THE APPLICATION OF SYNCHRONOUS CLOCKS FOR POWER SYSTEM FAULT LOCATION, CONTROL AND PROTECTION

J. ESZTERGALYOS, D. C. ERICKSON, J. N. ANDRES
U. S. Department of Energy
The Bonneville Power Administration
Portland, Oregon

ABSTRACT

Recent developments in fault locating technology by the Bonneville Power Adminstration (BPA) on its 500-kV system provide a unique opportunity for major advancements in the science of fault location, power system control, and protection. A most significant advancement is the installation of highly accurate synchronous clocks of microsecond accuracy at major 500-kV substations. Initially, these clocks will be synch-pulsed from a master oscillator at BPA's Dittmer Control Center, but future plans include the use of satellites for synch-pulsing. By using the synchronous clocks to measure the traveling voltage wave time at line end terminals, a microsecond accuracy gives 300-meter fault locating resolution. Relaying performance will be enhanced on reclose once the location of the fault is known. In addition, reclose selection based on fault location and fault evaluation will be possible. Synchronous time measurement of the sinusodial voltage at the zero crossing allows for the calculation of the generator angle and its rate of change between two or more locations. This will open up new approaches in system steady-state and transient stability control.

INTRODUCTION

At present BPA is in the process of updating its "Type B" fault locators with a new Automatic Fault Locating System named "Microtime".(1) A most significant aspect of Microtime is that it requires the installation of highly accurate synchronous clocks in BPA's major 500-kV substations. Initially, these clocks will be synch-pulsed from a master oscillator located at BPA's Dittmer Control Center in Vancouver, Washington. Future plans, however, include the use of satellites for synch-pulsing. By using satellites to disperse the time code of a master oscillator, it will be possible to synchronize clocks between substations located within BPA's service area or between the BPA system and power systems located outside the Pacific Northwest.

For those who may not be familiar with it, the "Type B" fault locator was developed by BPA in 1957 and is based on the detection and accurate timing of the Travelling Voltage Wave (TVW) generated by a fault. The system has been in service since 1965 on 500-kV and 230-kV transmission lines. There are several papers available which describe its working principle in detail.(2,3)

Briefly, the "Type B" fault locator uses the master/remote configuration depicted in Figure 1.

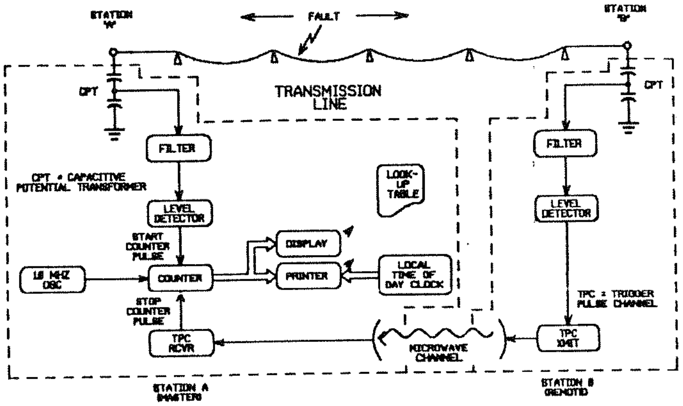


Figure 1 - The "Type B" Fault Locator.

As can be seen, when a TVW transient is detected at master station A, it starts a counter. When the TVW transient is detected at the remote station B, a trigger pulse is sent to the master station A via microwave radio which stops the counter. The elapsed counter time is then compared to a master file which first identifies the faulted line via breaker status data, then the tower location by matching the counter time with the corresponding time data on the master file. One problem with this fault locating technique is that many remotes may report the fault to the master. The other is that the TPC is used as a "party line" which leads to possible ambiguity between a noise and a real stop signal.

THE "MICROTIME" CONCEPT

BPA introduced the Microtime fault locating technique in 1982. Please refer to Figure 2., which depicts BPA's Microtime Automatic Fault Locating System.

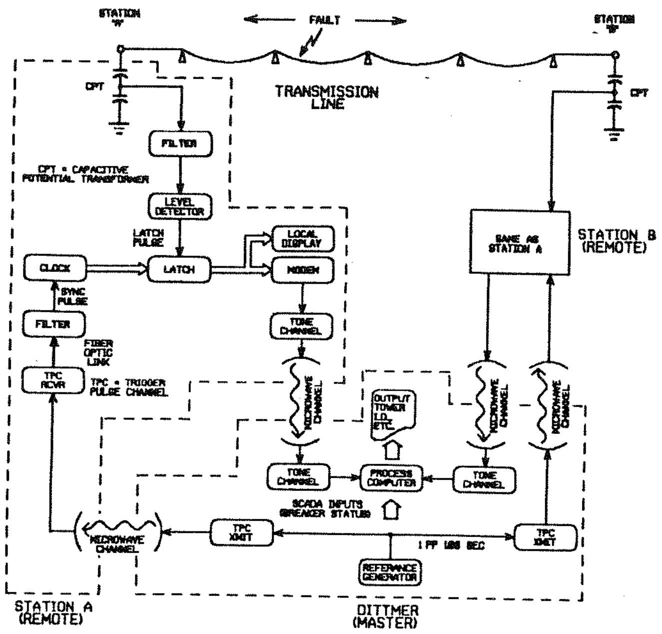


Figure 2 - The "Microtime" Fault Locator

The one-line diagram in Figure 2 shows two synchronous clocks of microsecond accuracy installed at substations A and B. A master oscillator located at the master station sync-pulses the two clocks at predetermined time intervals. The travelling voltage wave is created by a fault. When the TVW is detected by the wave detector logic circuit, the time of the local clocks is latched, coded, and transmitted to a central computer. The computer analyzes the time code, subtracts the proper numbers, and by using tables stored on a disc, derives the proper tower indication. Since the speed of TVW is essentially equal to the speed of light, a synchronous clock of microsecond accuracy will give a 300-meter resolution. This is the approximate distance between two high-voltage towers. BPA plans to install the new Microtime units at sites where the "Type B" units are being retired.

It should be noted that the Microtime fault locating technique, as designed, is very limited since the scheme requires a dedicated microwave Trigger Pulse Channel (TPC) for synchronizing the station clocks to the master clock. TPC is not readily available at every substation within BPA's service area and certainly is not available to the power industry as a whole.

Consequently, BPA began to investigate techniques and systems with which Microtime Fault Locator could be synchronized without TPC.

SYSTEM PLANNING REQUIREMENTS

Table 1 lists the optimum accuracy for synchronous time measurements from the viewpoint of power system planning.

System Function	Coverage	Optimum Accuracy	Time Code Format
Fault Locator	300m	1μs	Absolute Time
Relaying	1000m	3μs	Absolute Time
Transient Stability Control	±2°	100μs	Absolute Time
State Estimator	±2°	100μs	Absolute Time
Oscillo-graph		1ms	IRIG-B
Event Recorder		1ms	RS232

Table 1. System Synchronous Time Requirement

Table 1 clearly demonstrates that synchronous time of 1 μs accuracy satisfies all the system planning requirements.

TIME DISSEMINATION TECHNIQUES

There are three basic time dissemination techniques available:

1) Optical time dissemination - the most novel approach. Similar to the lighthouse concept, a hypothetical optical time dissemination system would reference a rotating neutron star (pulsar) which periodically sweeps the earth with a narrow light beam. This beam can be intercepted at night with a (24 in.) telescope and a photosensor logic to synch-pulse the local clocks. Atmospheric and space disturbances can affect the pulsar signal level therefore such a system would require a highly stable clock (Rubidium) capable of maintaining the accuracy through the time period between synch-pulses. (8)

2) Portable clock time dissemination - basically, a portable clock consists of a highly stable Cesium beam or rubidium clock which can be transported to different locations to provide the time synchronization.

3) Electromagnetic time dissemination - this approach includes all existing VHF/UHF/SHF and other radio communication systems either on the ground or via satellites, which can be used to synch-pulse the local clocks.

NATIONAL INDUSTRIAL TIME SERVICE

Based on extensive discussions between BPA and the U.S. National Bureau of Standards (NBS), it is our conclusion that the NBS has the technological capability to provide the power industry and others a satellite-based National Industrial Time Service (NITS) with sub-microsecond accuracy. A hypothetical system is shown in Figure 3.

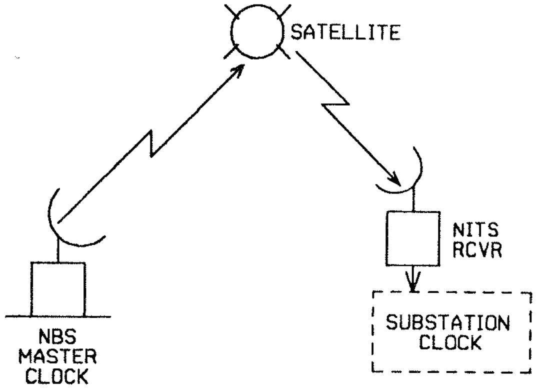


Figure 3 - National Industrial Time Service

This system would employ a triply redundant atomic clock as the master clock and use domestic satellites to disperse the time code over North and South America.

The satellite time code signal would be maintained and controlled by the NBS. There are several techniques under consideration for time code dispersion, some of which are listed below:

1) The use of an exclusive frequency allocation of 400.1 MHz from satellite to earth broadcast.

2) The use of Fixed Satellite Service and a technology called the "spread spectrum communication", in the 4-GHz and 12-GHz band.

3) The use of trilateration ranging signals associated with GOES or other satellites.

4) The use of high-power television broadcasts from satellites in the Broadcast Satellites Service transmitting from satellite to earth in the 12.2-GHz to 12.7-GHz band.

These techniques either exist already or will be available soon.

Beyond its technical feasibility, it should also be noted that from the NBS's point of view, the cost of operation and maintenance of the NITS System should be fully covered by the users of the system preferably on a subscription basis. Subscription fees would depend on the number of users but our initial estimate is that it would be several hundred dollars per year.

SUBSTATION SYNCHRONOUS CLOCKS

One proposed system consists of a satellite to earth time code receiver with a 2-foot parabolic antenna, a receiver circuit, and a time code pulse output circuit accurate within a few tenths of a microsecond. The time code receiver in turn synch pulses the substation clock. To offset the cost of operation and maintenance the time code signal could be encrypted and its key provided by the NBS to users on a subscription basis. Our preliminary estimate is that, with competition, the cost of a substation time code receiver could be less than five thousand dollars.

The substation synchronous clock would consist of a precision crystal oscillator or rubidium oscillator. At present, BPA has selected the Piezo Systems 2810007 oscillator as the synchronous clock for its Microtime system. The drift rate of the PS2810007 without the synch pulse is less than $5x10^{-10}$/day, or 1.8μ sec/hr. However, rubidium clocks are proposed at critical substations and major generating stations. The drift rate of a Rubidium oscillator without the synch pulse is less than $1x10^{-12}$/day.

Once local clocks can be synchronized via NITS there will be a unique opportunity for major advancements in the science of power system control and protection. At a minimum synchronized time would ensure that existing sequence of event recorders, oscillographs and all other recording devices are put on the same time base. This would be a major benefit to engineers trying to evaluate or reconstruct events after a system disturbance or analyse the cause of a misoperation between line end terminals.

SYSTEM PROTECTION

Three specific examples will be discussed. First, let us assume that a fault on a transmission line is detected by conventional analog type distance relaying, but now the Microtime fault locator TVW data is not sent to the central station directly. Instead, the TVW time is exchanged between the line end terminals during the 30-50 cycle "dead time" preceeding the fist reclose. By evaluating the analog relay data to determine the type of fault and the exchanged time data to locate the fault, a substation computer or relay (4) microprocessor could direct the reclose scheme to initiate or prevent reclose. In addition, since the location of the fault is now known the speed of relaying on reclose can be accelerated by shorting out Zone two time delay or momentarily cutting in a "switch into fault" type of relaying scheme.

A second, more advanced technique could use a Travelling Wave Detector (TWD) (5) relay. This relay when combined with synchronous time could be operated in the same fashion as the "Type B" fault locator described in the Introduction. The synchronous TWD relay has the advantage over the "Type B" scheme because it detects not only the traveling wave voltage but the current wave as well, which provides instantaneous directional selectivity. Briefly, in this case, when the disturbance is detected by the synchronous TWD logic it is time-tagged at both end terminals. At the same instant, the scheme would key a trigger pulse to the remote stations via microwave radio. The trigger pulse would be time-tagged at the receiving end and compared to a file which, by subtracting the local TWD time from the trigger pulse time can simultaneously identify the fault location and initiate the trip. The benefit of a synchronous TWD scheme is that it is both an accurate fault locator and a very high-speed relay. Fast fault locating capability is an important relaying requirement on major 500-kV intertie lines where real time controls (generator dropping, dynamic braking, capacitor switching, etc.) are necessary when the fault is within a certain distance to one particular terminal. The microwave trigger pulse requirement, however, will limit the synchronous TWD scheme to special applications.

A third system protection technique is described by Baker and Flechsig (6) and Tagaki et. al. (7), with which it is possible to locate a fault using the data from one end only, if the elapsed time between the incoming traveling voltage and current waves, the line characteristic impedance, and the propogation constants are known. This technique will require more study but the availability of synchronous clocks in substations would accelerate the research.

By time-tagging the traveling wave values BPA could provide synchronous field data from the end terminals to confirm the theory and aid the development of the Baker-Flechsig-Tagaki scheme.

These three examples indicate a trend which we believe will become an industry standard in the future. That is, combining fault locating technique with relaying protection and using the fault location information during the reclose cycle, to block, allow, or delay reclose.

PHASE ANGLE MEASUREMENT

The proposed technique for measuring the voltage phase angle between two or more terminals is depicted in Figure 4.

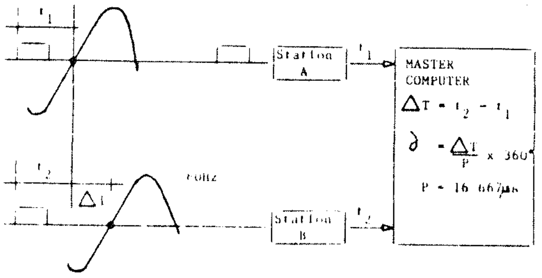


Figure 4. Phase Angle Measurement Method

A synchronous train pulse is generated at stations A and B at 30 pulses per second and the time delay t_1 and t_2 between the leading edge of the synchronous train pulse and the voltage wave is latched, tagged, and sent to a master computer file over a high-speed communication channel. The elapsed time t_1 is subtracted from t_2, and from the time difference Δt the master computer can evaluate the phase angle δ . The accuracy of the measurement with one microsecond resolution is $\pm$.0225 degrees.

POWER SYSTEM DISPATCHING

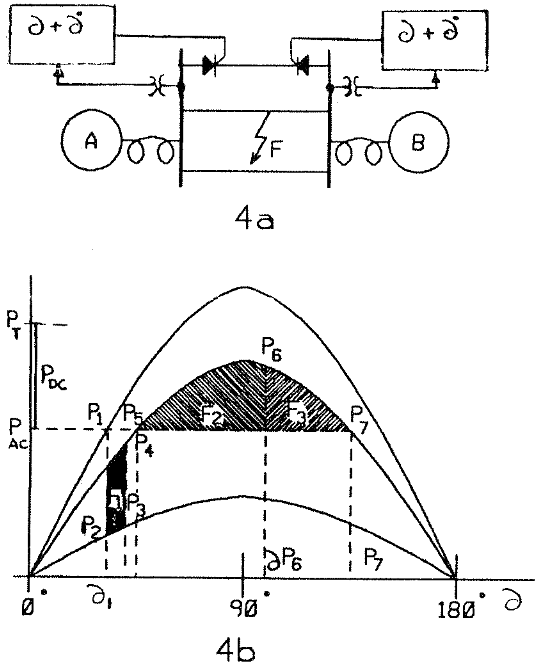
BPA's Dittmer Control Center receives a continuous stream of voltage data from selected substations and generating points. Since the voltage magnitudes are usually held constant, the system power flow and reactive power requirements are basically determined by the voltage phase angle δ between the busses. Therefore, phase angle is a "state variable" and the knowledge of it on a real-time basis from a few key locations can provide the dispatcher with an intuitive assessment of the system condition. One simple example would be a lightning storm moving through a district and tripping out several major lines. A small phase angle between one or two substations within the district and a major generating plant in the PNW region would indicate a stable system, even though the remaining lines in the district could be severely overloaded, and might require remedial action.

STATE ESTIMATION

The State Estimator receives V, P, Q, and breaker position data from selected substations. The primary purpose of the state estimator is to identify gross measurement errors and compute a good estimate for the on-line power flow program. The state estimator, however suffers from various limitations. One major problem is that the sampling of the input data is relatively slow (the order of 10 seconds) therefore, convergency problems can occur when bad data is presented during a change of status. The performance of the state estimator can be improved by the synchronous sampling of the input data. Additional validation could be achieved by adding the voltage phase angle measurements as a new input than comparing the measured results to the calculated results from the state estimator.

POWER SYSTEM STABILITY CONTROL

An example of the benefits derived from applying synchronous time measurement techniques to power system stability control is depicted in Figure 5. Briefly, assume that in the two machine system. A represents the PNW and B represents the SW region.



4a

4b

Figure 5 Two Machine Diagram

If the 500-kV AC Interties are assumed to be mostly reactive, and if we assume V_A and V_B are equal, then the power P_{AC} transmitted from A to B is the function of the angle between the two voltages. This is represented by the formula.

$$P_{AC} = \frac{VA \bullet VB}{X} \sin \partial_1$$

The ±500-kV HVDC Intertie power P_{DC} does not depend on the phase angle therefore the total power P_T transmitted from A to B is equal to

$$P_T = P_{AC} + P_{DC} \text{ or}$$

$$P_T = \frac{V_A \bullet V_B}{X} \sin \partial_1 + P_{DC}$$

As long as ∂_1 is less than 90°, the two machine system has steady-state stability, and the larger the angle change from the original working point P_1 the greater the danger to steady-state stability. The same is true for transient stability. If, for example, a fault occurs at F (Figure 4a), the power is reduced from P_1 to P_2. The difference of power transmission capability represents the accelerating energy, which cannot be transmitted until the fault is cleared. During the fault the accelerating energy is stored in the rotating machine A. This can be accomplished only by increasing the phase angle to P_3. When the fault F is isolated, the power is changed abruptly from P_3 to P_4 on the power curve with one line out of service. P_4 is still less than the required demand (P_T) so the power angle increases up to P_5. The accelerating energy of machine A will further increase the phase angle to ∂P_6 until its kinetic energy is used up. The area F_1 represents the transient kinetic energy, and the available transient stability limit is represented by $F_2 + F_3$.

It is well understood that instability would result if F_1 were larger than $F_2 + F_3$. A typical power swing study for system 4a at different generation levels is represented in Figure 6.

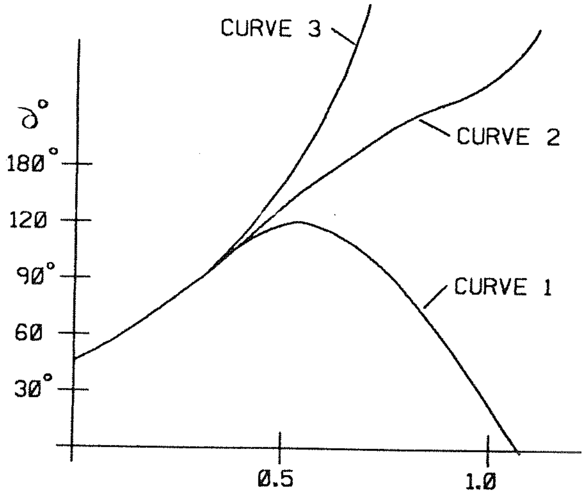


Figure 6. Power Swing Study

The power swing study indicates that the system is unstable if the maximum angle δ P_6 exceeds 120°. The fast ramping capability of the ±500 kV HVDC Intertie which increases P_{DC} is a powerful tool for improving system stability (9,10,11,12). The relationship between the total transmitted power P_T and the voltage phase angle δ and its rate of change $\dot{\delta}$ can be used as a supplementary method of controlling power flow after steady-state and transient-state disturbances.

BPA is planning to replace the existing Type B fault locator on the 500-kV HVDC Intertie between Celilo (PNW) and Sylmar (SW) with the "Microtime" fault locator system. We plan to use the synchronous clocks of the fault locator as follows:

a. To monitor the phase angle δ of the voltage in relation to the total power P_T transmitted to the SW.

b. Compare the on-line power flow program, and transient the fault program phase angle calculations with the measured field data.

c. To develop a control device for fast HVDC ramping for sudden loss of power on the parallel AC system based on P_T and $\delta + \dot{\delta}$. It should be noted that since a dedicated TPC for synchronizing Celilo and Sylmar is already in service, this specific development does not depend on the availability of a satellite-based NITS. However a large-scale integrated control system has to measure several phase angles such as the angle between Arizona, California and New Mexico, where synchronous clocks via NITS are required.

CONCLUSION

BPA is actively supporting the development of a satellite-based National Industrial Time Service to provide the power industry and others with a means of synchronizing clocks between two or more geographical locations. This paper presented specific examples of how synchronous time techniques can be used for fault location, relaying, and control. Synchronous data would also be beneficial for system planning, economics, operation, and maintenance.

Synchronous time measurements of the travelling voltage and current waves at line end terminals and the measurement of the phase angle between power systems will provide the necessary data for researching and developing a new family of control and protection devices.

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