaction, we can loosen the assumption on the constant time delay value, which might not fit the real case. We can also simulation what will happen if a small amount of packet is lost and discuss its impact on controller performance and system stability. Such interaction will also enable us to insert more complex power control application and algorithm.

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