# Decentralized Communication and Control Systems for Power System Operation

Yannan Wang, Pradeep Yemula, and Anjan Bose

***Abstract*—Due to the rapid deployment of phasor measurement units (PMUs) on large power grids, the system operators now have access to high speed high resolution data. A new class of monitoring and control applications are made possible with the PMUs. Although PMU based monitoring systems have been well developed, implementations of PMU based fast acting closed loop wide area control systems are relatively rare. To meet the stringent latency requirements of a wide area controller the communication and power infrastructures have to collaborate strongly. In this paper, a combined process for design and simulation of both communication network and power network has been presented with the objective of damping interarea oscillations. A method to determine the optimal location of data routing hubs so as to minimize the volume of communications is also proposed. The 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. One of the conclusions of the paper is that the decentralized communication architectures involving data routing hubs are better suited for control applications requiring fast control actions.**

***Index Terms*—Communications, power system operation.**

## I. Introduction

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 close to its margins [1]. Phasor measurement units (PMUs) obtain synchronized measurement of voltage and current phasors at rates of about 30 to 120 samples per second. Smart grid of the future is expected to have PMU data available widely across the grid. To meet the latency requirements and to handle the huge amounts of data, the need for a real-time information infrastructure has been proposed [2]. Smart grid applications are designed to exploit these high throughput real-time measurements. Most of these applications have a strict latency requirement in the range of 100 ms to 5 s [3], [4]. Among the other delays [5], communication delay also adds to the latency and needs to be minimized. The communication delays on the network are comprised of transmission delays, propagation delays, processing delays, and queuing delays [1]. Each of these delays must be looked into to understand the complete behavior of the communication network. With the advances made in ubiquitous computing systems, the notion of distributed data and distributed analytics becomes amenable. The question then becomes—what should be the design of the new communications architecture? Given that the data and computations are going to be distributed, which data should reside where? How is data to be moved to the applications efficiently meeting the latency requirements? This paper attempts to answer these questions by presenting a possible design of communications architecture for wide area control and protection of the smart grid.

In [6], a detailed survey of smart grid applications based on latency and bandwidth requirements has been presented. Latency is a measure of time delay experienced in a communication system. Where as, bandwidth is the rate of data transfer in bits per second, that can be achieved by a communication resource. According to [6], applications pertaining to power system operation can be classified in the increasing order of their latency requirement as follows: 1) transient stability ($<$ 100 ms); 2) small signal stability ($<$ 1 s); 3) state estimation ($<$ 1 s); 4) voltage stability (1–5 s); and 5) post-postmortem analysis of grid disturbances ($>$ few minute). It is difficult for human operators to quickly respond to problems pertaining to transient and small signal stability in a large power grid. Typically, the stability is achieved by local controllers operating with local information. However, due to large interconnections of power grids, disturbances in one region can spread to other region. Hence, wide area controllers, which rely on remote signals become necessary.

The rest of this paper is organized as follows. Section II presents an overview of design process. Section III focuses on design and simulation of communication network. Section IV describes preprocessing steps needed. Then, Section V describes the simulation of dynamics of power network with controller and presents the results. This is followed by the conclusion in Section VI.

## II. Overview of the Design Process

### A. Architectural Considerations

The following are some of the factors considered in design of the communication architecture.

*1) Location of Data:* Each substation (SS) 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 [6]. The approach here is

Manuscript received October 25, 2013; revised April 16, 2014 and August 5, 2014; accepted October 9, 2014. Paper no. TSG-00811-2013.

The authors are with the School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA 99164 USA (e-mail: yannan.wang@email.wsu.edu; yemula.pradeep@gmail.com; bose@wsu.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2014.2363192

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.


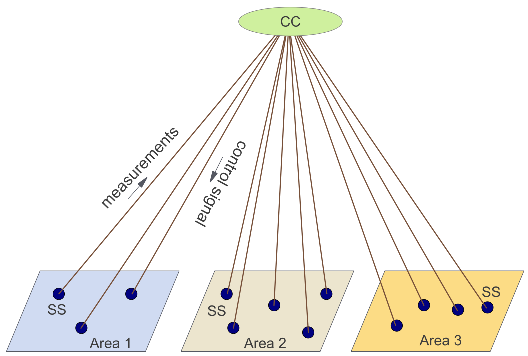


Fig. 1. Centralized communication architecture.

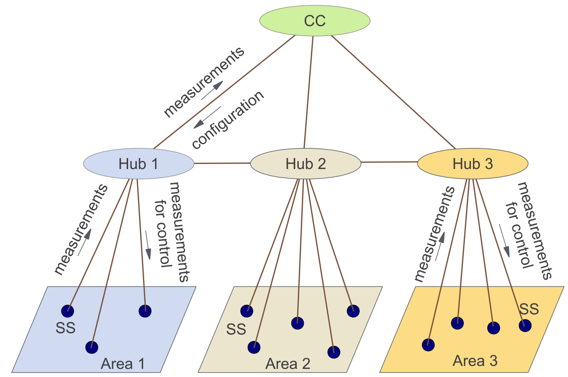


Fig. 2. Decentralized communication architecture.

to keep the data distributed and close to the power network components from which the data is measured.

*2) Location of Applications:* There is no need to centralize all the applications at one place. The fast control applications can be located closer to the controllable equipments.

*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 it to the required application. The characteristics of such an infrastructure are described in [2]. 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.

*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 [7] is used in practice for communication of PMU data. Among the four frames that are defined in C37.118, the data frame is one that is sent out from the SS 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.

### *B. Centralized Communication Architecture*

Fig. 1 illustrates the typical communication architecture with a centralized control center (CC) which receives all the measurements from each SS. The structure shown in Fig. 1 represents the logical connection, where as, the SSs are interconnected to the CC through a physical network which can have meshed structure similar to the power network. The logical connection refers to a connection defined by only its source and destination, independent of the path between them. This data 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 been implemented typically in the time scale of a 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 control action within a few cycles. For example, wide area special protection schemes (SPS) require fast breaker actions after a fault. For such cases, it is faster to deliver the input data directly to the controller instead of a central database.

### *C. Decentralized Communication Architecture*

As shown in Fig. 2 a new layer of communication nodes which act as data routing hubs, is added between the SS and central CC. The main function of data routing hubs (or simply referred as hubs) is to receive the measurements from all the SSs in the area and route them to main CC and/or to SSs with controllable devices. The control algorithms themselves run in parallel at respective SSs, where as, the hubs only route the measurements as per their predefined configuration. The configuration itself is flexible and can be remotely changed time to time by the main CC as per the changing state of power system. Hubs are also interconnected in a peer-to-peer fashion to exchange information across areas. In Section III, we will show that in the distributed architecture the total time between the SS 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 supported. Development of similar middle-ware systems to provide the latency and other QoS requirements is one of the objectives of the North American synchrophasor initiative [8], [9] and some research initiatives like GridStat [10], [11].

Based on the above considerations 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

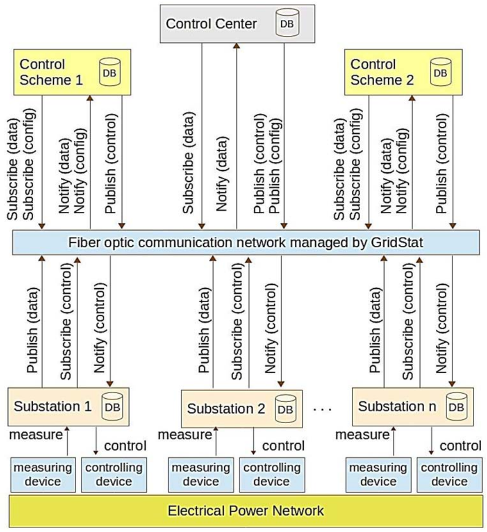


Fig. 3. Distributed communications architecture for power system control.

a publish/subscribe communication scheme and distributed databases is described in Fig. 3.

The key feature of the proposed architecture is that the databases are distributed at each level. Each SS stores the measured data locally. Applications that need real-time data for transient stability monitoring and control are not located in the CC but can be located on a computing node near the SSs, identified as "control schemes" in Fig. 3. The SPS being used in power systems are one example for such control schemes. 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 CC 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 nontime 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.

## D. Choice of Protocol Stack

Time-sensitive applications often use user datagram protocol (UDP) because it is preferred to drop the packets instead of waiting for delayed packets, which may not be an option in a real-time system [12]. UDP is also faster, as there is no error checking, no ordering of messages, has light weight header (8 bytes), and no need to setup prior transmission connection and handshake. We assume that the chance of losing packets is so small in a dedicated network that the fact that UDP cannot guarantee the delivery of data is not a serious concern. Using point-to-point protocol like UDP also means that for confidentiality we can use encryption technology such as, SHA-256 [13] which takes negligible time to encrypt the data. As the PMUs are sending out a stream of data frames on the network, at the application layer, the constant bit rate (CBR) is a good choice to carry the continuously generated data frames. The maximum transmission unit size of the link layer can help in the design of application level software to receive a complete C37.118 packet and not a broken one. Optical fibers and broadband over power line are the suitable choices at the link layer. Hence, the protocol stack can be summarized as follows: 1) link layer—optical fiber; 2) data layer—Ethernet; 3) network layer—internet protocol (IP); 4) transportation layer—UDP; and 5) application layer—CBR. Adoption of this protocol stack will make the implementation, platform independent and, hence, achieve interoperability among different hardware and software operating systems.

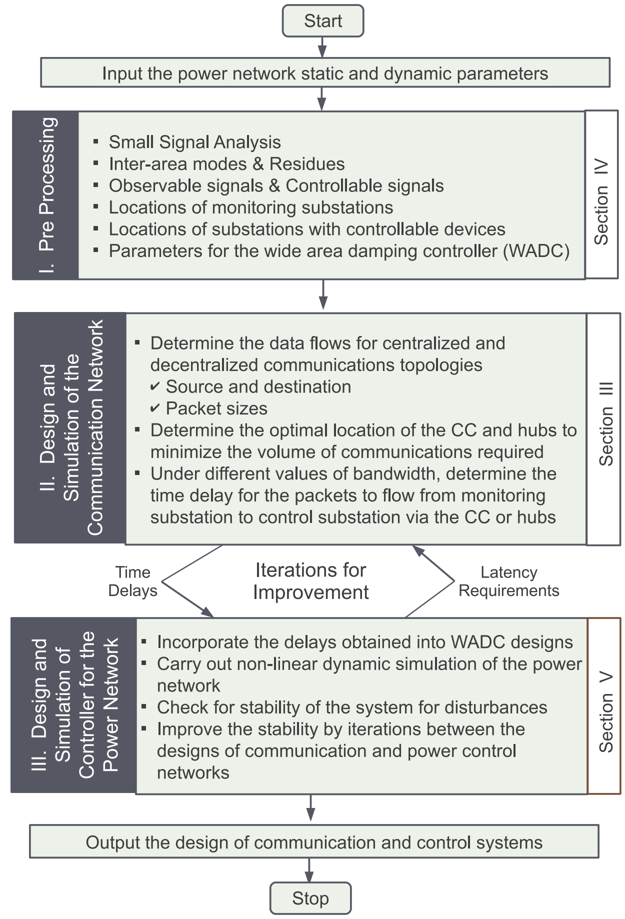


Fig. 4. Process for design of communication architecture.

## E. Process for Design of Communication Architecture

The flow chart of Fig. 4 describes the proposed process for the design of communication architecture for a large power system. In the preprocessing block, small signal analysis is carried out to determine the parameters of the damping controller. The second block, focuses on the design and simulation of the communication network for both centralized and decentralized topologies. The optimal location for the hubs is also determined based on minimization of volume of communication. The simulation also determines the time delay for communication network for various values of bandwidth. The third block, focuses on the nonlinear time domain simulation of the power network incorporating the time delay in the wide area damping controller (WADC). This process of blocks II and III can be iterated until a suitable overall solution for stability is achieved. The criteria 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 and/or to install larger bandwidth fiber optic cables. In this paper, since the criterion is already met by the network we present, iterative process is not considered. The subsequent three sections elaborate the process and explain the various steps and results obtained for the design and WADC for IEEE 118 bus system.

## III. Design and Simulation of Communication Network

Since, it is assumed that the communication network will be overlaid over the power network both will have a similar topology. However, the data routing hubs can be connected to any SS in the area. Different locations of hubs will result in different amount of traffic volume. Thus, the notion of optimal hub location arises which would result in minimum amount of communications.

### A. Choice of Metric: Mega-Bit-Hops

In order to define a criteria to evaluate optimal location of hubs, we introduce a metric, namely mega-bit-hop

$$\mathrm{Mbh}_c = \sum_{i=1}^{N} (h_i \times p_i) \tag{1}$$

where $c$ is the location of hub, $i$ represents the flow ID, $N$ is the total number of flows, $h_i$ is the number of hops taken by the packets on $i$th flow, and $p_i$ is the packet size of $i$th flow. The propagation delay is assumed to be negligible as the information flows at speed of light, where as, major part of time delay occurs when the packets are enqued and dequed at the intermediate nodes.

Each SS sends all its measured data to the CC, hence the packet size depends on the number of feeders connecting to the SS. Each of such flow from SS to CC can be assigned a flow ID. Thus the packet size $p_i$ for each flow, is calculated based on the number of feeders and the data frame format defined by IEEE C37.118 standard for each SS. We assume that each feeder has one PMU that measures six phasors, namely three-phase voltages and three-phase currents. Each PMU has nine digital channels and analog channels [6]. For the IEEE 118 bus system it has been calculated that the packet sizes for flows from various SSs, vary from a minimum of 234 bytes to a maximum of 1440 bytes, with an average packet size of 409 bytes. Using the same communication network the CC also sends data to the local controllers which may be located at all generation SSs. These flows are also assigned flow IDs and the packets only contain the predefined remote measurements useful for wide area control. Hence, the packet size for these controller inputs is assumed to be 200 bytes.

### B. Communication Delay and the Number of Hops

To further establish the relationship between communication delay and the number of hops a simulation was carried out

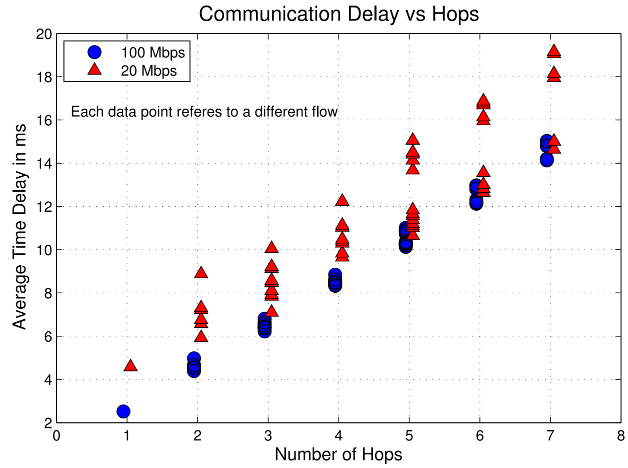


Fig. 5. Relationship between communication delay and number of hops for various flows with different link capacities.

using the NS3 network simulator for a communication network topology based on the IEEE 118 bus system. Each SS is modeled to send its data to the central CC which is connected to one of the SSs. The communication links are modeled as two cases, assuming high and low capacities of 100 and 20 Mb/s, respectively. The results are shown in Fig. 5. From this paper, 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 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 in the Mbh metric, hence, it should be ensured that the link bandwidths are sufficiently high.

The communication network can be considered as a connected graph where the nodes represent SSs and links represent the communication lines. Each flow is between SS node and the chosen CC 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. The shortest path between two nodes for a given graph can be determined by Floyd–Warshall algorithm [14]. 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. In this paper, the Floyd's algorithm has been implemented using MATLAB code and the $\mathrm{Mbh}_c$ is calculated by connecting a CC node to each SS node one at a time. Then, we identify the optimal location of CC or the hubs based on the lowest value of the $\mathrm{Mbh}_c$ and shortest average delay in the system. However, the optimal location does not necessarily lead to shortest delay on each link individually. Since the Floyd's algorithm only calculates the shortest path, the communication network is simulated in NS3 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 NS3 for all flows, as long as the communication network is not overloaded. Floyd's algorithm

TABLE I
REDUCTION IN NUMBER OF HOPS

| Flow | Topology 1 with 100 Mbps links (Centralized) | | | | Topology 2 with 100 Mbps links (Distributed) | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Path (Bus numbers) | Hops | Pkt' size | bit-hops | Path (Bus nos.) | 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** |

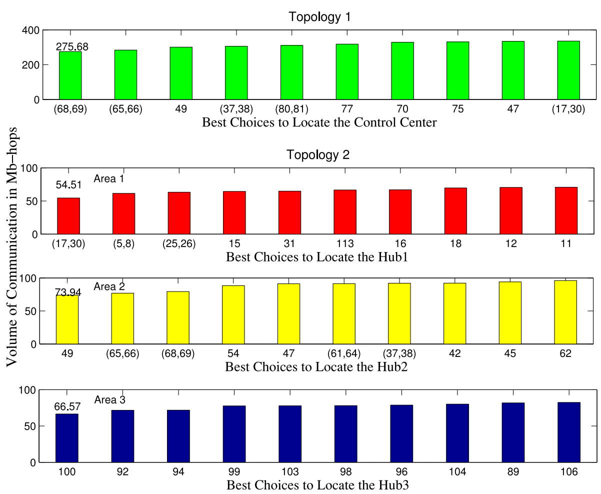


Fig. 6. Optimal location of CC for topology 1 and data routing hubs for topology 2.

is convenient for solving multiple scenarios in a single program loop, where as, NS3 simulation also calculates the delays in communication.

### C. Design and Simulation of the Communication Network

Having defined a metric for volume of communications, we proceed to determine the optimal location for CC. For this, the communication network topology is derived from the power network of IEEE 118 bus system. Two topologies are considered, namely: 1) topology 1 (centralized), where there is a single central CC co-located at one of the SSs; and 2) topology 2 (decentralized), where there are three hubs which communicate among themselves and an overall high level CC. Each of the three hubs is located respectively in each control area of the IEEE 118 bus system, as shown in Fig. 7. In the process of deriving communication network from power network, the buses connected by transformers are merged into a single communication node at the SS. As a result, the SS numbers are different than the bus numbers of the IEEE 118 system. Assuming the location of CC at each of the SS, the Mbh is calculated using Floyd's algorithm. A sample of results showing the hops taken by the information for individual data flows is shown in Table I, in which the path column shows the route taken by the packets. In this sample, we assume the location for CC of topology 1 is bus 69, and the locations for the hubs of topology 2 are buses 31, 49, and 100. Those bus numbers connected by a dash mean that they are located in the same SS. Therefore, they are counted only as one hop. The results are sorted in the increasing value of Mbh to determine the optimal location of CC. The best ten locations along with the volume of communication, are plotted in Fig. 6. It can be observed, that for the case of topology 1, the best location for CC is at bus 69 resulting in total Mbh $= 275.68$. Where as for the topology 2 the best location for three hubs are bus numbers 17, 49, and 100 (which translates to SSs 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. It should also be noted that, by moving from centralized topology to decentralized topology the volume of communication reduced significantly from 275.68 to 195 Mbh. With these location settings, we now have a design that brings the shortest average delay over the whole communication network under normal 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.

### D. Calculation of Delay in Communication

Having determined the volume of communication with optimal locations for CCs and hubs, the next step is to determine the communication delay. For determining the delay, a simulation on NS3 has been carried out for both topologies 1 and 2. The results are shown in Tables II and III. Transmission delay and queuing delay are simulated by the build-in model provided by NS3 and processing delay and propagation delay are negligible. For the topology 1, two kinds of flows are involved, namely flow of measurement from bus 10 to CC, and then from CC to bus 89. It is configured in this way, because the small signal analysis (discussed later) of the system identified that the observable state is in bus 10 (SS 9) and controllable state is in bus 89 (SS 80) for damping a particular interarea oscillatory mode. Judged by number of hops on these links, such configuration will generate one of largest delays in the system. The obtained values of communication delay will be later used in the simulation of WADC in Section IV.

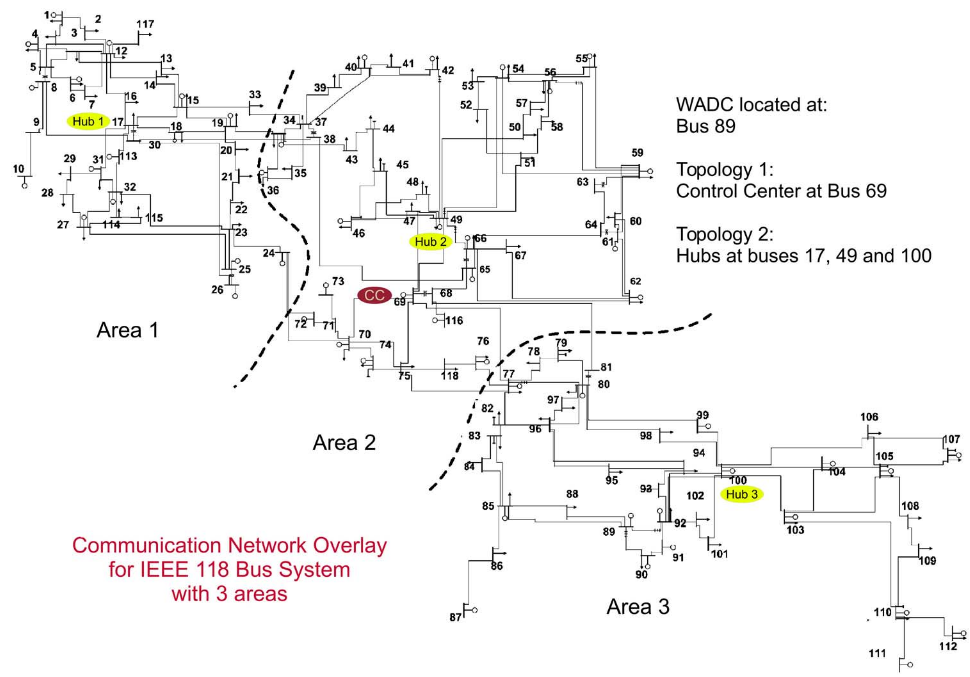


Fig. 7. Communication network overlay for IEEE 118 bus system with three areas. The single line diagram is from [15].

TABLE II
CALCULATION OF DELAY IN COMMUNICATION FOR TOPOLOGY 1

| 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 |

TABLE III
CALCULATION OF DELAY IN COMMUNICATION FOR TOPOLOGY 2

| 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 |

### *E. Conclusion on Centralized and Distributed Topologies*

Based on the simulation results, it can be concluded that the decentralized topology results in lesser volume of communication (occurring in real-time) and also lesser amount of time delay. The reduction in volume of communication can be attributed to the decentralized localization of data in real-time. The reduction in delay can be attributed to the reduction in length of communication path, due to 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 SS. Based on the off-line linearized analysis of the power system dynamic model, the interarea oscillatory modes of the system can be determined. With further study on observability and controllability analysis, the remote monitoring signal and location of wide area controller can be determined. These results can be used to configure the communication flows when simulating the communication network for determining the delays in the signal.

## IV. PREPROCESSING: DESIGN OF WADC

In this section, the design and implementation of a WADC incorporating a delay in the remote signal is presented using the IEEE 118 bus system. Apart from the monitoring applications, the real-time data received over the communication links can also be used to excite close-loop control applications such as WADC. The controllers using remote signals have certain constraints on latency. The objective of this paper is to demonstrate the effect of communication time delay on the performance of closed-loop WADC.

### *A. System Description*

In the IEEE 118 bus system considered, there are 118 buses, 186 branches, three control areas, and 19 generators with nonzero active power output. The generators belonging to area 1 are at bus numbers 10, 12, 25, 26, and 31, where as for area 2 are at 46, 49, 54, 59, 61, 65, 66, and 69, and for

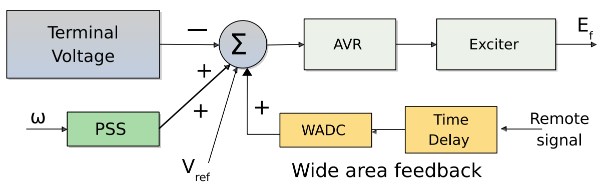


Fig. 8. Excitation system with WADC with remote signal.

area 3 are at 80, 87, 89, 100, 103, and 111. This allocation of generators into three control areas is taken from [15]. The system dynamics consist of generator machine parameters, excitation systems, and power system stabilizers (PSS) for each of the 19 generators. The dynamic parameters as well as the parameters for local controllers (PSS) and the excitation systems are taken from [16] and [17]. As described in the previous section, the WADC uses the measurement from bus 10 and the controller is installed at bus 89. In order to test the performance of PSS and WADC, the damping coefficients of all the machines are set to zero [18]. Thus, all the damping has to be provided by the controllers. Conventional PSS using $\Delta\omega$ as an input ($\omega$ 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 bus 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 $\Delta(\omega_{89} - \omega_{10})$. The transfer function of the controller is calculated based on residues compensation [19]. The parameters are as follows:

$$H(s) = 26\left(\frac{10s}{1+10s}\right)\left(\frac{1+0.503s}{1+0.0288s}\right). \tag{2}$$

For simulation of dynamic behavior, the disturbance scenario considered is a step change of automatic voltage regulator set point by 0.05 p.u. at generator at bus 10 for duration of 0.2 s. It was observed in the simulations, that a higher value of controller gain would result in faster damping, but also requires stricter limit on allowable time delay. Reference [20] has investigated the delay-dependent stability of power system equipped with WADC. 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.

Here, an interesting question arises, namely, whether it is prudent to design the entire communication system around minimizing the delay between buses 10 and 89. The answer to this is that the proposed decentralized communication system is in fact flexible and it can be reconfigured depending on the topology of the system. The changes in the topology and the operating point may result in different set of observable and controllable modes. This suggests that an outer loop of control should be added which recalculates the observable and controllable locations. This information can be dynamically passed onto the hubs, which can accordingly route the measurements from most observable node to the most controllable node as per the availability of the controller.

TABLE IV
CENTRALIZED AND DECENTRALIZED TOPOLOGIES FOR COMMUNICATION

| 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 V
SMALL SIGNAL ANALYSIS RESULTS FOR IEEE 118 BUS SYSTEM

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

While the power network and controller parameters are discussed above, for the communication network parameters, two topologies are considered. For the topology 1 all the SSs send their data to CC, and from there the specific predefined measurements needed by the controllers are forwarded from CC to the controller located at SS. In the case of topology 2, each area has a hub which can be configured remotely with the measurement routing specifications. The parameters of communication topologies are summarized in Table IV.

## B. Small Signal Analysis

In order to determine the interarea modes existing in the base case of the system, a linearized small signal analysis was carried out including the excitation systems, PSS but not including the WADC. Out of the many eigen values of the system, a few have been identified as interarea modes, which are summarized in Table V. The last column of Table V shows the mode type which indicate the number of generators exhibiting the presence of the mode out of the total number of generators.

The system is then simulated without the WADC. Following the disturbance, it was observed that, while the local modes are damped by around 5 s, the interarea modes persist beyond 20 s. The first column of plots in Fig. 9 shows the active power generation of two generators from each area. It can be observed that the generators in area 3 are oscillating against the generators in areas 1 and 2. Now, the WADC is introduced with time delay of the remote signal set to zero. The response of generators with the WADC is shown in the second column of Fig. 9.

# V. SIMULATION OF CONTROLLER FOR THE POWER NETWORK

The nonlinear time domain simulation of the power network is carried out for both topologies 1 and 2 incorporating the

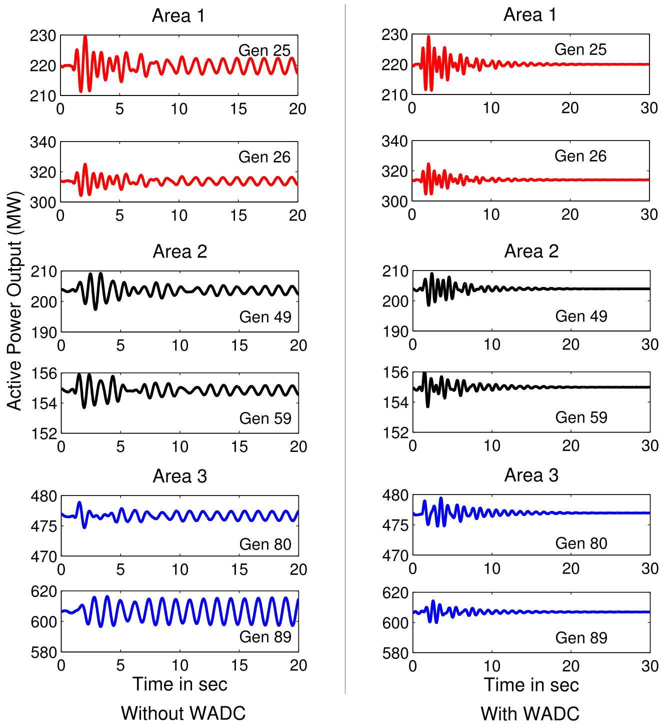


Fig. 9. Dynamic response of generators.

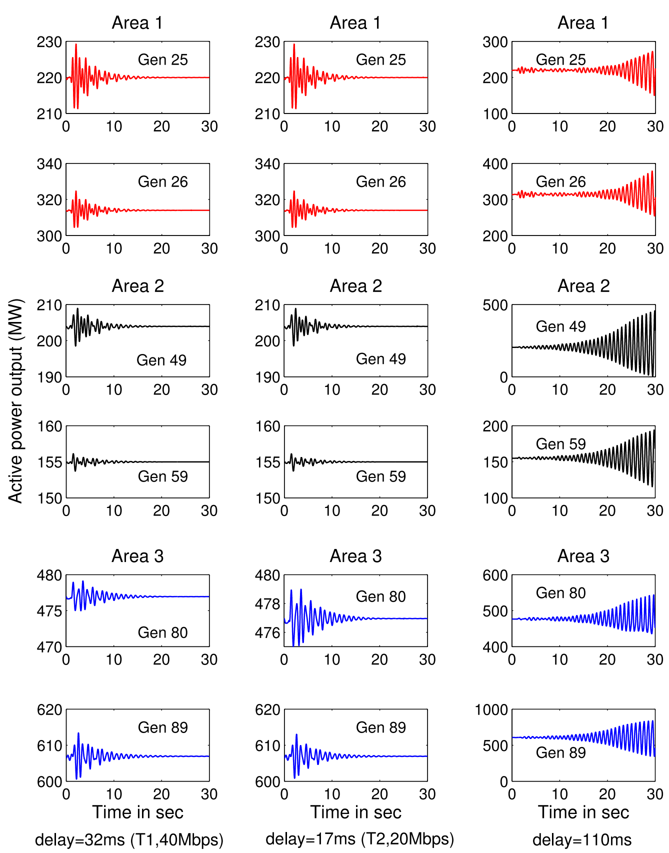


Fig. 10. Dynamic response of generators.

time delays obtained respectively. For the simulation of topology 1, a case with 30 Mb/s bandwidth having 32.1 ms delay is chosen. And for topology 2, a case with 20 Mb/s bandwidth having 17.6 ms delay is chosen. These values are chosen from the results shown in Tables II and III of Section III-D. The design of the controller has been described earlier in Section IV.

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

## VI. Conclusion

This paper presented a process for combined design and simulation of communication and control systems for the IEEE 118 bus system with WADC as a demonstration of power controller with high latency requirements. In the preprocessing step, WADC parameters have been determined which also models the time delay in communication. Then, a procedure is proposed for optimal location of CC and data routing hubs to minimize the volume of communication. The time delays and bandwidths for centralized and decentralized topologies are determined through NS3 simulations. These time delays are then incorporated into the WADC and a nonlinear 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, thereby a reliable and suitable choice for WADC spanning multiple control areas.

## References

[1] P. Kansal and A. Bose, "Smart grid communication requirements for the high voltage power system," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PES)*, San Diego, CA, USA, Jul. 2011, pp. 1–6.

[2] A. Bose, "Smart transmission grid applications and their supporting infrastructure," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 11–19, Jun. 2010.

[3] D. Tholomier, H. Kang, and B. Cvorovic, "Phasor measurement units: Functionality and applications," in *Proc. IEEE Power Syst. Conf. (PSC)*, Clemson, SC, USA, Mar. 2009, pp. 1–12.

[4] F. F. Wu, K. Moslehi, and A. Bose, "Power system control centers: Past, present, and future," *Proc. IEEE*, vol. 93, no. 11, pp. 1890–1908, Nov. 2005.

[5] M. Chenine, K. Zun, and L. Nordstrom, "Survey on priorities and communication requirements for PMU-based applications in the Nordic region," in *Proc. IEEE PowerTech.*, Bucharest, Romania, Jul. 2009, pp. 1–8.

[6] P. Kansal and A. Bose, "Bandwidth and latency requirements for smart transmission grid applications," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1344–1352, Sep. 2012.

[7] *IEEE Standard for Synchrophasors for Power Systems*, IEEE Standard C37.118-2005 (Revision of IEEE Std 1344-1995), Apr. 2006, pp. 1–57.

[8] NASPI. (2009). *Actual and Potential Phasor Data Applications* [Online]. Available: http://www.naspi.org/phasorappstable.pdf

[9] N. Data and N. M. T. Team. (2007). *Phasor Application Classification* [Online]. Available: http://www.naspi.org/resources/dnmtt/phasorapplicationclassification_20080807.xls

[10] H. Gjermundrod, D. Bakken, C. Hauser, and A. Bose, "GridStat: A flexible QoS-managed data dissemination framework for the power grid," *IEEE Trans. Power Del.*, vol. 24, no. 1, pp. 136–143, Jan. 2009.

[11] C. Hauser, D. Bakken, and A. Bose, "A failure to communicate: Next generation communication requirements, technologies, and architecture for the electric power grid," *IEEE Power Energy Mag.*, vol. 3, no. 2, pp. 47–55, Mar./Apr. 2005.

[12] J. F. Kurose and K. W. Ross, *Computer Networking: A Top-Down Approach*, 5th ed. Upper Saddle River, NJ, USA: Pearson, 2009.

[13] C. Hauser, T. Manivannan, and D. Bakken, "Evaluating multicast message authentication protocols for use in wide area power grid data delivery services," in *Proc. 2012 45th Hawaii Int. Conf. Syst. Sci. (HICSS)*, Maui, HI, USA, pp. 2151–2158.

[14] R. W. Floyd, "Algorithm 97: Shortest path," *Commun. ACM*, vol. 5, no. 6, p. 345, Jun. 1962.

[15] W. Jiang, V. Vittal, and G. Heydt, "A distributed state estimator utilizing synchronized phasor measurements," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 563–571, May 2007.

[16] S. Koch, S. Chatzivasileiadis, M. Vrakopoulou, and G. Andersson, "Mitigation of cascading failures by real-time controlled islanding and graceful load shedding," in *Proc. iREP Symp. Bulk Power Syst. Dyn. Control (iREP)—VIII (iREP)*, Rio de Janeiro, Brazil, 2010, pp. 1–19.

[17] P. Anderson and A. Fouad, *Power System Control and Stability* (Institute of Electrical and Electronics Engineers). Piscataway, NJ, USA: IEEE Press, 2003.

[18] Y. Zhang and A. Bose, "Design of wide-area damping controllers for interarea oscillations," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1136–1143, Aug. 2008.

[19] Y. Zhang, "Design of wide-area damping control systems for power system low-frequency inter-area oscillations," Ph.D. dissertation, Dept. Elect. Eng., Washington State Univ., Pullman, WA, USA, Dec. 2007.

[20] W. Yao, L. Jiang, Q. Wu, J. Wen, and S. Cheng, "Delay-dependent stability analysis of the power system with a wide-area damping controller embedded," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 233–240, Feb. 2011.

Authors' photographs and biographies not available at the time of publication.