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SYNCHRONIZED SAMPLING AND PHASOR MEASUREMENTS FOR RELAYING AND CONTROL

Prepared by Working Group H-7 of the Relaying Channels Subcommittee of the IEEE Power System Relaying Committee

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ABSTRACT

This paper describes the concept of utilizing time synchronized sampling over an entire power system to simultaneously obtain the phasor values of voltages and currents at particular instants of time. Uses of the phasors are reviewed and the necessary accuracy of synchronization for several applications is established for magnitude and angle of the phasors. Various methods of providing synchronizing signals are examined, and a possible format for transmitting the phasor measurements to remote locations is described. Finally, some possibilities for applications of this technique in protection and control tasks of the future are explored.

1. INTRODUCTION

It has been recognized that the information available to relays can be used by other monitoring and control processes, leading to improved power system operation. In this sense, relays may be considered to be instruments which measure power system voltages and currents directly from their waveforms.

Most modern digital relays and measurement systems use sampled data obtained at sampling rates varying between $4f_0$ and $40f_0$, where f_0 is the nominal power system frequency. A sampling frequency of $12f_0$ has been used in many relays and phasor measurement systems that have been installed in the field in recent years. Although relaying tasks may require very fast response times, most phasor measurement systems utilize a one period (at f_0) data window, implying a measurement time constant of about one cycle of the nominal power system frequency. The major components of such a measurement system are shown in Figure 1. The primary power system voltages and currents are transformed by voltage and current transformers, filtered by analog anti-aliasing filters, and converted by A/D converters at sampling instants defined by a sampling clock. The surge isolation stages have been omitted from Figure 1, although they must be included in any practical measurement system.

Synchronized sampling and measurements can also be implemented in other monitoring and control devices and systems, such as Remote Terminal Units (RTUs) of the Supervisory Control and Data Acquisition (SCADA) Systems, digital fault recorders (DFRs), fault locators, and sequence-of-events (SOE) recorders.

A sample obtained by the system shown in Figure 1 is irretrievably linked to the instant defined by the sampling pulse. A measurement derived from several samples - such as a phasor - is associated with the data-window spanning the sample set. It is intriguing to consider the possibility of making measurements of several voltages and currents over the same data window, which would produce a ***simultaneous measurement set***. Simultaneous measurements have a very special role in network analysis, as they can be used to form a consistent picture of the network, which is the basis for all network monitoring, protection and control functions. Such measurements also permit tracking of faster system dynamic phenomena, and provide new opportunities for improved control of system dynamics.

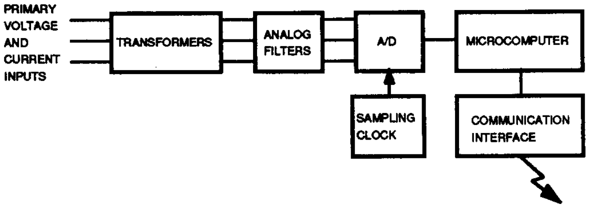

Figure 1. Functional block diagram of a synchronized measurement system.

Simultaneous measurements across the power system can be obtained by synchronizing the sampling clocks at each measurement site. The synchronization must be achieved over long distances (hundreds of miles), and a certain precision in synchronization with a high degree of reliability must be maintained.[1,2] This paper examines the available techniques for measurement synchronization, and various attributes of these techniques.

2. PRECISION IN SYNCHRONIZED MEASUREMENTS

Required accuracy of magnitude measurements

The error model conventionally [3] used in static state estimation assumes an error that depends upon both the magnitude of the measurement and the full scale value of the instrument. Although this type of error has been associated with an rms measurement, it seems plausible that a similar error model may be used for sample data values as well. If it is assumed that the input quantities V are essentially one per unit, and that it is sufficient to have a full scale of 1.5 pu, the variance of magnitude measurements may be assumed to be

$$\sigma = (0.02\ V + .0052\ f_s)/3$$

using full scale $f_s = 1.5$

$$\sigma = (.0278)/3 = 0.00927 \text{ per unit}$$

This is essentially of the order of 99% accuracy. It is possible to achieve greater accuracy, if high precision transducers are used, or if the transducers are calibrated. The parameters of the error model would be appropriately chosen in such cases.

Required accuracy of synchronization

State Estimation

In considering the synchronization accuracy required to produce phasors for static state estimation, it must be recognized that the estimates of angles produced by the conventional estimators (without phasor measurements) are accurate to tenths of a degree. Such accuracy may be required to determine the flow on a short, high-voltage line, and is expected by current standards in state estimation literature. If an estimator using only phasor measurements is developed, then synchronization

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accuracies of tenths of a degree will be required in order to match existing systems. It would seem that the uses of a dynamic estimate are sufficiently different from those of the static estimate, so that lower accuracy of synchronization in dynamic estimation could be acceptable.

Stability Monitoring and Control

If synchronized phasor measurements are used to track the power system state in an attempt to predict instability for out-of-step relaying [4] or control of transient swings, the accuracy of synchronization must be comparable to that of a dynamic estimator. That is, measurement accuracies of a tenth of a degree are more than sufficient and accuracies of a degree would be adequate in many situations.

Fault Location

Fault location may be based upon phasor measurements, or on travelling wave concepts. If phasor measurements are used, it is possible to make the best possible estimates of fault location from each end, and then average the two results to obtain the double-ended fault location result. If this procedure is followed, it is not necessary to have highly precise synchronization between the measurements of the two ends. Alternatively, one may solve a set of simulataneous equations using measurements from both ends. If the latter procedure is used, a 0.1° accuracy of synchronization should be adequate, as this is usually the accuracy limit of a transducer. This translates into a 5 μsec precision requirement for synchronization.

If travelling waves are used for fault location, an accuracy of fault location to within 1000 ft. would be possible if synchronization to 1μsec is achieved. Of course, the dispersion phenomena on ground modes would make the task somewhat more difficult, and a greater precision - say of 0.5μsec - may be needed to achieve a 1000 ft. estimation accuracy. For higher accuracies, a correspondingly increased precision would be required. Of course, for such specialized applications, special transducers with wide bandwidth would also be required.

Adaptive Relaying

It has been recognized that many relay settings are often compromise settings, which are reasonable for many alternative conditions that may exist on a power system, but not the best settings for any one condition. Thus, many relay settings are compromises in terms of sensitivity or speed of response for ***every*** fault, in order that they be adequate for ***all*** faults. A definition of adaptive relaying, which embodies this idea, is as follows [5], *"Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection functions automatically in order to make them more attuned to prevailing power system conditions."*

Adaptive relaying usually calls for more information about the power system in each protection task. Since this information must correspond to the state of the power system, it must be a snap-shot or simultaneous measurement set. Clearly, synchronized measurements are a necessity in many adaptive relaying applications. Most adaptive relaying tasks would be served by a synchronization accuracy of about 0.1°.

Stability of analog pre-filters

Each input channel must be equipped with an anti-aliasing filter to preclude errors in the captured signal. The input filter will introduce an equivalent phase shift at 60 Hz which can be taken into account in subsequent analysis if the phase shift is known and if it is not time varying.

This problem can be illustrated with a first order RC low pass filter. Assume that the input is being sampled at 1200 Hz and the filter has a cutoff frequency of 480 Hz (somewhat below the Nyquist frequency of 600 Hz). This results in a phase shift of 7 degrees at 60 Hz. Even in the case where a highly stable resistor/capacitor combination with 100 PPM/°C drift is used, this would result in a change in phase through the filter of 0.014° for a change in temperature of 20°C. This is equivalent to a sampling error of 0.6 μseconds. The problem is exacerbated if the required high order filters are used. A tenth order filter would result in a sampling jitter on the order of 6 μseconds.

It is instructive to calculate the cutoff frequency required if a phase shift of less than one degree is required at 60 Hz. For the simplest case of a first order RC filter, the cutoff would be approximately 3kHz, implying a required sampling rate in excess of 7kHz. Again, the required cutoff frequency and resulting sampling rate is even greater in the case of higher order filters. In fact, if one assumes a 100 PPM drift in the phase angle, then a minimum sampling rate of 5kHz must be used if a 10 pole filter is employed, and an equivalent sampling error of 1 μsecond is desired over a 20°C temperature range.

The problem can be resolved however, using the recommended approach of high frequency sampling which generates large volumes of data and subsequently reducing data content by digital filtering techniques. Digital filters are not prone to variations in component values resulting from manufacturing tolerances or temperature. It should be emphasized that this approach does not eliminate the introduction of phase shifts in the input channels but allows calculation of a phase difference which is constant.

3. SOURCES OF SYNCHRONIZING SIGNALS

Time synchronizing signals can be broadcast by a variety of methods, each with its own advantages and limitations. As shown below, in general there are five types of amplitude-modulated (AM) signal methods, and two satellite methods. (see Table 1) In some cases, Central site retransmission to the remote locations may be desireable. Where the user has some control over the circuit media, various results are obtainable. (See Appendix 1) For example:

<u>Microwave:</u> Analog-Phase shift of modulated CW signal. Resolution of 1 μs, w/o fade. Digital-Packet reconstruction uncertainty of 70 μs.
<u>Fiber Optics:</u> Neglecting repeater effects, one can expect 0.5 μs uncertainty.

Also, the user should be aware that inaccuracies can be further introduced by the front-end filters on equipment. For example, directly at the CT/VT, the signals may be faithfully reproduced. Cable burdens and impedances may modify the phase delay; equipment filters may add another 20-60 μs per input.

Current and Voltage Transformer, and Recorder Response

Consideration should be given to the response of the source of typical inputs to be recorded. Normally when data is recorded for analysis, it is to review fault, transient, or steady state conditions with time accuracies of 1 to 10 mseconds between recorders. If tighter specifications are placed on the synchronization between recorders (1-5 μseconds) the actual input signals derived from CTs and VTs as well as how the recording systems capture this data must be fully understood. Refer to ANSI IEEE C57.13-1978 "IEEE Standard Requirements for Instrument Transforermers" for additional information on CT/VT accuracies and tables of standard burdens during accuracy testing. Additionally, ANSI C93.2-1976 "Requirements for Power-Line Coupling Capapcitor Voltage Transformers" provides similar data references for CCVTs.

Studies have shown that typical EHV CTs and VTs are capable of faithfully reproducing the primary quantities when loaded with a resistive burden at the device under test. Unfortunately, the normal installations require long runs of various lengths of different types of cables to get the input signal to the station control house. There, the burdens change and in many cases can change drastically and become either inductive or capacitive, depending on the types and numbers of protective relays, meters, and other measuring devices.

Burden changes will affect the measurements of the apparent output and can cause differences between the primary and measured values and waveforms on the secondary of the transformer. These inputs are then applied to a recording or measurement device, and it's response to these signals must be considered. The calibration stability, including temperature variations, of modern recording systems should be within 1%

Table 1

3.1 SOURCES OF SYNCHRONIZING SIGNALS

Type †	Transmit Freq.	Time code	Suceptibility	Primary Use	Resol.	Cost in K$	Location
AM							
WWV	2.5-20 MHz	BCD/1PPS/ IRIG	Fading, Propagation	Time	5ms	1	US
WWVB	60kHz c shift	BCD/IRIG	Atm noise	Freq, time	2ms	2+	US/ Canada
OMEGA	10-14 kHz	IRIG,BCD,1PPS		Navigation	1-10ms	3	Worldwide
MSFDCF	60 kHz c shift	IRIG-B,TTL	Noise	Time	1-10ms	3	W. Europe
Loran-C	100 kHz	1PPS	PLC, Noise	Navigation	20μs*	3-10	N Hemis.
SATELLITE							
GOES	468 MHZ	IRIG, TTL	Loss of sat Ch. 14 interference	Weather, Time	100μs	4	W Hemis.
GPS	1575.42 MHz	IRIG,1PPS RS-232(ASCII)	lock on 3-4 satellites	Time, Position	0.2-0.5μs	5-15	Worldwide

† Note: See Appendix I for explantion of acronyms.

* Note: Requires 2nd time source input.

over a 12 month period assuming stable burdens on the input circuits.

Isolation circuits on the front end are used to condition the input signals and will introduce certain phase delays. These delays vary on an individual input basis and can approach 20 μseconds in some cases. Input filtering that may be used to tune the frequency response of the measuring device may also add additional delays to the input signal. These delays could be in the 40 to 60 μsecond range for some inputs. Again, the delays may vary on a "per input" basis, and vary from one type of equipment to the next.

Maintaining 1 μsecond synchronization between different measuring devices assumes the input to these devices occurs within less than the synchronizing resolution. While this may well be the case for the primary quantities under analysis, it may not be the case by the time these primary quantities are converted to secondary values and actually recorded.

The user must establish the obtainable parameters based on the final measurement device capabilities. Varying signal and phase delays introduced by the signal conditioning equipment must be considered in establishing initial specifications on the synchronizing of many remote devices.

4. SYNCHRONIZED MEASUREMENTS

Functional Diagram

Figure 1 shows a typical layout for a relaying or a measurement system processor in a substation. Simultaneous sampling of input variables is commonly used, but sequential sampling could also be used with software correction for sample delays. The relays themselves will likely use the phasor and the line frequency information. Techniques for computing phasors and frequency from sampled data have been previously reported. [6,7,8] Fourier transform technique, and its use for calculating phasors and frequency are summarized below.

Fourier Transform and Phasor Computation

A sinusoidal quantity

$$x(t) = X_m \cos(\omega t + \varphi) \qquad (1)$$

has a phasor representation

$$X = \frac{X_m}{\sqrt{2}} \varepsilon^{j\varphi} \qquad (2)$$

Although the concept of a phasor is defined for a pure sinusoid, it can be used in the presence of transient components by stipulating that the phasor represent the fundamental frequency component of a waveform observed over a finite duration (observation window). In case of sampled data x_k, obtained by sampling the signal x(t) at $t=k\tau$, where τ is the sampling interval, the phasor X is given by

$$X = \frac{1}{\sqrt{2}} \frac{2}{N} (X_c - jX_s) \qquad (3)$$

where

$$X_c = \sum_{k=1}^{N} x_k \cos k\theta, \text{ and } X_s = \sum_{k=1}^{N} x_k \sin k\theta \qquad (4)$$

and N is the number of samples in one period of the nominal power system frequency. The sampling interval τ corresponds to the sampling angle θ

$$\theta = \frac{2\pi}{N} = 2\pi f_0 \tau \qquad (5)$$

where f_0 is the nominal power system frequency. Equation (3) represents a phasor measurement performed by the Discrete Fourier Transform (DFT) of one period data window.

The DFT procedure described above provides the phasor with a very modest amount of computation. By selecting an appropriate sampling interval, the computations can be made particularly simple. [9] A sampling rate of 12 times the nominal power system frequency (720 Hz for a 60 Hz power system) has been found to be quite advantageous in many relaying and measurement functions. As time progresses, and a fixed-length data window is used, equation (3) represents a non-recursive DFT calculation. Essentially, calculation during each data window is performed in an identical fashion: equation (3) is repeated in its entirity. This is somewhat wasteful of computing power, and a more efficient algorithm results if a recursive form of equation (3) is used.

Let X^r be the phasor corresponding to the data set $x\,\{k=r,r+1,\cdots,N+r-1\}$, and let a new data sample be obtained to produce a new data set $x\,\{k=r+1,r+2,\cdots,N+r\}$. The phasor corresponding to the new data window X(r+1) is then given by

$$X^{r+1} = X^r + \frac{1}{\sqrt{2}} \frac{2}{N} (x_{N+r} - x_r) \varepsilon^{-jr\theta} \qquad (6)$$

The difference between the recursive and non-recursive phasor calculations is illustrated in Figure 2. The non-recursive phasor rotates in counter-clockwise direction by an angle θ as the sample time advances, whereas the recursive phasor remains stationary. More importantly, the computations implied in the recursive formula (6) involve only two samples: x(N+r) and x(r), whereas the non-recursive formula (3) implies computations with N samples. All phasor measurement systems currently in service use the recursive form of phasor calculations.

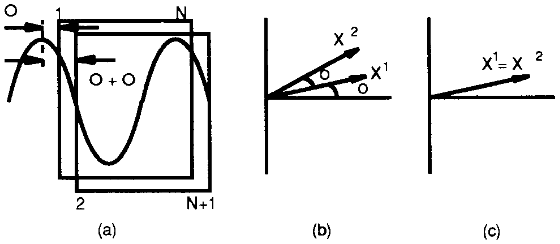

Figure 2. Phasors from sampled data. (a) Moving window. (b) Non-recursive, and (c) Recursive computation.

There are now many Digital Signal Processing (DSP) chips which are custom built to implement the FFT (Fast Fourier Transform) on line. A common form of the FFT requires that there be 2^n samples in the data window, viz. 8,16,32 etc. whereas the DFT based algorithms of the previous sections can be used for any number of samples in a window. The FFT computes all harmonics up to the Nyquist limit. If, for example, the window is taken to be a 60 Hz. cycle, then 32 samples per cycle would allow calculation of up to the 15th harmonic for each variable. It is unlikely that any relay application will require higher harmonics than this. Presently available DSP's can calculate an FFT for ten input variables in a sampling interval of (1/32x60) second.

If we concentrate on the fundamental components coming from, say, one set of three-phase variables as shown in the functional diagram of Figure 1, the microprocessor can calculate the sequence components and make them available for use in a number of functions internal to the station. If the sampling frequency and the frequency of the measurands are not synchronously related, then there will be errors in the phasor calculations and the positive sequence voltage will not remain stationary. The latter fact is used to measure the line frequency and in some relays may be used to adjust the sampling frequency to make the phasor remain stationary (phase locked loop). The errors in the phasors are likely to be small provided the frequency variation is small. By combining the three phase voltages any oscillating component in the individual phase voltage phasors tends to cancel out [9]. The window length of one 60Hz cycle is about optimum for relaying purposes but consecutive phasor estimates could be averaged over several cycles in the master computer if higher precision is required for metering or control purposes, and a slower response is acceptable.

Whether one uses the recursive DFT, or the angle-compensated FFT described in the previous paragraphs, it will lead to the measurement of a stationary phasor at steady state network conditions if the sampling rate is fixed and corresponds precisely to N times the network frequency.

If the network frequency undergoes a change characterized by a frequency offset Δf, it has been shown in [10] that for a small Δf the positive sequence phasor will undergo the following change, at each r'th sampling interval,

$$X^r(60+\Delta f) = Xe^{-j(N-1)\pi\Delta f\Delta t}\left\{\frac{\sin N\Delta f\Delta t}{N \sin \Delta f\Delta t}\right\}e^{j2\pi r\Delta f\Delta t} \qquad (7)$$

The first fraction in equation (7) shows that the magnitude of a phasor is in error by an attenuation factor, as the frequency of the power supply deviates from the nominal value. A frequency difference of 5 Hz produces an attenuation of 1.2%. For all practical purposes, this effect can be neglected for normal frequency excursions. The second term in equation (7) represents a phase shift of constant magnitude. The last term in equation (7) depends upon the sample number. The rate of change of the local phasor angle will then be provided by

$$\frac{d\psi}{dt} = 2\pi\Delta f \qquad (8)$$

Phase, frequency, and amplitude measurements by demodulation

These algorithms apply quadrature demodulation, which consists in multiplying the signal under analysis by a complex exponential of known frequency f_0:

$$x(t) \rightarrow X(t) = x(t)\, e^{-j2\pi f_0 t} \qquad (9)$$

Substituting x(t) by its expression in equation (1) provides

$$X(t) = \frac{X_m(t)}{2}\left[e^{j\phi(t)} + e^{-j[\phi(t) + 4\pi f_0 t]}\right] \qquad (10)$$

Filtering the interference term at frequency $2f_0$ gives:

$$W(t) = X_m(t)\, e^{j\varphi(t)} \qquad (11)$$

The phasor of the original signal, x(t), is then obtained by extracting the modulus and phase from the complex expression W(t). The signal is demodulated first, then filtered by a fixed filter to remove harmonics and by an adaptative filter to remove the image frequency. Frequency is calculated by determining the rate of phasor rotation as in equation (8) above.

Once the complex signal has been filtered, its modulus and phase must be extracted. This means transforming the Cartesian coordinates into polar coordinates. Analytically, we can write:

$$X_m = \sqrt{(W_r^2 + W_i^2)}, \text{ and } \varphi = \arc\tan\frac{W_i}{W_r} \qquad (12)$$

Reference [11] describes efficient practical techniques for obtaining the magnitude and phase angle from the real and imaginary components.

Measurements Based on Zero-Crossing of Waveforms

Recent techniques for precise zero-crossing detection developed for use in HVDC modulation systems [18], offer the potential for the use of zero crossing of waveforms for advanced techniques for measuring power system quantities. Advances in precise zero-crossing detection make use of phase locked loop techniques, and stable, low frequency filtering to reduce synchronous and non-synchronous harmonics. These advances have been shown to produce highly accurate zero-crossing measurements for use in dc modulation schemes for improved power system stability.

One of the methods [12] to measure the phase angle between two buses consisted of generating two synchronized 30 Hz reference waveforms at two distant stations and to measure at each station the delay between the zero-crossing of the reference and the voltage waveform. Phase difference was then computed in a straightforward fashion by sending the measured delays to a central point.

Other techniques of absolute phase measurement

It should be borne in mind that it is not necessary to have external sources of synchronization to achieve coherent phasor measurement. At least two methods have been used to implement line differential relaying using alternative synchronization techniques. The first method [13] is based upon directly measuring the time difference between the sampling instants at different stations, and then converting this delay to a phase angle correction factor. The second method is used extensively in Japan [14] and consists in synchronizing two clocks at the extremities of a line by sending synchronizing signals, and adjusting them locally to compensate for the propagation delays in the synchronizing signals.

5. TRANSMISSION OF SYNCHRONIZED MEASUREMENTS

It is anticipated that communication requirements for phase angle data will span a wide spectrum of data types, data rates, and communication media. Nonetheless, a need exists for the various utilities generating this data to be able to share and interpret it among themselves either in real time or off-line. In order to facilitate this task, a flexible data format that can accommodate all users, is proposed here. A discussion of related issues will be found in Appendix II.

Recommended Format for Communication of Phasor Data

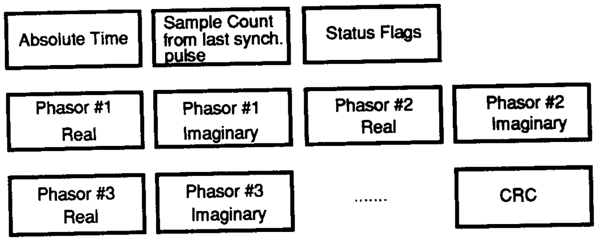

Figure 3. Format for real-time phasor data.

The time stamp, consisting of the the day, hour, minute, second, and the sample number of the first sample used in the phasor calculation (varying between 1-720 for a sampling frequency of 720 Hz), constitutes the unique synchronization parameter of the phasor on the Universal Time base.

6. RELIABILITY OF PHASOR MEASUREMENT SYSTEMS

Reliability is composed of dependability and security, i.e., a reliable measurement system must work well when called upon, but not misoperate - especially at critical times. Just how reliable the system must be depends upon the application. For electric utilities, measurement applications are usually classified (in order of increasing reliability needs) as monitoring, control, and protection systems. Inasmuch as protection applications demand the most reliability, the following discussion of potential reliability problems and solutions will assume that a protection application is being attempted using phasor measurements.

Problems with phasor measurement systems

These problems include clock system failures and inaccuracies, cabling problems, instrument transformer problems, filter instabilities and inaccuracies, calibration errors, component failures, software errors, etc. Of all these, the reliability problems which are the most unique to phasor measurement are ***clock reliability, software problems associated with absolute angle measurement, and message delivery errors.*** The others are potential problems shared by most digital relaying systems and therefore will not be discussed here.

Clock Reliability: The choice and design of the synchronizing signal (usually a clock receiver) are crucial to the success of any phase angle oriented protection system. The requirements for accuracy are set forth earlier in this paper. With regard to reliability, only two of the systems surveyed have the capability to drive protection applications: GPS and dedicated fiber optic channel systems. Since a fiber optic system is very difficult to justify for this application alone, this leaves the GPS system as the only practical system now available for synchronization in protection applications. The GPS system's reliability is nearly ideal because:

(1) It is maintained by the US military for defense-critical purposes and is steadily building a massive civilian clientele, so it assuredly will be well maintained [15];

(2) It has superb built-in redundancy because of the "many-satellite" concept, in-orbit spares, and back-up atomic clocks on each satellite;

(3) It is ubiquitous from any point on the earth where there could be a power system;

(4) With its sub-microsecond resolution it is well within the accuracy requirements of protective applications and therefore will not require frequent receiver calibrations;

(5) The market is now driving the price of each receiver down and the vendor availability up, so future product availability is assured;

(6) Enough GPS system experience has been obtained to verify that it is performing well within its specifications; and

(7) The cluster of satellites is now nearly complete.

Angle-oriented Software Problems: In a phase-angle oriented system the synchronizing signal (or "zero reference phasor") is asynchronous with the power system voltage. Therefore any power system voltage phasor is nearly always rotating with respect to this reference -- sometimes clockwise, sometimes counter clockwise. This means that the "absolute angle" of a voltage phasor with respect to the reference phasor is not bounded, so very large angle measurements can result unless the designer imposes a "rollover" limit (such as 360°). Such a limit imposes algorithmic challenges to the software engineer because when a voltage phasor is "teetering" on the 0°-360° border, the angle message can undergo rapid and violent changes which are not noise and must be handled by any reasonability-checking algorithm as a normal and correct occurrence. This complicates the real-time software and can lead to errors if the algorithms are not well conceived and tested.

Message Transmission Errors: Protection oriented phasor measurement requires nearly constant data transmission -- often across long distances. In monitoring applications this might not be a problem because time for retransmission or delayed retrieval of messages can be allowed. But for protection applications the communication must be done in real time (typically 30 messages per second), and this is often the "Achilles' heel" of a phase angle measurement system as noise and other errors often creep into the communication path along the way.

Inasmuch as there is usually no time to retransmit the message for relaying applications, there are only two remaining recourses for data which are corrupted by channel noise: ***error and reasonability checking***.

- In ***error checking***, options range from simple parity checking to sophisticated "CRC" or "BCH" schemes, sometimes with data reconstruction. However, the goal here is usually not to detect errors and reconstruct the data. Rather it is to detect errors and mark the corresponding message as "unreliable." On one such experimental phasor measurement system [16] with channel failures logged during 1989, channel errors (including modems) were reported as about 50 carrier losses, hundreds of receive buffer overflows, and 10,000 parity errors per month per channel. These statistics were for a utility-owned microwave system with dedicated phasor channels operated at 9600 bps. For each of these errors the system was programmed to mark the corresponding message as unreliable. Also, on this system it was found that simple parity checking was inadequate, and that CRC error checking would be a desirable upgrade.
- In ***reasonability checking***, the receiving system must compensate for the errors which "leak" around the error checking "filter." Here there are no established algorithms or standards. The programmer must simply look at the bounds of reasonability for the incoming data in all conceivable contexts and provide appropriate algorithmic contingencies for data which fall outside these bounds - a task which is easier said than done.

Message Misalignment: With synchronized sampling, measurement messages must come to a receiving system tagged with the time of their occurrence unless that time can be assumed because time ambiguity is impossible. With the high data rates required for protection applications, time ambiguity must be considered as a possibility. Therefore, at least rudimentary message time tagging is essential.

This poses an interesting problem: What if the time tags don't agree for a given sample time? Such "message misalignment" could be caused by unforeseen path delays, computational problems at the source of measurement, or clock receiver problems. One way to solve this problem is to assume that a given time tag is correct and "disqualify" (another form of reasonability checking) all channels without the qualified time tag number. The assumption of which tag number is correct could be driven by real time channel voting (majority wins) or a local reference tag number.

Other Reliability Considerations: After the messages are received and qualified as reliable, the reliability issue of the system then moves up a level to scheme reliability. The system designer needs to determine which phasors to use and how. Such decisions often rely on the ability of a power system planner to foresee possible power system problems for which the phasor measurement system could provide a remedy. Here reliability depends on the skill and experience of the planning engineer. In this arena an added measure of redundancy could be obtained by using multiple measurement locations to confirm the presence of certain system instabilities.

7. SUMMARY AND CONCLUSIONS

(1) It is recognized that synchronized measurement of power system quantities is now possible in practical economic hardware systems.

(2) Of the many sources of synchronizing signals available at present, the one showing most promise for power system use is the one using GPS satellite transmissions.

(3) Relays, and other substation systems, are capable of using these synchronizing signals, and providing phasors of voltages and currents, which can be used in several monitoring, protection, and control functions in a power system.

(4) The paper presents a set of recommendations for various timing signals and data structures, which have been found to be useful in such systems currently being evaluated. These recommendations could form the basis of an interim standard, and eventually lead to standardization by an appropriate committee.

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APPENDIX I

TECHNIQUES OF SAMPLING CLOCK SYNCHRONIZATION

AM RADIO

WWV: The most popular stations in North America are radio stations WWV, WWVB, and WWVH (Colorado and Hawaii, respectively). These systems are very well documented and commercial receivers and synchronizing systems are available. A timing system could be synchronized to ± 100 μs , assuming a constant and predictable propagation delay. This latter assumption is far from being easily reachable, and for this reason, time synchronizing resolution can reach a few milliseconds in practice. Receiving equipment, which can be used for time synchronization purposes, is available for less than $1000.

WWVB: Radio station WWVB (Fort Collins, CO) broadcasts on a continuous basis time information by carrier-level-shift of the 60 kHz carrier. Time code is BCD and is synchronized with the carrier. The main advantage of WWVB is that propagation delays remain relatively constant and are more predictable. Time information is available to ± 50 μs, but this figure can jump to a few milliseconds due to frequent conditions of noise and signal amplitude fluctuations. It turns out that WWVB has been a reference used more for power network frequency calibration and measurement than for clock synchronization.

Equipment costs, depending upon options selected, would start at approximately $2000.

Loran-C Timing and Navigation System: Loran C [17] was conceived primarily as a long-range precision navigation system providing 150 meter resolution to users at ranges in excess of 1800 km, and is very well documented. Within that framework, it can provide precise time and frequency dissemination. Cesium beam frequency standards are installed in each Loran-C station and the frequency is set to the universal time coordinated (UTC). The pulsed format allows the recovery of time information without providing a specific time scale. A Loran C system comprises one master and two or more secondary station. For time synchronization purposes, reception of a single master's signal is sufficient. A 1PPS reference frequency, UTC synchronized, can be generated with a Loran-C signal, taking into account the propagation delay between the Loran-C station and the actual receiver location.

A 1 μs time resolution can be achieved using the groundwave mode of propagation, but this resolution deteriorates to ± 20 μs, using sky waves. Commercial receivers and synchronizing equipment is available, but some difficulties have been encountered in substations with power line carriers (PLC) operating in the vicinity of 100 khz. Also, corona effect has been found to introduce adverse interference in the same frequency range. [17]

An additional source of time input must be known to within approximately 10 mseconds to fully realize high accuracy. Inputs can come from other time receiver sources such as WWV or WWVB. The Loran-C system can require more active operator interface for good results. Propagation delays in both the transmission path and equipment must be accurately known to realize absolute time transfer. Performance may be degraded by installation in an electric transmission EHV station due to interference from switching, corona, and other transmitters near the 100kHz frequency. Equipment costs vary widely ($3000-$10,000) considering the options, features, and degree of accuracy desired. External equipment normally would be synchronized via a 1PPS output from the Loran-C receiver.

Microwave Transmission Systems: In many applications, a central site may be desired to contain the primary frequency and time source, with transmission to many remote sites. A time code signal output from the central site may then be transmitted via microwave facilities to the receiving equipment that requires synchronizing. Unless special transmission modifications are made, the best resolution of synchronizing pulses would approach 1 msecond using microwave facilities.

Analog microwave: By utilizing direct phase shift modulation of a CW signal on the baseband, it is possible to synchronize oscillators to an accuracy of ± 1 μsecond over large geographic areas. The baseband requirements are for 150 kHz of spectrum that is not demodulated at each drop, but is passed directly from receiver to transmitter.

Digital microwave: Due to the method of gathering the data into packets, the digital microwave introduces time delays from one packet to the next which can be as great as 70 μseconds. The throughput of the digital system is very high, but there is no attempt to maintain the relative time between packets. Digital microwave cannot maintain timing accuracy to less than ± 70 μseconds per hop, due the way data is transmitted in packets. If the packets are not demodulated at a drop, it may be possible to maintain the 70 μsecond resolution over several hops. This system is custom designed and built, and the microwave it is used on was specified to have one supergroup above the normal baseband available for this purpose. The terminal equipment is approximately $5000 per installation. The present usage of the terminal equipment is to time tag pulses. There is no provision for generating 1PPS or other timing signals. The oscillator output could be interfaced to produce the required outputs for relaying and control.

Fiber Optic Transmission Systems: Transferring time synchronizing signals via fiber links means is similar to the above discussed microwave system. Basic timing equipment is located at the central site, and remote sites would remain unchanged. The fiber would replace the microwave as the method of transmission. Improvements result due to the elimination of signal distortion and jitter introduced by the microwave single sideband transmitters and pilot frequency phase lock errors. More stable output signals result, and higher reliability has been demonstrated. Time synchronization resolutions of 0.5 mseconds are easily obtainable via fiber transmission methods.

It should be noted that leased or owned wire line circuits could also be used in place of microwave or fiber systems. Generally, the user has no control over long distance circuits, while routing changes, costs, and reliability, combine to make this method less than desirable.

GOES Satellites

The Geostationary Operational Environmental Satellite (GOES) system consists of two satellites in geostationary orbit with occasional in-orbit spares. The two satellites orbit in nearly fixed locations over the equator at 75° west and 135° west longitude for "GOES-East" and "GOES-West" satellites, respectively. Their primary mission is hurricane monitoring for the Western Hemisphere with "time transfer" as a secondary mission.

The GOES time signal is produced by the U.S. Naval Observatory on Wallops Island, Virginia, by atomic clocks which are UTC-traceable. The signal is then advanced by about 260 mseconds and sent to the satellites where the time signal is then immediately rebroadcast to the Western Hemisphere such that it arrives at the earth's surface at about UTC time. If a GOES receiver's location is programmed and the receiver decodes the satellite's position from the time signal, a GOES receiver can resolve the time to within 25 μseconds of UTC time for a brief period. However, a more realistic expectation of accuracy for a well maintained and calibrated quality receiver is 100 μseconds year round. With this in mind the typical GOES system time signal user should not rely on the clock receiver for an accuracy of better than one msecond (with infrequent calibrations).

Whether or not the GOES system can be used to synchronize relay/control applications also depends on reliability issues. Things which can cause further degradation of the above-described performance are satellite relocation, TV/radio interference, equinox blackout, diurnal shifts, and solar interference. Thus, even though the clock receivers are affordable at about $4,000, these problems make the GOES system generally inadequate for phasor measurements.

Conventional transmission system by geostationary satellite

Another system using geostationary satellites as sources of synchronizing signals has been proposed, and is described more fully in reference [18]. A timing pulse is transmitted via satellite from a Hub to various receiving stations (VSAT), which can correct for the spatial dispersal effects, and for the displacements of the satellite in tits positioning window. Through this technique, simultaneity of within 15μsec can be achieved over distances of the order of 1000 km. Fall-back schemes for loss of the transmitted timing pulse could be provided for. Certain additional corrective measures can be implemented, which can further improve synchronization accuracy to within a few microseconds.

GPS (Global Positioning Systems) Satellite

This is a new technology and the timing application for the power industry is an unusual application for the major manufacturers. One of the previous major receiver manufacturers has made the decision to leave the business. The potential market of the power industry is now large and the manufacturers are aware of our needs and have made significant advances to be competitive in the last four years. This is a military system and the military has been reluctant to provide this service to civilian users. The reluctance has decreased markedly.

(1) **Accuracy achievable.** The basic accuracy of the system while a satellite is in view is ±0.2 μseconds. These devices presently attain an accuracy of ±0.5 μsecond, although technical problems with some units can cause excursions of up to 50 μseconds. The manufacturers are working to overcome these problems and it is believed that the units will provide continuous operation with a maximum time error of ±0.5 μseconds.

(2) **Signal availability.** Reception of the timing signal from one satellite will allow synchronization of the timing signal. There are 24 satellites planned for the complete system which will give four satellites continuously in view at any location in the world. Locations in deep valleys will limit availability.

Presently there is global 24-hour continuous coverage of at least one satellite.

(3) **Relative cost and trends.** The timing systems were priced at $24,000 to $250,000 in 1986. An adequate system for the power industry was in the upper end of the cost range. The manufacturers were made aware of the power industry requirements and design changes were made to the low end units so they were generally acceptable. With the addition of more satellites, the requirements for Rubidium oscillators to maintain timing accuracy for six hours while satellites were out of view was eliminated and reduced the price further. Competition and increased production has led to the least expensive units that are satisfactory for power industry application to $5,000-15,000.

(4) **Outputs from these devices.** There are two required, and several optional outputs. The first is a precise digital output with 50 nsecond risetime that occurs once per second. The second is an ASCII message transmitted at 9600 baud that identifies the year, day, hour, minute and second of the digital output. The output pulse is non-standard between manufacturers of these devices, and the timing edge can be the rising or the falling one, depending on the manufacturer. The ASCII string is unique to each manufacturer and there is no standard as to the preceding or following digital pulse being identified. The manufacturers have been flexible in providing other outputs requested for specialized uses. Examples are one pulse every 100 seconds synchronized on the hour, IRIG-B, and a 720 Hz pulse train synchronized to the one second pulses. In general, all manufacturers have been willing to provide custom inputs and outputs. The following are suggested specifications which would meet the needs of synchronized power system measurements.

TTL outputs: A 20 ± 5 μsecond positive going pulse with a rise time of 50 nseconds or less. The rising edge of the pulse shall be the timing mark . The primary output shall be a pulse that occurs on the second transition of UTC time. Additional TTL outputs shall be coincident with the rising edge of the one second pulse to an accuracy of ± 50 nseconds.

- A pulse train at a user selectable rate, such as 720 pulses per second.
- A single pulse every 100 seconds that occurs on the even hour

ASCII outputs: The outputs shall conform to RS-232 asynchronous format. The message to contain:

(a) TIME STAMP: The time of the preceding one second pulse shall be transmitted in the following sequence: Year, day of year, hour (24 hour day), minute and second. Transmitted at a user selectable rate.

(b) Additional ASCII data that the manufacturer deems necessary to maintain and troubleshoot his system. Transmission rate as determined by manufacturer. For remote communication, the transmission rate should be settable between 240 and 9600 BPS.

Alternative outputs may be desirable for certain other substation functions. For example, it may be useful to have an over-wire IRIG-B signal, a TTL input/output for synchronizing existing equipment, standard RS-232 input for control purposes, fiber optic IRIG-B output, etc.

APPENDIX II

HEADER FILE FOR CONFIGURATION DATA

The basic requirements considered in establishing a generalized communication/file format for Phase Angle Data are as follows:

1. Only measured and computed data should be transmitted in real time. Informational data should be transmitted only on request.
2. All data must be traceable to an absolute time reference.
3. The data transmitted should be in the most compact form possible to fit the available channel bandwidth. However, consideration must be given to optimization of host computer hardware and software.
4. A wide range of basic sampling rates as well as data transmission rates must be supported.
5. The format should support bi-directional real time control functions in a full duplex communication mode.
6. A mechanism to transmit bi-directional status information should be provided.
7. Data integrity checks and an option for re-transmission should be provided.
8. The amount and type of data transmitted over a sample interval must be user definable to adjust to the wide range of data requirements.

The recommended format for real-time phasor data transmission was given in section 5 of the paper. Header and configuration files are to be used to provide supplemental information, and is not intended for real-time high speed transmissions. The Header file, to be retained at the PMU, and to be available for remote access should contain data which helps identify the source and nature of the data being provided by the PMU. The information contained in this file should include:

1. PMU identification.
2. Sampling rate used by the PMU.
3. Rate of transmission of real-time data.
4. Instrument transformer ratios.
5. Data acquisition system conversion factors for analog signals.
6. Accuracy characterization of the timing source.
7. Settings for event triggers used to capture and save data.
8. Miscellaneous diagnostic and control information.

Discussion

Carson W. Taylor, Bonneville Power Administration, Portland Oregon: I commend the Working Group for a very valuable paper. With regard to the section "other techniques of absolute phase measurements," I will describe additional methods that approximate phasor measurements and that may be effective (i.e, cost effective) in some applications.

R-Rdot relay. The BPA-developed R-Rdot out of step relay [A] determines out of step tripping needs based on an apparent resistance, rate of change of apparent resistance phase plane switching line. Apparent impedance could be used in place of apparent resistance. The reference shows that the R, dR/dt phase plane is similar to the $\delta_1 - \delta_2$, $\omega_1 - \omega_2$ phase plane, where the angles and speeds are of equivalent generation at each end of an intertie. The local apparent resistance based measurement has the advantage of inherent filtering of local modes.

The relay has operated successfully on the Pacific 500-kV intertie for about ten years.

Synthesized angles. There have been proposals to synthesize internal system angles based on local measurements near an electrical center. The angles could be used for out of step relaying, or for control [B].

Transient excitation boosting based on angle. Although not an absolute angle measurement, Ontario Hydro has effectively used an angle based method to improve interarea transient stability [C]. Rotor angle increase is obtained by integration of speed to provide a discontinuous voltage regulator input. This control is used when both local and interarea oscillations are present, and where the back swing of the local mode would otherwise bring the excitation off limit before the true peak of the angular swing.

Reference:

A. J. M. Haner, T. D. Laughlin, and C. W. Taylor, "Experience with the R-Rdot out-of-step relay," *IEEE Transactions on Power Delivery*, Vol. PWRD-1, No. 2, pp. 35–39, April 1986.

B. E. Lerch, D. Povh, and L. Xu, "Advanced SVC Control for Damping Power System Oscillations," *IEEE Transactions on Power Systems*, Vol. 6, No. 2, pp. 524–535, May 1991.

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R. E. Wilson (University of Wyoming, Laramie, WY): Members of Working Group H-7 of the Relaying Channels Subcommittee of the Power Systems Relaying Committee have produced an excellent summary of the issues involved in synchronized sampling and phasor measurements. This paper covers a wide range of technical issues in a complete yet compact manner and was a pleasure to read. Following are a few minor comments, one question, and issues for consideration by the committee.

Table 1, Sources of Synchronizing Signals, lists the primary use of the Global Positioning System (GPS) as time and position. GPS is a Department of Defense (DOD) system primarily designed to provide position and velocity information in three dimensions [1]. Precise timekeeping information is available because the GPS navigational system operates on a ranging principle. Ranging systems use the principle that distance equals rate times time and a subtle trick to recover timekeeping [2]. A GPS receiver-clock has to have four satellite transmitters in present or past view or have precisely known geodetic coordinates to solve for what is called "timing offset." Once these conditions are met, the receiver-clock can be precisely synchronized to GPS system time.

In Section 6, Reliability of Phasor Measurement System, the paper lists several advantages of the GPS system, but no disadvantages are listed. A possible disadvantage is that GPS is a military system. Pragmatically, the large number of civilian users in the aviation, surveying, and other industries are pushing DOD toward an official civilian use statement. Official Federal guarantees that the system will always be available for civilian use are being developed and promulgated in early 1993.

The 1992 Federal Radionavigation Plan (FRP) states the GPS Standard Positioning Service (SPS) can be interrupted until an Initial Operating Status (IOC) is achieved. IOC is expected in mid-1993. The FRP states, "Subsequent to IOC, any planned disruption of the SPS in peacetime will be subject to a minimum of 48-hour advance notice provided by the DOD...," [3]. Note the use of the word peacetime. The SPS timekeeping accuracy is listed as 340 nanoseconds with a 95% probability. The DOD is very reluctant to allow access to the higher precession Precise Position Service.

Presently GPS is operated with a deliberate decrease in positional and timekeeping accuracies. This policy is called Selective Availability (SA) [4]. The present level of SA decreases GPS timekeeping accuracy from roughly +/− 100 nanoseconds to the stated +/− 340 nanoseconds. Since the most accurate power system application is 1 us, SA is not of concern at this time. If needed, there are methods to partially circumvent the effects of SA [5].

The author of this discussion believes GPS services will be available to the power, aviation, and surveying communities. The power industry will need to continue to follow GPS civilian access issues and the level of timekeeping degradation caused by SA in the future.

Another possible synchronization source is the Global Orbiting Navigation Satellite System (GLONASS). GLONASS is a satellite based navigational system operated by the Commonwealth of Independent States (CIS), formerly the Union of Soviet Socialist Republics. The GPS and GLONASS systems both use a constellation of middle altitude satellites and are very similar [6, 7]. The power industry may never use the GLONASS system as a primary timekeeping service, but GLONASS could supplement the reliability of GPS.

Given some uncertainty in the navigation-timekeeping field, the author of this discussion recommends the following. Power system personnel should specify that the synchronization-timekeeping portion of their equipment be card-based. A typical GPS receiver card presently costs about $1,500–$3,000. This would allow the replacement of a GPS receiver card with a GPS-GLONASS card, or a card incorporating the global navigation system of the twenty-first century. Global navigation and timekeeping are rapidly becoming almost a utility. There are proposals for international control of navigation (hence, timekeeping) services [8]. Built-in equipment flexibility would protect large investments in software and substation wiring and answer some concerns of management.

In Appendix 1, Techniques of Sampling Clock Synchronization, the committee states synchronization limits on low-frequency radio station WWVB as +/− 100 microseconds (us), assuming a constant and predictable propagation delay. However, many commercially available receiver-clocks list accuracies of 1 ms. Except in northern Colorado near the transmitter, WWVB is hard to receive in a substation [9, 10].

The committee points states that WWVB has been used for the syntonization of power system frequency measurements as opposed to clock synchronizations. The older generation of "power system time-standards" and WWVB synchronized new equipments use WWVB for frequency measurements and clock synchronizations [11, 12]. The clock in the power system time standard must be synchronized to UTC (Universal Coordinated Time) to compute the difference between "power system time" and UTC.

The committee has provided a good summary of the LOng RAnge Navigation (LORAN-C) system. Is the committee aware of any successful use of automatic LORAN-C equipment in a substation? Burnett has reported unsuccessful attempts to receive LORAN-C in a substation [9].

Within the paragraph on LORAN-C, the committee gives the impression that there is only one version of UTC. There are many versions of UTC, such as the U.S. Naval Observatory UTC (USNO), or the National Institute of Standards and Technology, UTC (NIST). Over 70 nations contribute astronomical, stability, and accuracy information to the Bureau International des Poids et Mesures (BIPM) in Paris, France. BIPM coordinates UTC (BIPM), the actual world-wide standard. The power system researcher must be aware of possible sub-microsecond differences between the UTCs maintained by different national laboratories. On December 23, 1992, UTC (BIPM)-UTC (USNO) = 0.02 us, and UTC (BIPM)-UTC (NIST) = −0.31 us [13]. A related point is that raw GPS time differs from UTC (USNO) by several seconds because GPS time does not include leap seconds. Most receiver-clocks should automatically adjust for this difference.

In the paragraph on Microwave Transmission Systems, the committee states that unless special transmission modifications are made, the best timekeeping accuracy transfer is roughly 1 ms. Recent work has confirmed this [14]. Missout has achieved transfer accuracies of 40 us by modifying the form of the serial time code and using custom designed equipment [15].

In the discussion of the Geostationary Orbiting Environmental Satellite (GOES) system, the committee states that GOES timekeeping is provided by the U.S. Naval Observatory. The GOES system is operated by the National Oceanic and Atmospheric Administration (NOAA) while the timekeeping is maintained by NIST. NIST monitors the received time signal at Boulder, CO and steers timecode transmission from the NOAA up-link facility at Wallops Island, VA [16]. In February, 1993 there is only one fully usable satellite for timekeeping. The western GOES has run out of fuel for satellite maneuvers and is drifting. Its orbit is inclined at over 10 degrees to the earth's equator which produces an uncorrected error of roughly 10 ms peak-to-peak [17]. Replacement GOES satellites are scheduled for launch starting in April, 1994 [18].

The committee discusses the use of geosynchronous satellites for time transfer. An accuracy of 15 us was reported. Better accuracies can be achieved. In 1985 the Bonneville Power Administration funded a study by the Time and Frequency Division of the then National Bureau of Standards (now called NIST) on how best to provide the power industry with a microsecond time base [19]. One result of this study was the possibility of using commercial communications satellites to provide an Industrial Time Service (ITS) accurate to less than one us. Two way satellite techniques can improve the accuracy to sub-nanosecond levels [20].

In summary, Working Group H-7 is to be commended for producing a concise and readable report that will be useful to researchers and practicing engineers in the phasor measurement or timekeeping field.

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Manuscript received March 2, 1993.

A.G. **PHADKE**, (Chairman, WG H7 of the Power System Relaying Committee.):

The Working Group appreciates the discussions provided by Professor Wilson, and by Mr. Taylor. Professor Wilson has provided a great deal of pertinent information about the GPS system, and other sources of synchronization signals. The page limitation of a PES paper places severe limit on how much information can be included in a paper of this nature. The Working Group had to discard a great deal of information in order to bring the paper to within the seven page limit. There is no doubt that the additional information provided by Professor Wilson, and the list of references would be of interest to readers of our paper.

As pointed out by the discusser, if position information is to be acquired from the GPS system, at least four satellites must be in view of the receiver. However, in power system applications, the location of the substation where the receiver is located is known, and once this is entered into the receiver, only one satellite need be visible in order to achieve the 1 μsecond accuracy of synchronization.

In response to the question asked by Professor Wilson, the Working Group members are not aware of any successful use of LORAN-C receivers in electric power substations.

Mr. Taylor describes three instances where alternatives to the synchronized phasor measurements have been proposed for various control and protection applications. A great deal of ingenuity and engineering judgment is demonstrated in the cited applications, which were developed before the technology of synchronized phasor measurements became available. It is to be hoped that with the advent of this new technology, even more spectacular results in the field of power system monitoring, protection, and control will be achieved.

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