Synchronized Processing of Distributed Signals for Smart Grid Applications

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***Abstract*-- Due to the nature of geometrically distribution, many smart grid applications require data from distributed locations. The performance of the power system is then highly correlated with the communication network that transmits sensing and controlling signals. This paper explores the impact of not only network delays but also signal synchronization processing on power system stabilization. Synchronization schemes are proposed and compared to the conventional scheme by simulation under different network conditions. Critical values of system performance are identified regarding network delay. Experimental results demonstrate potential drawbacks of the conventional scheme that can be considerably improved by the proposed schemes. It is important to improve wide area monitoring and control performance by not only reducing network delays but also synchronizing signals with an appropriate tradeoff between data accuracy and timely responses.**

***Index Terms*-- smart grid; power system stablization; signal synchronization; network delay**

I. INTRODUCTION

Smart grid enables better energy efficiency and stabilization of power systems by utilizing information technology [22]. Wide area monitoring and control (WAMC) is one of such smart grid applications. In a WAMC system, distributed PMU signals are collected from different geographic locations and sent to a centralized controller via the communication network. Since the power system is dynamic with all kinds of incentives and potential faults that may deteriorate the system stability, the above procedure is a continual and close-loop feedback control procedure.

Issues in a WAMC system are two-fold: controller design and communication protocol. Researches on controller design have investigated critical values of delays for controller stability where fixed delays in a single input channel or common delays in multiple channels are considered [7]-[9]. WAMCs face new challenges with stochastic and heterogeneous delays in multiple input channels, and research beyond existing results is required. For the consequent problems, researches on communication protocol have to take into consideration diversified network environment.

Due to the long distance between the controller and the distributed phasor measurement units (PMUs) in all regions, the performance of the controller is heavily influenced by the communication network. One of key impacts is the delay of receiving monitoring signals from PMUs. Relevant researches on signal delay generally fall into two categories. The first category is on the design of controllers on a prediction basis, such as $H\infty$ controlling strategy [7] or the gain tuning method [8] to trade-off delay tolerance and controller performance. The second category is on the modeling of system delays. The deterministic and stochastic delays of a single channel are calculated based on a queuing network [6]. Besides the two categories, a generic result on system stability with delay is provided in [10]. Theoretic results are only available for linear and small scaled networked control systems. Related reviews are available in [17]-[21]. The above researches have provided results on the signal delay in a single channel. Long delay as compared to the sampling period and multiple-input cases remain challenges. In this paper, the WAMC is characterized by the nonlinear large scales power system and multiple channels with asynchronously delayed inputs, where theoretical results are intractable. The PMUs are distributed in different locations and PMU signals are sent from different communication channels. Due to various traffics in these channels, a common delay is insufficient to characterize the asynchronous signals from various channels.

Synchronization of asynchronous signals from multiple channels is the focus of this work. Three schemes that provide different trading off between data accuracy and timely control response are proposed and compared. This tradeoff is the major problem arises in the synchronization process, which can be explained as follow. Since the closed loop signal processing is continuous, its real-time performance is important for timely feedback controlling commands. However, during a certain sampling interval, there is no guarantee that the signals from all sources are available. Waiting for the missing signals is equivalent to increase the time delay, whereas it loses the accuracy to estimate these missing signals. The real-time performance and the data accuracy is thus to be tradeoff by any synchronized processing schemes.

In this paper, a WAMC across multiple provinces and its

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power flow oscillation between two subnets is studied. Historical data are used in simulation to recreate incentives and faults that lead to oscillations. A well-designed central controller is applied. To evaluate different synchronization processing schemes proposed herein, the stabilization performance of the whole system is investigated under a variety of network conditions.

The rest of paper is organized as follows. Section II provides a detailed description to the WAMC system. In Section III, network delay models and different synchronization processing approaches are elaborated with observations in practice. Numerical simulation results and their analysis are illustrated in Section IV. It concludes in Section V.

II. THE WAMC SYSTEM

A. WAMC of China South Power Grid

The WAMC system of China Southern Power Grid across two provinces is taken as a case study in this work [23]. The frequency difference between subnets will lead to power oscillation between these subnets and make the power system unstable. The frequencies of different regions in the power system are monitored and to be controlled to be consistent in this WAMC system.

As illustrated in **错误!未找到引用源。** below, PMU measurements of four buses are selected to represent the frequencies of two regions where they located, two PMUs for each region. The average frequency of the two locations represents the frequency in their regions. Those signals are sent to a centralized controller through the communication network with 10ms sampling intervals.

On detecting difference, the centralized controller starts to stabilize the system by sending back controlling signals to selected local motors in each region separately so as to reduce the difference.

Difference of the average frequencies of the two regions is to be controlled to within 0.002% standard frequency, that is, 0.001Hz.

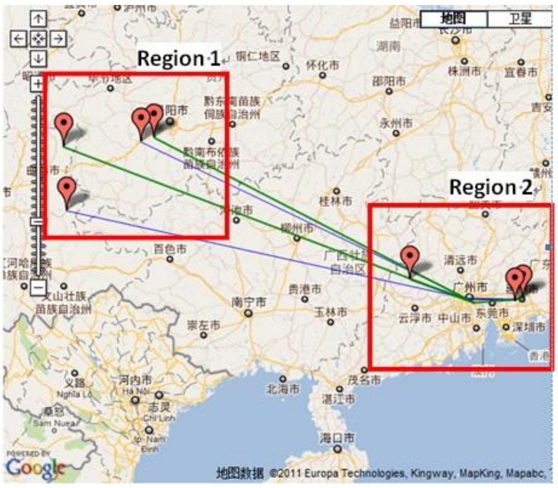


Fig. 1. Magnetization as a function of applied field. (Note that "Fig." is abbreviated and there is a period after the figure number followed by two spaces.)

B. Damping Controller

The average frequency of a region is calculated from the selected PMU measurements distributed in this region. By comparing the average frequencies in region 1 and region 2, the controller derives the corresponding signals to control the local motors as 0 below shows.

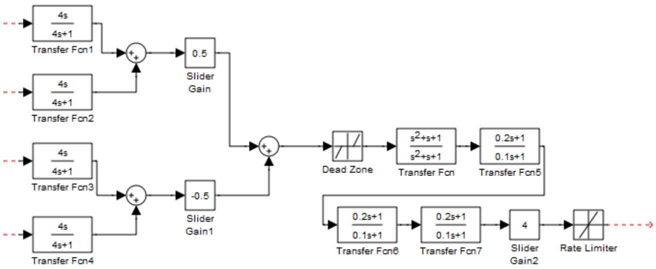


Fig. 2. The basic structure of a WAMCs damping controller.

The China Southern Power Grid in study consists of 1392 nodes, 2371 buses, and two high voltage DC transmission lines. For such a realistic system, the optimal controller is hardly attainable. The controller used in the testing is a combination of suboptimal ones under typical seasonal patterns.

In an ideal case where no network delay exists, this damping controller is supposed to stabilize the system within two seconds under a given set of failure modes, and reduces the system transit time back to stabilization. Just like other WAMC applications which are affected by the communication network, such as bandwidth, routing etc. [3], this feedback control in the power system is also affected by the network environment, and its performance of stabilizing a power system will not reach the same level as in an ideal environment [4].

The performance of this technique depends on three aspects: the design of controllers, the schemes for the data transmission, and the traffic on the communication network. In designing the controllers, H∞ control has been studied for the single delay in a single channel or the common delay in multiple channels [7]-[9]. It should be noted that the delays are not fixed due to the time-variant network environment. It is thus challenging to design a controller for uncertain delays. The delay of signals received by the controller is also affected by different schemes, especially, different ways of handling unsynchronized and missing signals from different channels. The scheme design also has to take into consideration the uncertain network traffic. In the studies on traffic shaping, the traffic models are established based on analytical models or commercial software [1][2].

C. System Performance Metrics

A comparison of system dynamics with and without the damping controller is shown in 0. The dynamic with controller is in the ideal network environment of no delays.

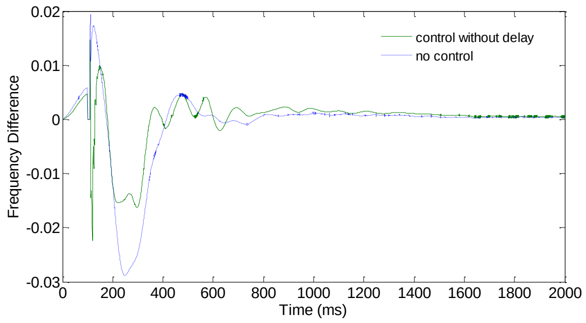


Fig. 3. System dynamics comparison (no control vs. control under zero delays).

To investigate the impact of network delays and synchronization processing on the controlling performance, the performance metric for system stability γ is used for evaluation purpose, which is defined below:

$$\gamma = \int_{t=0}^{\infty} s^2 dt \ , \tag{1}$$

where s stands for frequency difference between two regions.

As shown in 0, the transition process is as short as two seconds. In fact, if the system cannot be stabilized within two seconds, it fails in most cases. Thus we calculate the performance metric γ over a period of 2000 milliseconds. This performance metric represents the waste of energy during the stabilizing process. The smaller γ is the better the controlling performance.

D. Communication Network and Issues therein

Among all types of communication links for PMU signals, optic-fiber cables are widely applied for their interference immunity. Besides its high initial investment, only a very small part of bandwidth is occupied by PMU signals in WAMC [5], which introduces economic wastes. There are two ways to efficiently utilize the massive bandwidth that optic fiber cables provide. The first way is to replace the dedicated bandwidth by other low cost installation, especially when more sampling locations of PMU are added to the whole system. Secondly, the bandwidth can be shared with data traffic of other secondary applications. The consequent issue with either of the two ways is the increase of communication delays, since delays play a critical role in WAMC for it enlarges the time-lag of the controller that corrects power grid instabilities and oscillations.

As pointed in [5], the link delay can be calculated by summation of the fixed delay associated with transducers used, DFT processing, data concentration and multiplexing, the link propagation delay, the transmission delay and a stochastic jitter. In addition to such a link delay, the synchronization delay has to be considered and is the focus of this paper. The sampling data from different PMUs are all labeled with GPS time stamp before delivering. Difference of GPS time stamping is ignored here and the sampling PMU signals with the same time stamp are regarded as synchronous data of the same time. As those synchronous data are sent from different PMU locations, they arrived at the centralized controller with different communication delays. These delayed signals from all channels have to be synchronized again before the controller can derive an output. The synchronization delay therefore comes from the difference of communication delays in multiple input channels of the controller.

III. Network Delays and Signal Synchronization

A. Delay Modes

The major delays in concern are categorized into three modes: link delays, pure random delays and delays due to secondary applications that share bandwidth with the controlling signals. In this work, since WAMC uses dedicated channels for communication, we mainly consider pure random delays.

B. Synchronization Schemes

Suppose there are N channels of signals, that is, the controller has N inputs. The signal of time t from channel n is denoted as $S_n(t)$. The set of received signals from all the N channels is denoted as an available set $\mathbf{A}$. Signals in $\mathbf{A}$ are available for synchronization processing and can be set as the input of the controller.

In view of the low signal utilization of the widely applied scheme Drop in practice, we propose herein three different schemes for receiving asynchronous signals, SCH (single channel history), SCI (single channel interpolation) and SCI-T (single channel interpolation with timestamp).

Drop In the conventional method *Drop*, if any of the latest signals are missing at t, controller inputs $x_n(t)$ are set to be zero for all n. It writes as:

$$x_n(t) = s_n(t_1) \cdot I_{\left\{s_n(t_1)\in \mathbf{A}, t_1 = \max_n \{\tau | s_n(\tau) \in \mathbf{A}\}, n=1,\cdots,N\right\}}, \quad \forall n \tag{2}$$

where $I_{\{\cdot\}}$ is the indicating function, taking one if $\{\cdot\}$ is true and taking zero otherwise. It can be seen that when the signals from all channels are not received all together, the incomplete signals are ignored under *Drop* scheme. The waste of data prevents the functioning of controller. The three schemes proposed below compensate the missing data to put the controller into functioning.

SCH To reduce the waste of received signals, Single Channel History (SCH) scheme compensates missing signals with the latest historical data in the same channel. The input of controller is written as:

$$x_n(t) = \begin{cases} s_n(t_1) & \exists t_1 = \max_{\tau \in [0,t]} \{\tau | s_n(\tau) \in \mathbf{A}\} \\ 0 & otherwise \end{cases}, \quad \forall n \tag{3}$$

Such an approximation cannot avoid asynchronous and inaccurate inputs, but is expect to provide prompt controlling output.

SCI Rather than using historical data directly as a substitute for the missing data as in *SCH* scheme, Single Channel Interpolation (SCI) estimates the missing data by the linear interpolation of the latest two signals available in the same channel, which writes:

$$x_n(t) = \begin{cases} s_n(t_1) & s_n(t_1) \in \mathbf{A} \\ \dfrac{s_n(t_2)(t_1 - t_3) - s_n(t_3)(t_2 - t_3)}{t_2 - t_3} & s_n(t_1) \notin \mathbf{A} \text{ and } t_2, t_3 > 0, \\ 0 & otherwise \end{cases} \quad \forall n \tag{4}$$

where

$$t_1 = \max_n \{\tau | s_n(\tau) \in \mathbf{A}\}, \tag{5}$$

$$t_2 = \max_{\tau\in[0,t_1]}\{\tau \mid s_n(\tau)\in \mathbf{A}\}, \tag{6}$$

$$t_3 = \max_{\tau\in[0,t_2]}\{\tau \mid s_n(\tau)\in \mathbf{A}\}. \tag{7}$$

This linear interpolation utilizes two latest signals received to estimate the missing data of the latest received signals. This estimation of controller input is expected to be more closed to the missing data at *t*.

SCI-T Different from all the previous schemes that compensate the missing data among the latest received signals, Single Channel Interpolation with Timestamp (SCI-T) takes into consideration the timestamp of the current time *t*. That is, it estimates the signals of current timestamp *t* to eliminate the latency due to network delay. Specifically,

$$x_n(t) = \begin{cases} s_n(t) & s_n(t)\in \mathbf{A} \\ \dfrac{s_n(t_2)(t-t_3) - s_n(t_3)(t-t_2)}{t_2 - t_3} & s_n(t)\notin \mathbf{A} \text{ and } t_2, t_3 > 0, \\ 0 & \textit{otherwise} \end{cases} \quad \forall n \tag{8}$$

where

$$t_2 = \max_{\tau\in[0,t]}\{\tau \mid s_n(\tau)\in \mathbf{A}\}, \tag{9}$$

$$t_3 = \max_{\tau\in[0,t_2]}\{\tau \mid s_n(\tau)\in \mathbf{A}\}. \tag{10}$$

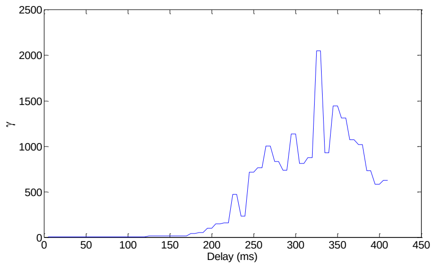
In case that the latest signal arrives without delays or the delay is less than the sampling period, *SCI-T* reduces to *SCI*.

IV. Experimental Results

In the simulation experiments, system performance is tested and compared with these synchronization schemes under a set of delay configurations specified hereafter. A recorded fault from real historical data is used to generate the scenario where the system starts to oscillate. In different delay patterns, common random numbers are used to generate the stochastic delay sequences. The results will demonstrate the characteristics of different synchronization schemes under the same delay configurations.

A. *Critical value of the system tolerance*

For comparison purpose, the system stability performance is explored under fixed delays and delays of all input channels are set to be the same. The plots below depict the system performance curve and the critical value of maximal delay is 105ms for current stabilization controller.



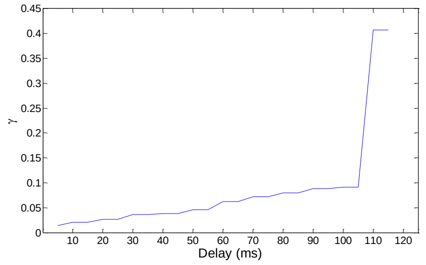


Fig. 4. Critical value: System stabilization performance with common delays of increasing means under current controller.

B. *Results of different synchronization schemes*

In 0-0, the error bars of the stability performance metric γ of the system are plotted. They characterize the performance of different synchronization schemes under delays of increasing means and a common variance 25/3. The mean delay ranges from 5ms to 100ms with increasing step 5ms. With increasing delays, all the schemes degrade in terms of the increasing γ.

As pointed out in Subsection IV. .A, the system tolerance of synchronous delays is 105ms. In this testing, the system tolerance is expected to be less than 105ms regarding asynchronous signals. For Drop, SCH and SCI schemes, a slight change appears on the curves at 65ms, and obvious changes can be observed at 85ms for all of the four schemes. When delays approach 100ms, scheme Drop and SCI-T fail to stabilize the system on some sample paths. The failed sample paths are excluded in generating the error bar, and the corresponding points on the error bar are marked with a red asterisk.

Drop It can be seen in 0 that along with the increasing mean delays, the conventional Drop schemes oscillates and degrades gradually. To demonstrate the oscillation, its performance error bar with unit increasing steps of mean delays is plotted in 0The oscillation is due to the Drop scheme itself and the period of the oscillation is due to the system sampling period. With Drop scheme, signals will be ignored when they do not arrive on time all together and the controller will not take effect. In this WAMC system, sampling signals of PMU are sent every 10ms. Correspondingly, the controller receives input signals every 10ms. If the delayed signals arrive in the same sampling interval, no matter how much the delays are, these signals are treated by the controller as synchronized signals that arrive together and the controller takes effect. While when the delays of PMU signals distribute over more than one period, the probability becomes small for all signals arrive within the same sampling period, which means the controller is less likely to take effect along the run. From 0, it can be seen that the period of oscillation is 10ms, equivalent to the sampling period. The high peaks of γ, that is, the low peaks of controlling effects, take place when the mean delays are multiple of 10ms; and the contrary performance takes place when the mean delay is at the middle of the 10ms sampling periods. Furthermore, all peaks increase with the mean delay increases, the performance get worse gradually, but still, the oscillation dominates the degradation over the increasing network delays.

Besides the above drawbacks, this conventional Drop scheme is not good enough compared to other schemes. It does not provide good stability performance even when the delays are still small. It also fails in stabilizing the system when the mean delay is larger than 85ms. The general improvement by the proposed schemes below can be as large as about ten times in terms of γ.

SCH It can be seen that SCH method archives better stability performance than the conventional Drop scheme in terms of γ. SCH's performance degrades gradually with the increasing mean delays. For delay larger than 80ms, SCH worsens rapidly in terms of mean and variance of γ.

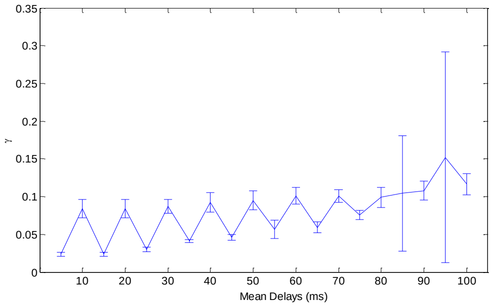


Fig. 5. Drop performance error bar with delays of increasing means and a common variance.

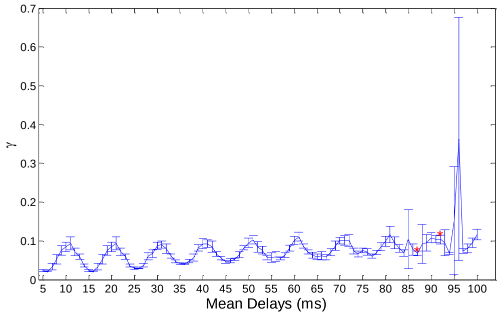


Fig. 6. Drop performance error bar with delays of unit increasing mean and a common variance.

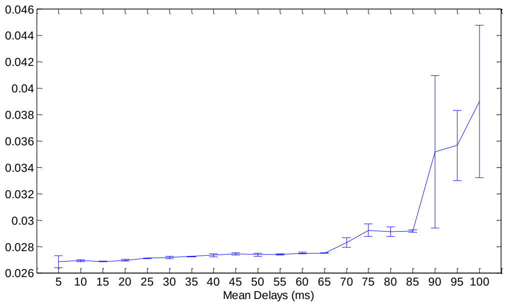


Fig. 7. SCH performance error bar with delays of increasing mean and common variance.

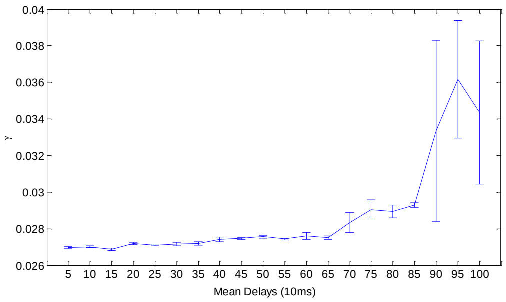


Fig. 8. SCI performance error bar with delays of increasing mean and common variance.

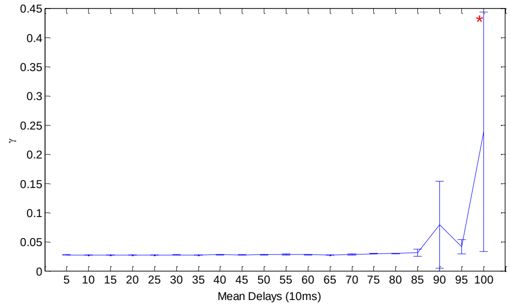


Fig. 9. SCI-T performance error bar with delays of increasing mean and common variance.

V. Concluding Remarks

This paper presents experimental study results on signal synchronization for a damping control application in smart grid. In presence of random and non-uniform delays of multiple input channels, the system tolerance for delays is decreased, and the critical values on delay tolerance depend on the synchronization scheme being applied.

A synchronization scheme has to tradeoff the loss of either accuracy or stringent time requirements. With conventional schemes, if signals of a common timestamp from different input channels arrive with different delays and cannot serve as the controller's inputs, they are either ignored or being waited till all are available. That is, the signal accuracy remains. In this paper, three schemes that provide more timely controlling response are proposed and compared with the conventional scheme Drop in the testing. The three schemes SCH, SCI and SCI-T compensate the missing signals, respectively, with historical data, with linear interpolation and with linear interpolation weighted by time stamp. With different approximations to the original synchronous signals from the sourcing PMUs, these schemes offer different tradeoffs between data accuracy and timely control response, which can be roughly illustrated by 0 below.

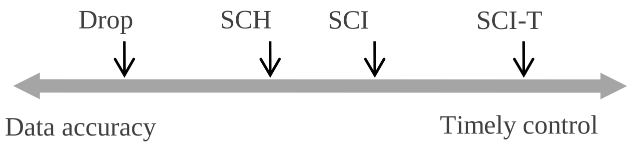


Fig. 10. Illustration of tradeoffs between accuracy of approximated synchronous signals and timely control response that different synchronization schemes offer.

Numerical testing results demonstrate that timely response is important for this real-time controlling application. SCH and SCI schemes achieve better performance among the four. In general, the improvement by SCH/SCI can be as large as ten times in terms of the performance metric γ, in addition to the lower possibilities in failing to stabilize the system.

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