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OPPORTUNITIES IN WIDE AREA CONTROL AND MEASUREMENTS (WACAM)

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ABSTRACT

The paper presents and overview of global position system (GPS) signal based power system angle measurements and control. In this we shall discuss phasor measurement units (PMUs), wide-area measurement (WAM) and wide-area control system (WACS). We shall also discuss the opportunities that are currently arising due the use of satellite and high speed computer communication systems.

1. INTRODUCTION

Wide-area control and measurements (WACAM) pertains to the control of a large interconnected power system through synchronized phasor measurements at different points of the network. This has the following two components:

- Wide-area measurements (WAM) and
- Wide-area control systems (WACS)

The main purpose of WAM is power system oscillation monitoring. Power oscillations are caused to due periodic interchange of kinetic energy between the rotors of various generators. To detect the oscillations phasor measurement units (PMUs) are employed. The PMUs measure voltage and current phasors. The measurements are synchronized through satellite based global positioning system (GPS). The synchronization of each unit has an accuracy exceeding 1 μs. Typical sampling interval is 20 ms, i.e., synchronized data are collected every cycle. The synchronized phasor measurements enable comparison between the data sets of various critical nodes of the power system to determine its dynamic behavior. Based on this, the most important oscillation frequencies, the amplitude of the system angles oscillating at this frequency and their damping can be computed.

Power system oscillations associated with a single generator or a single plant are called local mode oscillations that have a frequency range of 0.5 to 2.5 Hz. Oscillations associated with a group of generators of a group of plants are called inter-area oscillations which have frequency range of 0.1 to 0.8 Hz [1]. The inter-area mode oscillations depend on the strength/weakness of the tie and the quantum of power transfer through it. The connection between two areas can be strengthened if a dc link is connected in parallel with the ac inter-tie. The inter-area modes are not excited if two areas are connected only through a dc link. Under zero tie-line flow, the generators of one area swing in anti-phase with those of the other area. With non-zero power flow, the modes do not necessarily oscillate in anti-phase, especially if exciters are in use. The loads also affect the inter-area modes. The loads act as sinks (or sources) of energy. Some motor loads can exchange kinetic-energy with the generator rotor shafts. Accurate load models are be required to determine the load effects on the system dynamics.

Inter-area oscillations can be viewed as the oscillations in the tie-line real power. It is logical to employ power system stabilizers (PSSs) to damp these oscillations. The PSS input signals traditionally used to inter-area oscillation damping for exciters and SVCs are: power, frequency, voltage amplitude and machine angle (δ). To obtain good control over multiple loads there are limitations of these local signals. Widely dispersed measurements are able to provide enhanced performance for inter-area mode control. Usually there are time delays associated with the communication of measured signals. If these signals are to be used in closed loop control of FACTS devices these delays may be critical. Recent studies are showing that WACAM will enhance stability limits through PSS and FACTS controllers.

Even though the inter-area oscillation control is one of the important aspects of WACAM, there are several advantages of employing it, such as,

- Better targeted load shedding strategy can be designed for effective congestion management.
- Since the PMUs are globally synchronized, frequency drift information can be easily inferred from them. Based on the frequency deviation information, better coordinate load frequency controllers can be designed.
- Cascaded outages can be reduced since information regarding developed oscillations and impending voltage collapse can be predicted early.
- Through WACAM it will be possible to have a better load representation, which in turn can be incorporated in the control strategy, will enhance the transient stability margin further.

In this paper we review the WACAM technology and its impact in the future operation of power systems.

2. PHASOR MEASUREMENT UNITS

Phasors are used to describe electrical quantities in their sinusoidal steady state. They can be computed online using discrete Fourier transform (DFT) but more commonly implemented using the Fourier series directly. For example, let us consider the following voltage waveform that contains fundamental and harmonics

$$v(t) = V_m \left\{ \sin(\omega t + \phi) + \sum_{m=3,5,7} \frac{\sin(m\omega t)}{m} \right\} \qquad (1)$$

where $V_m = 141.4214$, $\phi = 10°$ and $\omega = 100\pi$. The voltage waveform is shown in Fig. 1. Suppose now the voltage waveform is uniformly sampled. Then the voltage phasor is extracted using DFT as

$$\boldsymbol{V} = |V| \angle \phi = \frac{\sqrt{2}}{N} \sum_{k=1}^{N} v(k) e^{j(\pi/2 - 2k/N)} \qquad (2)$$

where N is the total number of samples per cycle and k is the sampling index. The phasors can be continuously computed using a moving average process in which the last N sample values are used. The results are shown in Fig.1 which depicts the absolute value of the fundamental component of the voltage (100 V) and its angle (10°). Note that due to DFT, the harmonic components are eliminated. Also note that the extraction process starts after the first cycle when the buffer is full with past N samples. Using (2), the phasors for each phase can be computed from which the sequence components can be extracted. Alternatively, the sequence components can be directly extracted using instantaneous symmetrical components [2]. The derivation of frequency and rate of change of frequency has been discussed in [3].

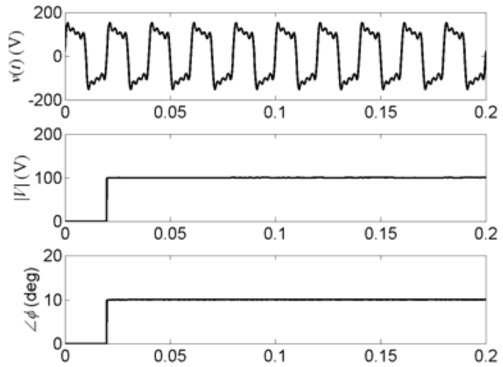

Fig. 1: Voltage and phasor magnitude and angle of its fundamental.

A common reference frame is required for the measurement of several voltage and current phasors in an interconnected power system. The reference frame is required to synchronize the sampling of all the measurement units. With the current state of art, the synchronization delay is less than 1 μs [4]. Traditional communication systems such as microwave links, AM radio broadcast etc. cannot be used for synchronization. A dedicated fiberoptic line can be used for synchronization, if available. However, the current preferred mode is to use global positioning system (GPS) satellite transmission [4]. GPS based car navigation systems are increasingly becoming popular with their cost dropping to AUD 500-600 range. These can detect the position of the car almost instantaneously to provide driving assistance. Similarly they can provide synchronization signals anywhere in the earth with 1 μs.

The QUT PMU receives signal from GPS in the form 1 pulse per second (pps) and 100 pps. The 100 pps signal is divided into 50N pulses for a 50 Hz system where N is the total number of samples per cycle (for the QUT monitor N = 200). The sampled analog voltage (or current) waveforms are converter to digital using ADC. These are then used to extract phasor signals using a digital computer that solves equations like (2). IEEE standard for synchronized phasor measurements at substations is given in [5]. Also IEEE working group report can be found in [6]. The extraction of 3 phase can be set to consider only the positive sequence voltage.

Several PMU applications have been reported in [4, 7]. Some these include protective relaying and fault recording, prediction of instability, state estimation [8]. Wide-area monitoring applications in Chinese power system have been discussed in [9]. Currently there are 70 installed PMUs in China with another 35 PMUs under construction. These PMUs are expected to perform basic and advanced functions. The basic functions involve dynamic monitoring and synchronized disturbance recording. Advanced functions include generator status monitoring, low frequency analysis, state estimation, angular stability prediction, model (parameter) identification etc. Even though these PMUs are used mainly for monitoring purpose, gradually they will be utilized in wide-area control problems.

3. WACAM

A typical scenario of catastrophic power system failure has been discussed in [10]. Assume that the power system is in a stressed state – generators operating close to their operating limits with minimal spinning reserve and deficient reactive power. Due to the lack of measurement and information exchange, the health of the system is not to the operators. A fault during this time may trigger events that will lead to cascading outages. Often under-frequency relays trip during such a contingency. One such event may cause false tripping of other protection devices. This may result in growing electromechanical instability or voltage stability. This will cause the formation of separate islands that are either excess in load or generation and finally in the collapse of the generation deficient islands.

A WAM system can monitor the health of the system on-line, and prevent such catastrophic failure to occur through early warning system, adaptive protection system and intelligent load shedding.

A power system state estimation relies heavily on the data collected from different substations to estimate the system state. Since this is an iterative procedure and because of the communication overheads, it takes several seconds to converge. Therefore the state estimation is, at best, a quasi steady state description of the system [10].

However if the fully synchronized data are now available, they can be incorporated into a high speed state estimation. Additionally the stream of phasor data can be used in the dynamic model of the system. The solution of the dynamic model can provide early warning of the impending doom.

The early warning can be used in adaptive protection system. The adaptive protection permits dynamic changes in the protection functions according to the prevailing power system condition [4]. An overview of the wide area system applications is given in [11].

Power system stability is the ability of an electric power system to regain its equilibrium state after being subjected to a disturbance. Power systems stability has been classified to be of three types – angle stability, voltage stability and frequency stability [12]. Angle stability is the ability of the system to remain synchronized following a disturbance. The system stability usually depends due to the availability (or lack of) both synchronizing and damping torque components. While the former is in phase with the rotor angle deviation, the latter is in phase with the speed deviation. The impact of the excitation system has been analysed in [13] where it has been shown how a power system stabilizer (PSS) can enhance both these torques in an interconnected power system.

Voltage stability is defined by the ability of the system to maintain voltage at buses following a disturbance. The leading cause of voltage instability is the dynamic response of loads and tap changers. In response to a voltage reduction in a bus following a disturbance, the power consumed by the loads is restored by the action of their own control mechanism (e.g., tap changers, voltage regulators etc.). This may cause the reactive power to increase causing a further drop in the bus voltage. This progressive drop in the bus voltage results in voltage instability [14].

Frequency stability refers to the ability of the system to maintain the system frequency following a disturbance that causes a mismatch in the power generation and load. Usually the power system frequency is regulated by a load frequency controllers through the so called are control error (ACE).

Even though the stability terms are defined separately, one of them may lead to the other. For example, a progressive drop in a bus voltage may result in angular instability and vice versa. Let us now discuss the situation when several generators in NSW were tripped on August 13, 2004. The results are given on the basis of data received from newly developed oscillatory stability monitor (OSM) client/server system.

Initially there was a low power transfer from Brisbane to Sydney through the QNI link. A fault caused the angle to rapidly change to 52° as shown in Fig. 2. The collective drop in the angles of Brisbane (B), Sydney (S), Melbourne (M) and Adelaide (A) is shown in Fig. 3.

In response to the frequency drop caused by the fault, there was substantial load shedding in Queensland. This was more vigorous than the other states. Despite this the link, which as initially almost unloaded, nearly reached its stability limit. Selective load shedding in NSW would have reduced the risk of a major blackout. Fig. 4 shows three distinct events all tending to increase the angle from Brisbane to Sydney. The frequency variation and df/dt variation are shown in Figs. 5 and 6 respectively.

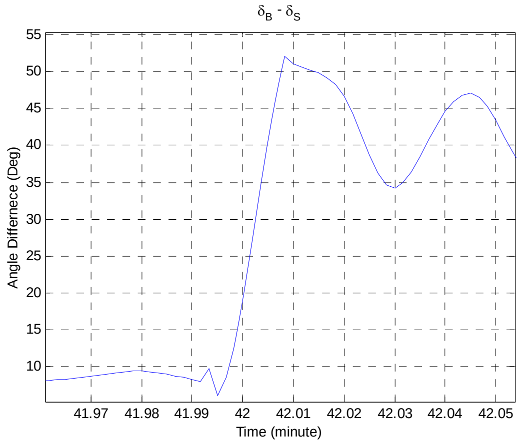

Fig. 2: Change in the Brisbane-Sydney angle due to a fault.

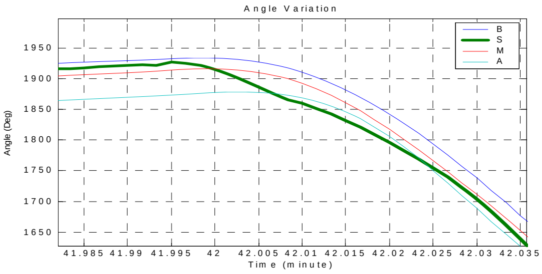

Fig. 3: Changes in the angle of four cities during the fault.

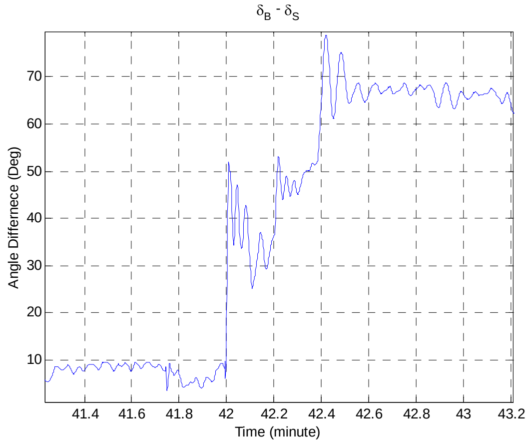

Fig. 4 Increase in the angle difference between Brisbane and Sydney due to three different trips.

The initial df/dt strongly shows that NSW had the largest initial acceleration and a biased shedding for NSW could have been identified by the drift in frequency and df/dt. The main reason why this event was of concern is that if the initial transfer from Queensland was higher then the risk of a separation of QNI would have significantly increased. The results show that regional load shedding based on synchronized angle measurements is desirable and feasible and would limit the peak stresses on interconnectors.

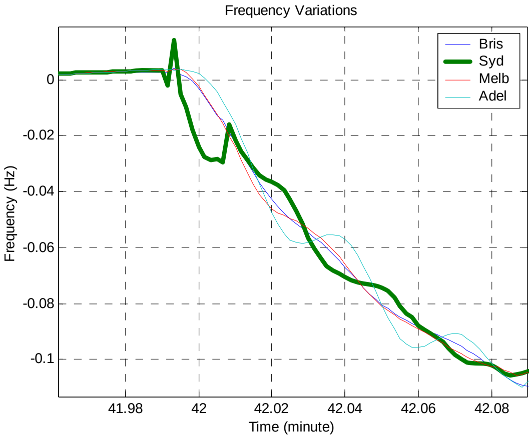

Fig. 5: Frequency variation recorded in 4 cities.

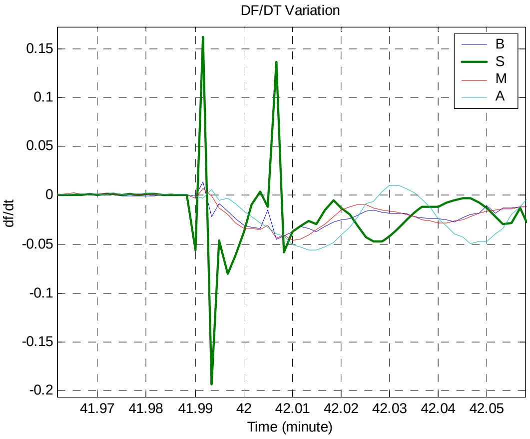

Fig. 6: Rate of Change of frequency in 4 cities.

One of the main applications of WACS is in the damping inter-area modes through PSS. A hierarchical PSS design is given in [15] and is shown in Fig. 7. In this there are a total number of *n* PMUs and *m* PSSs. The measured signals from the PMUs are fed into a SCADA system. The SCADA system routes the signal to different global PSSs. The overall excitation control signal is then a mixture of local and global PSS outputs. This is termed a decentralized control since not all PMU signals are given to all the PSSs.

One of the current approaches is to consider the WACS system in a multiagent framework. A multiagent system (MAS) contains intelligent hardware and software systems that are working together towards a common goal [10]. It is assumed that it is beyond the capability of an individual agent to achieve the global goal. However together they are capable of facilitating a safe operation of the wide-area control system.

The multiagent control concept has been discussed in [16]. A typical multiagent coordination is shown in Fig. 8 which is called “request and response” in [16]. Power system stabilizer design using the multiagent concept has been presented in [17]. In this local PSS (LPSS) and supervisor level PSS (SPSS) are coordinated to work in tandem. This essentially combines the hierarchical control with MAS. However, control agents used here are neuron-fuzzy and this may limit the applicability of such a design. A robust multiagent control is discussed in [18].

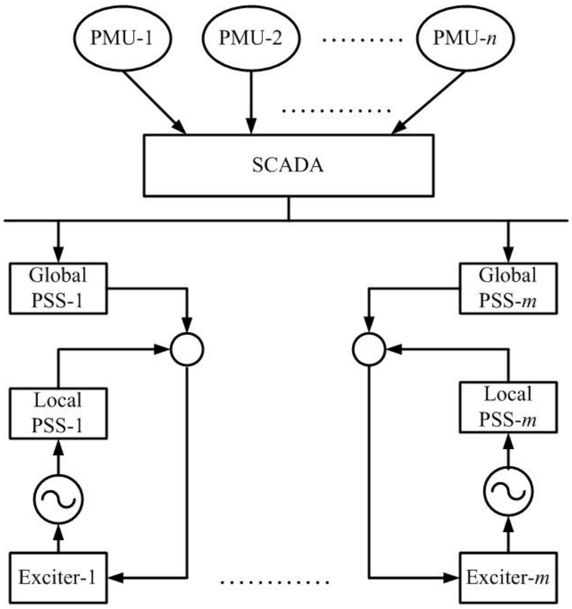

Fig. 7: Decentralized/hierarchical excitation control.

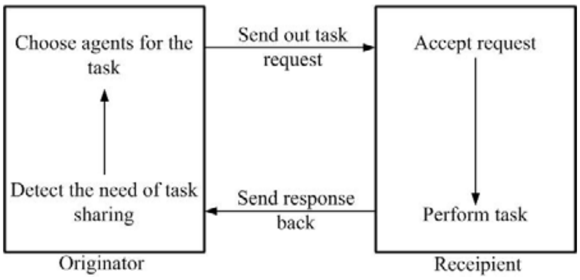

Fig. 8: Communication based coordination of a multi-agent system.

A GPS sends synchronized signals to each PMU within an accuracy of 1 μs. Once the PMUs complete the phasor extraction, they are then conveyed to the different controllers. This causes communication delays. The delay is minimum (3 ms) for dedicated fiberoptic channels and of the order of 100 ms for satellite channels [18] depending on the travel distance. It is therefore imperative that the control system takes into account the transmission delays.

In [19], the transmission delay is modeled as a Pade approximation which is then transformed using so called linear fractional transformation. A gain scheduled robust controller is then designed for each SPSS (see also [20]). In [21] a time delay is represented in a Smith predictor form based on which robust stabilizing controller has been designed for the PSS problem. One promising direction is to use Model predictive control and this would provide a correction for known delays as well as providing a powerful nonlinear control tool.

Unfortunately however the channel delays may be unknown and are variable. This is one of the major limitations of all the control techniques discussed so far and hence one of the open challenges preventing the wide acceptance of WACAM. The most useful control signals are often from the nearest neighbors and the control can be progressively updated as the more remote measurements are received.

Wide are measurement based voltage stability enhancement is discussed in [22] and load frequency control is discussed in [23].

4. OPPORTUNITIES FOR WACAM

To understand the opportunities of WACAM, we have to appreciate the limitations implicit in linearly designed local feedback controllers. For example, most SVCs are designed as voltage control units with local voltage feedback. For dynamic stability enhancement, a stabilizing signal is often created from lead/lag networks processing transferred power. The design of the lead/lag is based on linear phase shift concepts at a finite number of modal frequencies. Robustness is tested by examining over an exhaustive range of operating conditions. Inevitably the lead/lag design needs to make compromises over the phase and magnitude responses for each of the modal frequencies. It is particularly difficult to design different phase shifts for different modes when they are closely spaced in frequency. Over the nonlinear range of operating conditions from small to large transfers, feedback gains must be found which perform acceptably.

With angle measurements obtained at different sites, all modes are separably measurable and no compromise is necessary in designed contribution of the controller to each mode even when they may be closely spaced in frequency. The major nonlinearity in power transfer is due to the sine of the angle differences. When the measurements are made directly on system angles, the effect of the nonlinearity can be easily corrected. There is no compromise between small and large signal response performance if energy function [24] or model predictive control (MPC) [25] based designs are employed. This improved performance shows promise to lead to substantial increase in secure transfer capacity.

The major impediments to implementation of WACAM are discussed below.

4.1. COMMUNICATION ROBUSTNESS

Traditionally the remote measurements are not been seen as having the robustness necessary to be an integral part of power system controls. Developments in communication networks with redundancy providing designed levels of reliability have reduced this concern. For example, the control system for a first contingency response to loss of the cable in Basslink makes use of redundant communications to provide a sufficiently secure response to satisfy NEMMCO.

4.2. CONTROL DESIGN ROBUSTNESS

Globally optimized control designs can have robustness criteria built into the coefficient selection. For the Australian network, less than six remote measurements may be necessary for substantially improved system performance. In this case, each of the potential failures can be enumerated and a new control design can be evaluated. Upon detection of a loss of remote signal, the appropriate control parameter set is selected.

4.3. CENTRALIZED OR DECENTRALIZED CONTROL

The data from WAM system can be collected into a central energy management center from which control command to various areas can be generated. For example, the angle measurements in France are centralized in Paris. Investigation must be carried out to find whether this centralized control system is preferable over a decentralized design. For an Australian application there are two main limitations for centralized control. Travel time for a signal to go from Cairns to Canberra and back again adds substantially to the control delays. In addition, we are subjecting our national control system to a single point of failure. For a decentralized system however the angles from each measurement site must be transmitted to each relevant control site. This will reduce the delays and prevent single point failure.

5. CONCLUSIONS

We have presented an overview of both the wide area measurement and control. Ultimately the success in WACAM will depend on developing robustness in the communication links and control strategies along with advanced algorithms which show significant improvements in performance from the use of these measurements.

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