Telecommunication of Stabilizing Signals in Power Systems

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***Abstract*— The dampening of low-frequency inter-area oscillations using Power System Stabilizers (PSS) may require remote stabilizing signals. In this case, delays are associated with the signal transmission. In this paper, several telecommunication schemes are investigated and critical communication delays are determined for a two-area four-generator (2A4G) power system, widely used in the literature. OPNET Modeler, a discrete event simulator, is used to characterize those delays and also the number of packets dropped between each node. This information about the network delays is then used to study the performance of the 2A4G system in the presence of non-ideal communications.**

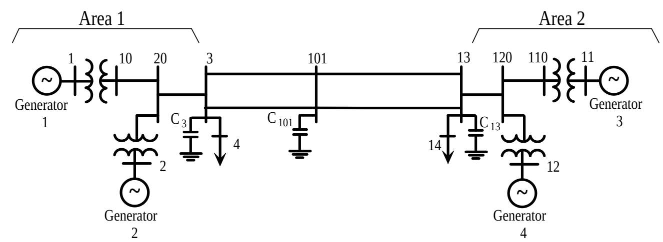

Fig. 1. The Two Area System.

I. Introduction

Electro-mechanical oscillations between interconnected synchronous generators are problems inherent to power systems. The oscillations associated with group of generators at different locations are called “inter-area modes” [1]. The inter-area modes of oscillation are affected by many factors, such as the types of controllers and the loading conditions, making them hard to analyze and control. Moreover, a realistic system will have a large size model. Hence, a benchmark system of small size has been suggested in the literature to study inter-area oscillation. This system is a two-area four-generator system, which will be called here “2A4G”. This system has been investigated by numerous researchers. Specifically, Power System Stabilizers (PSSs) have been considered to dampen inter-area oscillations. For example, a control strategy has been implemented in [2], where it is shown that one Power System Stabilizer (PSS) by itself, or the combination of one PSS controller and *local* measurement are not enough to stabilize the system. These results imply that the PSS controller needs *remote* measurements.

The objective of this paper is to study the communication aspects associated with dampening inter-area oscillations using PSSs with remote signals. The impact of actual telecommunication technologies on the performance of power systems are investigated. In particular, OPNET Modeler is used to characterize the nature of delayed and dropped packets within a typical network. These delays are then used to study the performance of the 2A4G system in the presence of non-ideal communications. In section II, the model of the test system is given. Section III is devoted to the OPNET case study. Section IV deals with the analysis of the problem, section V presents the results, and section VI is the conclusion of this paper.

II. System Model

A. The 2A4G System

The system configuration can be described as follows [2] [3]:

- Two sets of two generators on each side of the grid are separated by a total distance of 220 km. On each side, the generators are 20 km apart from each other. Each generator is connected to the grid via a tie line. Each generator is equipped with the same simple exciter and all the generators have the same configuration.

- Two loads are attached, one on each side, to the system. The power can be flowing across the system in either direction. A total of 12 buses are used between the controller, the four generators, and the loads.

- Several control strategies have been proposed, including the use of a *Static Var Compensator* (SVC) controller, a *Power System Stabilizer* (PSS) controller, a *Unified Power Flow Controller* (UPFC), and *Thyristor Controlled Series Capacitor* (TCSC) controller. Placement of these controllers depends on different factors such as transmission capacity, control and stability objectives.

B. Strategy

The strategy implemented is to place a PSS controller at one generator and feed it with remote measurements. This strategy was implemented because it generates the longest delays. The main advantage of this scenario is that the controller is implemented based on the worst case scenario making it more likely to work in a better case scenario.

C. Terminology

Each area is composed of different *elements* that play a particular role in the transfer of data within the network [4]. The network is also capable of supporting various types of *applications* that generate traffic. Several important terms are defined below:

- **Router:** A router is an intermediate device that connects communication links. A router takes information arriving on one of its incoming communication links and then forwards it on one of its outgoing communication link.
- **Switch:** A switch is a high performance multi-interface bridge. Like a bridge, a switch forwards and filters frames using LAN destination addresses. In OPNET, a switch can have a dozen interfaces that it can interact with.
- **FTP:** FTP (File Transfer Protocol) is a protocol used to transfer files between a client and a server. FTP permits the user to issue two basic commands for transferring a file: “get” and “put”. The “get” command triggers the transfer of a file from a remote server. The “put” command sends a file to a remote server. For connection-oriented transport protocols, (e.g. TCP), a new transport connection is opened for each file transfer. TCP is the default transport protocol for this application.
- **Connection:** A connection is an interconnecting circuit between two or more locations for the purpose of transmitting and receiving data. The link used by the connection can be either electrical or fiber optical cable (multiple different connection types and connection speed are available). For example, the *PPP base* is a point-to-point link that connects two nodes running IP (e.g., gateways) at a selectable data rate.

III. OPNET Case Study

In the case study, the PSS controller is placed at the first generator within the grid and receives remote measurements from all the other generators generating the longest delays. OPNET Modeler is used to characterize the *delays* and *number of packets dropped* between each node [5]. The results obtained using OPNET Modeler will later be used to characterize the effects of those delays on a real-time closed loop system. When modelling the network, one needs to make sure that the distances between the areas are respected. Then, one needs to define what type of connections are going to be compared in the different scenarios.

The different data rates that are used to model the system are 56 kbps (56K link), 1.544 Mbps (DS1), 44.736 Mbps (DS3), 100 Mbps (100BaseX), and 594.43 Mbps (OC-12)

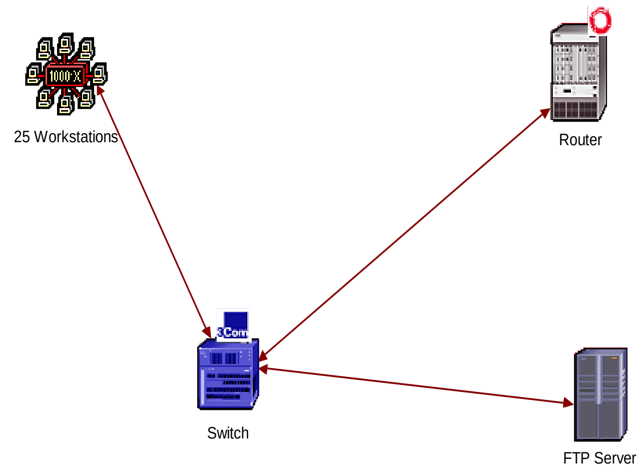

Fig. 2. Detail of an area.

[6] [7]. Each scenario serves as a benchmark for the next one. Comparing the results obtained will help one decide upon the acceptable solution for the 2A4G system. The only two assumptions made in the case study are that the power used to transmit the signal is large enough to avoid the use of repeaters within the network and the losses over the transmission medium are negligible. Each area contains a switch, an FTP server, 25 workstations, connected to each other in a star configuration, connected with a 1000BaseX (1000 Mbps) connection, and a router (see Fig. 2).

The PSS controller is characterized as a combination of a switch connected to a router and six servers (see Fig. 3). The servers are divided into two different sets that can perform the same tasks. The first set is used as the main servers allowing data to be transferred from a remote area back to the controller. The second set of servers is used as a backup set.

All the routers are connected together and traffic is added to the network. The transmitted packets have the same format and use the same protocol but have two different lengths (4500 bits and 400 bits). Having two different length allows one to characterize the effect of the size of the packets on the transmission delays. The next step is to setup the background utilization. The background utilization is a measure of the *strain* of the communications within the network, and has a direct effect on the delays measured. By including background utilization, the case study becomes very close to a real system. The three different background utilizations compared are as follows: 10%, 50%, and 90%. The applications available to the engineers are the following ones: email, file transfer, database, Telnet session, video conferencing, voice over IP, and web browsing.

Each application is supported by the network, and is available to every engineer working in the office. All applications are executed simultaneously, creating more stress on the network. The network is illustrated in Fig. 4. Subnets (the octagonal shapes shown in Fig. 4) are used to add clarity to

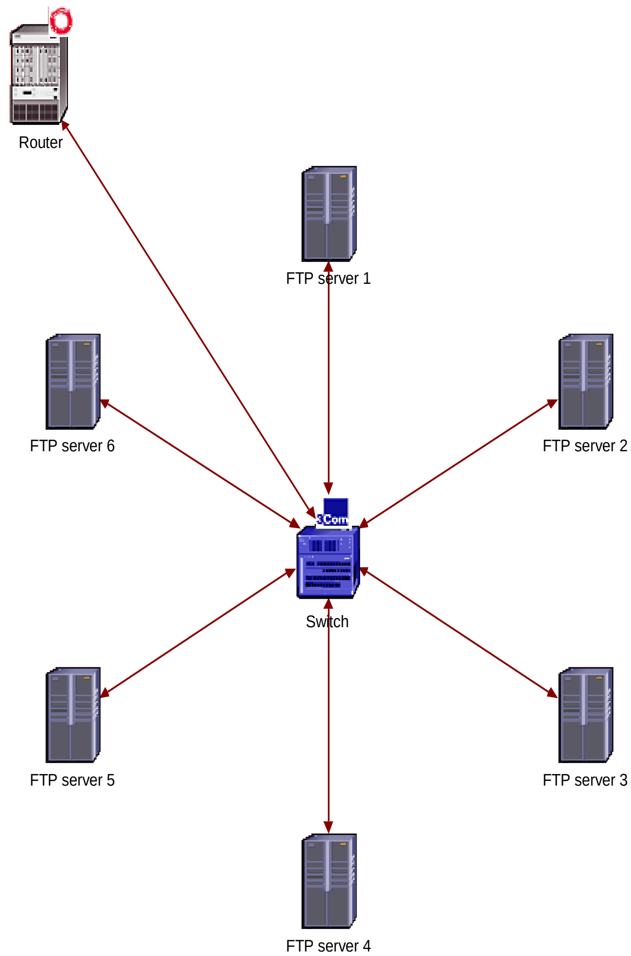

Fig. 3. OPNET model for the PSS controller.

the representation of the system. Each subnet has the same properties as the system that it represents and does not interfere with the simulation.

A crucial component of end-to-end delay is the random queueing delays in the routers. Because of these varying delays within the network, the time from when a packet is generated at the source until it is received at the receiver can fluctuate from packet to packet. This phenomenon is called *jitter*.

Let N be the number of transmitted packets and τ_i be the delay of the i^th packet, $1 \leq i \leq N$. The average delay, $\overline{\tau}$ is given by:

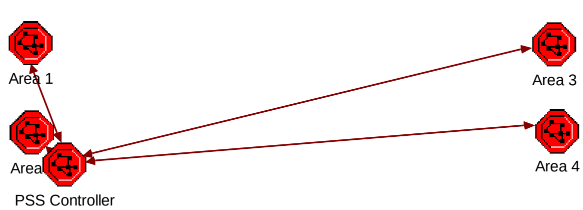

Fig. 4. The 2A4G network, as in OPNET.

$$\bar{\tau} = E[\tau] = \frac{1}{N}\sum_{i=1}^{N}\tau_i, \quad (1)$$

where $E[\cdot]$ represents expectation. Similarly, the delay jitter σ^2 is given by:

$$\sigma^2 = E[(\tau-\bar{\tau})^2] = \frac{1}{N-1}\sum_{i=1}^{N}(\tau_i-\bar{\tau})^2 \quad (2)$$

Delay jitter is an important measure in data communications. A small delay jitter implies that two consecutive packets are likely to arrive at approximately the same time, while a large delay jitter implies that two consecutive packets transmitted at approximately the same time will arrive at vastly different times.

In order to be able to represent the delay jitter as a percentage, one needs to normalize with respect to $\bar{\tau}$. In OPNET Modeler, the delay jitter is calculated using time stamps of every two consecutive packets.

$$\bar{\tau}_{Op} = \frac{\sum_{i=1}^{N-1}(\tau_i-\tau_{i+1})}{\alpha} \quad (3)$$

where α is the average delay over the N packets.

Delay and delay jitter are important measures of Quality of Service (QoS), particularly when the background traffic is bursty. Network conditions, including traffic load, traffic burstiness and burst-length, all significantly effect on delay and delay jitter.

IV. Analysis

A. Delays

The results we are seeking here are the *average* communication delays, the *maximum* communication delays, and the *delay jitter* for each communication link and for all of the three background utilizations (between the PSS controller and each remote area of the network). We are also looking for the number of packets dropped. All these results are important because they could be used later when implementing a second controller used to stabilize the system.

B. Real-time Closed Loop System

The implementation of a controller for a real-time closed loop system is derived below [3]. This implementation is based upon the communication delay results obtained with OPNET Modeler. The simulation is executed with Simulink. The system representation in the Simulink workspace is shown in Fig. 5. The system is first expressed with the *state space equation* [3]

$$\begin{aligned}\dot{x}(t) &= Ax(t)+Bu(t)\\ y(t) &= Cx(t)+Du(t),\end{aligned} \quad (4)$$

where A is a matrix of size 40×40, B is 40×1, C is 1×40, and D is 40×1. A, B, C, and D contain the generators and exciters dynamics of the whole power system. The linear transfer

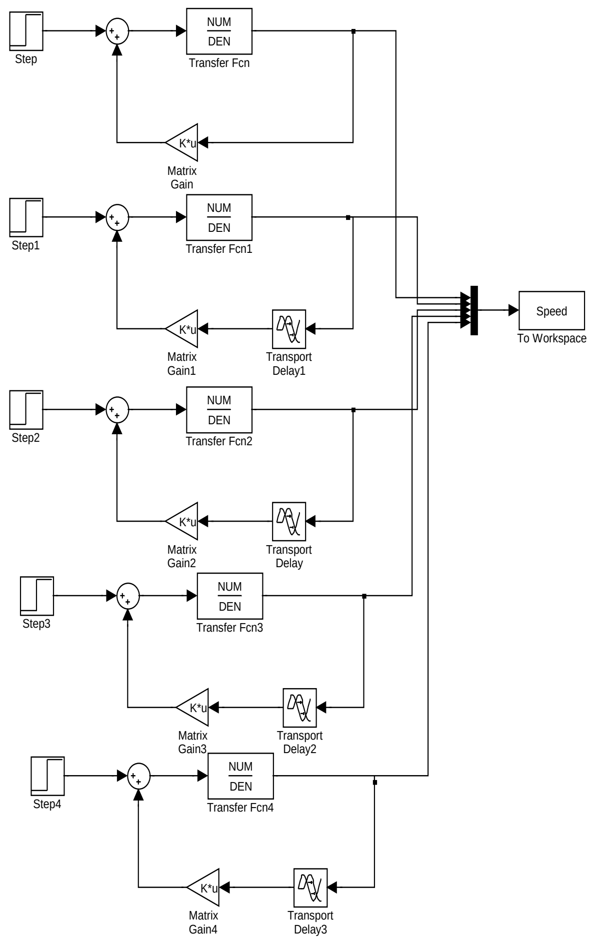

Fig. 5. Representation of the system with Simulink.

function H(S) of the continuous system 2A4G is obtained by using the SS2TF function into Matlab [3]. This function in Matlab converts the state-space filter parameters into a transfer function. The resulting transfer function is as follows:

$$\begin{aligned} H(s) &= C(sI-A)^{-1}B \\ &= \frac{|(sI-A+BC)|-|(sI-A)|}{|(sI-A)|} \end{aligned} \quad (5)$$

where $|X|$ indicates the determinant of the matrix X.

V. Results

- **Packets Dropped:** The results obtained [8] for **each type of connection** are summarized in table I. It shows that, despite the background utilization, even the link that has the slowest performance (e.g. 56K line) still manages **not** to drop a single packet. This result is due to the fact that there is not enough *strain* on the network because of its relative small size. The traffic generated is not significant enough to force the routers to drop packets.
- **Delays:** The results obtained with OPNET Modeler are summarized in table II and are expressed in milliseconds. The results obtained [8] indicate that the delays are proportional to the capacity of the links and also to the background utilization. The length of the packet has essentially no effect on the delay values. The small size of the network does not generate enough strain on the router within the network to make the size of the packets a factor that influences the value of the delays. The delays are minimum for a fiber optic cable used with 10% of background utilization (average delay of $1.25msec$ and maximum delay of $5.9msec$). The delays are maximum for the PPP 56K link used with 90% of background utilization (average delay of 130.5 msec and maximum delay of 158.1 msec). It is important to emphasize the consistency of the results which is a result of the tight confidence intervals of our simulations.

TABLE I
NUMBER OF PACKETS DROPPED FOR EACH TYPE OF CONNECTION.

Link	Packets Dropped
Area 1 to PSS Controller	0
Area 2 to PSS Controller	0
Area 3 to PSS Controller	0
Area 4 to PSS Controller	0

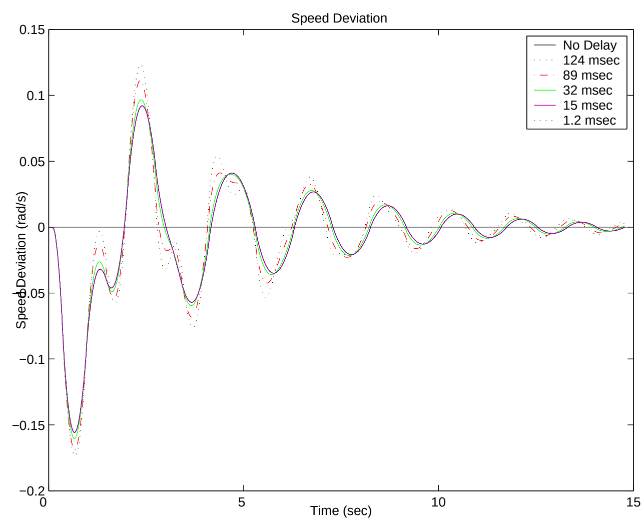

Fig. 6. Speed of the shaft ω_2 as a function of the delays.

The real-time closed loop system is simulated for a time duration of 15 seconds using Simulink and the delays are obtained with OPNET Modeler. The results are presented in Fig. 6. The output obtained is the speed of the shaft, "ω_2", of the second generator as a function of time. It is obvious that for the delays obtained, the system is still stable. The system becomes unstable when the delays reach the critical delay value D_c of 0.437 sec (see Fig. 7). The value of D_c is almost 2.77 times bigger than the maximum delay value obtained. Even if the $56K$ link is "fast" enough, it should be a link dedicated to the controller's information only. The margin between the maximum delay of the worst scenario and the critical delay is big enough to assume that even if the

TABLE II

DELAYS BETWEEN REMOTE GENERATORS AND THE PSS CONTROLLER.

	Utilization		10%			50%			90%		
Link	Delay (msec)		Avg.	Jitter	Max	Avg.	Jitter	Max	Avg.	Jitter	Max
56K	Packet	400	117.2	5.8%	124.1	117.5	7.9%	125.8	129.1	8.8%	158.1
	Size	4500	118.0	7.9%	127.8	118.3	7.9%	129.9	131.9	9.1%	152.2
DS-1	Packet	400	83.7	4.9%	88.7	84.5	5.1%	88.9	92.0	5.2%	97.1
	Size	4500	84.0	5.0%	89.2	84.4	5.0%	89.6	92.0	5.3%	97.5
DS-3	Packet	400	31.1	4.6%	33.9	31.5	4.7%	32.8	33.9	5.0%	37.5
	Size	4500	30.9	4.8%	34.2	31.6	4.7%	33.0	34.2	5.0%	37.8
100	Packet	400	13.2	3.9%	13.9	13.3	4.2%	13.6	15.3	6.9%	18.1
BaseX	Size	4500	13.1	4.1%	13.9	13.3	4.1%	13.8	15.9	7.2%	18.5
OC-12	Packet	400	1.3	2.0%	5.9	1.3	2.1%	5.6	1.3	3.3%	5.8
	Size	4500	1.2	1.9%	5.5	1.3	2.1%	5.7	1.4	3.2%	6.1

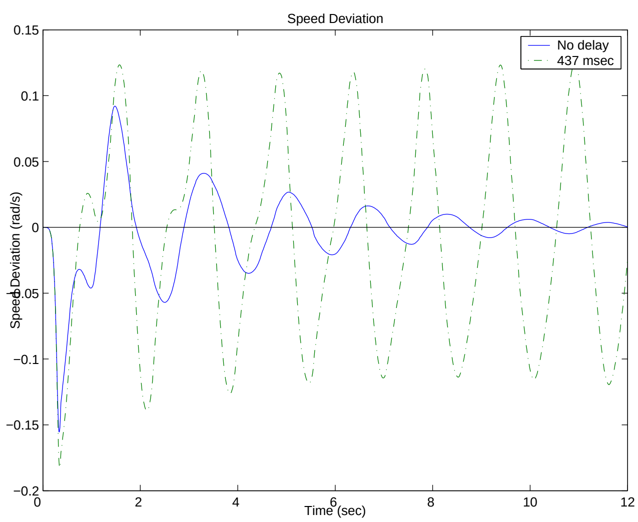

Fig. 7. Speed of the shaft ω_2 as a function of the delays (when delay bigger than Dc).

network expands, the controller will be able to stabilize the system.

VI. CONCLUSIONS:

The control and damping of low frequency inter-area oscillations can be achieved using Power System Stabilizers, which sometimes might require remote signals. In this case there is a delay associated with the transmission of the stabilizing signal. These delays depend on the telecommunication technologies used and they could affect the performance of the control scheme. This paper addresses the issues associated with telecommunication of remote signals. The issues are delay in transmission and packets dropped. OPNET Modeler has been used to determine the delays generated within the network, and this delay information can be used to help improve the design of the controller. The study is performed on the two-area-four-generator (2A4G) system that is widely used in the literature dealing with inter-area oscillations. Different telecommunication technologies have been considered and a critical delay has been identified for the test system. When designing a controller for the 2A4G system, one has to make sure that the links selected to carry the information from one area to another are *fast* enough to generate delays smaller than the critical delay value (437 msec). The average simulated network delays are between 1.2 msec and 131.9 msec. Thus, all the different types of connections modelled with OPNET proved to be fast enough to keep the system stable. Future work should consider a larger size system with different operating conditions and perform an economic analysis of the proposed communication scheme. The communication link could be used for other additional purposes (e.g. delivery of broadband content) which would help to economically justify its installation.

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