TIMING WITHIN THE WESTERN AREA POWER ADMINISTRATION

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ABSTRACT

The Western Area Power Administration (Western), U. S. Department of Energy, is a Federal agency which transmits and markets electric energy primarily generated at hydro-electric dams. The transmission system in the western United States was experiencing many hard-to-explain outages in the early 1980s. It became apparent that better post-outage analysis could be performed if the geographically dispersed generation and load centers had their disturbance recording systems on the same time base. The design criteria was selected to be 1 millisecond synchronization to UTC. One millisecond was the (1982) resolution of electric substation sequential events recorders and light beam oscillographs. With a common time base, analysis would answer the questions of what happened first and in what order. Western had primarily used the time services delivered by WWVB, GOES, and power system microwave systems. This paper discusses the system timing work that has occurred within Western to date.

In the next section, several applications of time accuracies greater than 1 millisecond are presented. Several authors believe that a 1 microsecond time base will permit improved wide area power system protection and control. An abbreviated bibliography is included.

SECTION ONE
PURPOSE AND OUTLINE

To improve the reliability of electric service, most utilities use equipment that continuously monitors various quantities. The type of equipment used varies from light beam oscillographs, data logging continuous magnetic tape drives, sequential events recorders (SERs), and more recently, digital disturbance-transient recorders. In addition, most power systems control the opening and closing of power circuit breakers from a central control (or dispatch) center using a Supervisory Control and Data Acquisition (SCADA) system. Typically, the SCADA system prints power system events, such as the opening of a power circuit breaker, with a time tag accurate from 2 seconds to 10 milliseconds. The time accuracy depends primarily on the size and age of the SCADA system.

If lightning strikes a transmission line, or if some piece of equipment misoperates, all the above systems record a vast amount of information. To make matters more interesting, these systems may be geographically separated by hundreds of miles and be in different states. This information is much more useful if the timing device on each recorder is time synchronized.

What was discussed above primarily relates to one utility. The need for synchronization becomes more critical when we realize that there are several hundred utilities, cooperatives, and Federal agencies involved in the generation and delivery of electric energy. Typically, disturbances do not occur on one utility's power system, but may involve two or more different entities. This has meant that most utilities who have synchronized their recording equipment have synchronized to Universal Time Coordinated (UTC).

Specifically in the western United States, we have many problems due to the large distances between energy generation and consumers. The operating group in this area is called the Western System's Coordinating Council (WSCC). Several times in recent years the WSCC has fallen apart, most of the time putting southern California "in the dark." After these major disturbances, a committee is formed of senior engineers and officials from all utilities involved. Until recently, everyone would bring their own records, all using different clocks. The problem of comparing records was very difficult. It was very hard to answer the question, "What happened and in what order?" Personally, I can remember going to meetings after problems in the Colorado-Wyoming-Montrose area and trying to make sense out of all the recordings which covered many tables.

Historically, utilities have used a time base accurate to 10 milliseconds. This was used to measure the local power system frequency with respect to a standard and to integrate this frequency over time and compare the "60-Hertz" time with standard time. This is the process by which electric clocks were kept accurate. Often it was necessary to adjust the output of power system generators to adjust this 60-Hertz time early in the morning. The usual source of standard time and frequency was radio station WWVB.

Sections Two through Six are primarily concerned with building a 1-millisecond timing system. These sections would be of most interest to a utilities engineer.

Section Seven goes beyond 1 millisecond and discusses present and future power system applications of precise time, such applications as protective relay testing, voltage phase angle measure, and finally, fault location. Citations to the literature on possible means to combine all this information are provided.

Commercial companies are identified in this paper in order to adequately discuss issues. Such identification does not imply recommendation or endorsement by Western Area Power Administration (Western), nor does it imply that any identified entity is the only or the best available for the purpose.

SECTION TWO
DESIGN CRITERIA

I first started in the power system timing business in the Phoenix District Office of Western. We had a short-circuit fault on the Parker-Liberty 230-kV line. The oscillograph clocks at Parker and Liberty differed by 2 minutes for the same fault. Our expensive investment in light-beam oscillographs was not being used to its full capacity. My supervisor asked me to correct this and the following design criteria have evolved since then.

1. The timing system should be accurate to within 1 millisecond (ms). One millisecond was chosen because this is the resolution of the typical SER. As the power system in the West grows, becomes more interconnected, and hence, more complicated, we need time resolution of this order to adequately analyze events. This 1 millisecond goal implies a criteria of at most ±500 microseconds (us) at each location.

   We are living both with the blessing and under the curses of solid-state relaying. One millisecond pulses are suspected of causing relay problems here in the Montrose District Office. We need a timing system that will use any SER to its maximum extent and accurately time future and faster monitoring equipment.

2. The timing system should be absolute rather than relative. By this I mean that our time standard needs to be related to an international standard, such as maintained in the United States by the National Bureau of Standards (NBS) and the U.S. Naval Observatory (USNO). We need this standardization so that if anyone else synchronizes their equipment properly, we can compare times. We could have built a Western (WAPA) timing system, but then the question would always be, how does our time relate to the rest of the world?

3. The system should be unattended. After installation, we do not have the workers to fine tune an oscillator every month.

4. The system should be reliable. The most accurate system does you little good if it is not working, especially during a disturbance. We want a system that will work day in and day out. Remember Murphy's Law.

5. The system should use standard hardware. There is no need to become involved in a research project when hardware is available off the shelf.

6. We want the costs per substation to remain reasonable.

SECTION THREE
TIMEKEEPING

One of the primary standards for time interval in the United States is located in the National Bureau of Standards Laboratory in Boulder, Colorado. This primary or "master" clock is a cesium beam atomic oscillator called NBS-6. This master clock drives other exotic oscillators that operate one of the time scales for the United States. Another equal source of time in the United States is the United States Naval Observatory.

Actually, there are several time scales in use throughout the world. The main reason for having different time scales is that the spinning earth wobbles on its axis and does not rotate with a uniform rate. However, atomic clocks are very stable. All of this has been taken care of in the time scale we are presently using, Coordinated Universal Time (UTC). UTC has evolved from the old Greenwich Mean Time (GMT) or Zulu. If you are a navigator, you would want to use a different time scale, UT1. UT1 varies with respect to UTC. Whenever UTC varies from UT1 by .9 ms, a correction is applied to UTC to keep the two time scales relatively close. This correction is called a "leap second." A utility that is using UT1 is Bonneville Power Administration (BPA).

The central problem in accurate timekeeping is transferring "the Time" from NBS or USNO to our substations and dispatch centers. Even at the speed of light, a signal does not get from there to here instantaneously. No matter how you try to transmit time information from the source to the user, there is a propagation delay. The amount of delay, the accuracy of these predications, and the uncertainty of these predictions (mean, standard deviation, etc.) varies with the methods of time transmission. The choice of transmission medium is a key issue in any synchronization program.

Every type of transfer technique is going to have outages. However time information is transferred from the time source to us, it is recommended that your local clock can "flywheel" or run on its own. You want your local clock or frequency standard to be able to keep generating accurate time information and then re-lock to UTC when the outage is over.

There are many ways of transferring time information to a user such as the Western Area Power Administration. These include transfer via:

a. Leased telephone circuits

b. High frequency broadcasts such as WWV or WWVH (2.5, 5, 10, 15, and 20 megahertz)

c. Low frequency broadcasts such as WWVB (60 kHz) and Loran-C (100 kHz)

d. Ultra-high frequency broadcasts from geosynchronous (stationary) or other satellites

e. TV signals and very low frequency broadcasts such as Omega

f. High accuracy portable cesium, rubidium, or quartz clocks moved between local time sources--so called "flying clocks"

g. Distributing of a serial code from a central site to a substation on a private or utility-owned microwave radio system

Initially, we can disregard several of the options above. The Omega navigation system and frequency transfer via TV signals offers high accuracy rates, but requires operator intervention. They are not automatic. Flying clocks are not stand-alone timing sources typically, but rather a way to physically carry standard frequency information from your local standards laboratory. They are expensive ($17,000 - $40,000). With this approach, you would need a time code generator (TCG) to change the very stable frequency source to a time format useable by your equipment.

In the next section, we will discuss some relative advantages and disadvantages of the remaining four techniques. Now we need to talk briefly about some digital languages (formats) used to tell our clocks exactly what time it is.

A time code is a series of pulses used to represent numbers. These numbers, depending on their position in a code, represent seconds, minutes, hours, or days. Other pulses are used as frame synchronizers; i.e., reference points. These synchronizing pulses tell you or your local substation clock when to start figuring out (decoding) what the pulses mean. Depending on the application, the code can be sent as a direct current level shift or as modulated pulses on a carrier signal. (1, 2)

There are a whole series of time codes which appear to be a spin-off from the space program. The time code we are most interested in is an Inter Range Instrumentation Group Format B (IRIG-B) serial time code. IRIG-B has a 1 second frame rate and contains complete time of day information, seconds through days. The code typically uses a 1 kHz carrier. It is not hard to count cycles of the carrier if this code is written directly on an oscillograph analog channel and obtain 1 millisecond resolution. This code uses amplitude modulation with the width of the pulses signifying whether that particular position stands for a 0 or a 1. Frame synchronization is marked by two 8-cycle wide pulses. (3)

Please note that IRIG-B is a serial time code. This means that complete time information can be transmitted over a single pair of wires or a voice grade multiplex (MUX) microwave channel. This is contrasted with a parallel time code. With a parallel code you need about 32 (for days through seconds) wires to transfer complete time information. Typically, you would use a parallel binary coded decimal (BCD) time code within a dispatch center or substation.

When you use a serial time code with a modern digital clock, the clock can be designed to lock its internal "fly wheel" oscillator to the incoming time code. Once you have locked your local clock in, a well designed local clock can "backpetal" itself to allow for any propagation delay. The local clock can thus put out a local time signal that is very close to standard time.

Another point concerns information content and noise. Basic theory says that you can only transmit a limited amount of information over a medium (channel) that has a finite band width and finite signal-to-noise ratio. That is to say that more accurate time can be transmitted using an IRIG-A (10 kilohertz carrier, .1 second frame rate) versus an IRIG-B code. However, with its higher carrier frequency, IRIG-A requires more channel bandwidth. This also means that the higher SNR a channel has, the more information can be transmitted. (4) As Mr. James Jesperson of NBS once said, "If you had a noise-free channel, perfect time information (nanoseconds!) could be transmitted with any time code." Of course, this never happens.

In real-life circuits a rough rule of thumb is that the best time you can transfer is about 1 percent of the time code carrier rate. This means that the best you can do with IRIG-B (1 kHz carrier = 1 ms carrier period) is about 10 us. Realistically, the accuracy may be around 50-100 us with IRIG-B.

In the long debate of what approach to take in power system timing, the above brings up an interesting point. It has been stated that the variation of a microwave path is in the microseconds. This is true; however, to use this stability you need a time code capable of transferring microsecond accuracy such as IRIG-A or even IRIG-G (100 kHz carrier). But IRIG-A or IRIG-G will occupy a large portion of your entire microwave capacity!

SECTION FOUR
ADVANTAGES AND DISADVANTAGES OF DIFFERENT TIMING TECHNIQUES

So far we have THE TIME available at NBS or USNO, time codes that can transfer this information to us, and several possible methods of getting the time to us. We are now going to launch into a short discussion of the relative advantages and disadvantages of each time service.

This paper is primarily concerned with disturbance monitoring equipment (oscillographs, etc.) and timing at the 1 ms accuracy level. An important question to ask is whether your utility wants to measure voltage phase angle or use a "time domain" approach to locate transmission line faults. These latter applications require more accuracy, typically in the microsecond region. (10, 19) One utility is using timing to measure the stability margin on their transmission system. (20) Hence, if you need a 20 us time base, you have the 1 ms time base for other equipment. Of course, the costs are higher. (See Section Seven.)

Option (a), leased telephone lines, are a continuous expense, with the tolls likely to increase in the future. To achieve the desired 1 millisecond accuracy, you need an IRIG-B or equivalent code with its 1000 Hz carrier. A higher grade of channel may be needed. Also, the multiplex equipment used by "Ma Bell" may not be synchronized end-to-end, and not synchronized with Western's microwave system. If all channels do not have a totally synchronized multiplex system, many time code generators on the receiving end of an unsynchronized channel are likely to be confused and generate erroneous time. (10) This is because the phase of the information on a serial time code (such as IRIG B) may drift and become inverted. Here the term synchronization is used with respect to the single side band process of frequency multiplexing many channels on a microwave radio circuit (or coax cable).

Another problem would be if the telephone circuit were re-routed. The progagation delay would change. It would probably be necessary to measure the propagation delay through the phone circuits and then reestablish accurate time and frequency information locally. (5)

WWV Next, let us dispose of WWV. Basically, WWV is not accurate enough outside of northern Colorado. Over 100 miles away from the Ft. Collins, Colorado, transmitter, the ground wave signal dies out. The signal you receive will have bounced off the sky (ionosphere). Unfortunately, the ionosphere is not a crystalline sphere, but varies in height above ground and in density. These facts mean that the length of the path the timing signal takes to get from Ft. Collins to you is hard to determine accurately. Also, the signal may fade in and out. This is the same process that causes nighttime AM radio or short wave signals to fade in and out. This fading plays havoc with time signals. WWV accuracy is typically 10 ms. (6, 7)

Loran-C Loran-C is a low frequency navigation service that offers the possibility of microsecond timing accuracy. Most Loran-C equipment is designed to correct a secondary (rubidium or quartz) standard. A typical receiver is around $10,000 with a rubidium standard costing $5,000 to $20,000. Obviously, we do not want one for each oscillograph! An additional problem is that you need other timing equipment to tell the time within 10 milliseconds, then Loran-C improves your accuracy to microseconds. Again, the field is rapidly changing and someone may design a new receiver tomorrow that does everything.

GPS The Global Positioning Satellite system is growing, offers great accuracy, can be received almost everywhere, and the receiver costs are coming down. The accuracies are about ± 250 nanoseconds and the costs range from $15,000 to $40,000 each. (See Section Seven.)

WWVB Another low frequency service that looks attractive initially is WWVB. WWVB has a carrier frequency of 60 kHz and a time code that repeats (frame rate) once each minute. Such a slow code rate is necessary because the carrier has a low frequency.

There are several problems with this service. First, because of the slow code format, the best you can do is come within ±500 microseconds of UTC. Such a specification would be acceptable for a WWVB receiver synchronizing one oscillograph at a substation. However, WWVB may not be a good source to use to distribute through a microwave system with unknown propagation delay variances and arrive at an overall accuracy of ±500 microseconds. It was suggested that this ±500 US accuracy would be better close to the Ft. Collins transmitter. This may not be true. The reasons for this are:

a. The code format is slow, one frame per minute, not one frame per second like IRIG-B.

b. The bandwidth of the transmitting antenna is very small. When a pulse tries to go through the antenna system, it gets "smeared." At the receiver, it is hard to say "this point on the smeared pulse train represents the point when the transmitter turned off." In other words, WWVB may have negligible variance in its path, but the low carrier frequency dictates an antenna system that makes timing pulses imprecise out in the field. (8)

I cannot guarantee that you can reliably receive this signal inside a substation. (8, 9) It seems that open disconnect switches and substations in general generate a lot of noise in the 60 kHz region. You can receive WWVB in a substation in northern Colorado, but many have had problems elsewhere. (9, 10, 11) It may turn out that the relationship between the antenna, the high voltage switchyard, and the Fort Collins, Colorado, transmitter is critical. WWVB may be harder to receive if the switchyard (the noise generator) is between your receiving antenna and Fort Collins. If you are only timing one substation and you can receive and remain locked to WWVB, this time service may be useable.

Another interesting phenomenon is the WWVB "black hole at Sacramento." Unfortunately, the ground wave and sky wave from WWVB may come together 180° out of phase and cancel. The same thing happens in portions of Texas and other places at similar wave distances from the Ft. Collins transmitter.

Partial Summary

Up to this point, we have eliminated several possible sources of time information. What is left? As I presently see the timing picture, there are three possibilities. First is the establishment of a center of standard frequency and time at some central point along a microwave system. From here, timing would be placed on a microwave channel and distributed to various substations. At "time central," we would need a highly accurate secondary frequency standard with backup. Another approach is to use satellite equipment. The third is to try WWVB receivers.

Microwave Timing Channel. The advantages are:

1. If you are willing to spend the time, money, and bandwith, better accuracies can be obtained and put to good use. (See Section Seven.)

2. Many substations that have monitoring equipment are critical enough to have a microwave "drop," hence, a timing service would be available.

3. Microwave systems have good, long-term reliability.

The disadvantages are:

1. It takes time to get a signal through a microwave multiplex system. Some paths within Western are long, with propagation times of 1 to 3 milliseconds. Hence, it is necessary to install a time code generator at each substation to compensate for system delays. The cost of a TCG is between $3,500 and $6,000.

2. This is basically a central station versus a distributed type of timing system. Failure or confusion on the part of the master (control site) time code generator causes errors throughout your system. Murphy says that this will happen during a major power system breakup.

3. If you want to use this approach for high accuracies, you may need an atomic clock or GPS receiver to measure the propagation delay through the microwave system. This measurement should be repeated occasionally, perhaps every 6 months to begin with.

4. The microwave systems are reliable, but not 100 percent. The internal oscillator in a TCG must be able to "flywheel" over short outages. This means that you must buy a synchronized time code generator (has an internal oscillator) as opposed to a time code translator or reader (no oscillator).

5. A catastrophe like the destruction of the microwave repeater would make useless such a timing system. From a reliability standpoint, it makes sense to have a second microwave path.

6. It is very important that any microwave timing channel be multiplex synchronized from time central to the furthest end. If sync is lost, the time code may invert, confusing many time code generators.

It is possible to estimate microwave propagation delay moderately accurately. (See Appendix A.)

A simpler version of the above is to not correct for microwave path delay. Simply write the received IRIG code on an oscillograph analog channel. We did this in the Phoenix District Office. After a fault, you have to shift your oscillograph time. The disadvantages are that if you need parallel (for example, BCD) information, it is not available. Also, time code generators locally rebuild the IRIG signal. The IRIG from a microwave may be very noisy and hard for unsophisticated equipment to work with.

Satellite Synchronized Clocks. The other approach is to use stand-alone clocks. The primary time repeaters are located 23,000 miles above the equator. In Western, we have used the commercially-available and field-proven satellite synchronized clocks. These clocks are locked to one of the three Geostationary Operational Environmental Satellites (GOES). These satellites were designed to gather geophysical data and relay these data to earth with a time tag. This time tag has grown to a highly accurate time service with day-to-day accuracies of ±100 us. (13, 14) Most offices (Areas) within Western are using this approach.

First let us discuss propagation delay and accuracy. The satellite is really just a repeater. The high precision clock is located at the transmitter (up-link) at Wallops Island. The signal takes about 260 milliseconds to travel in free space from Wallops Island to the satellite and back to the western United States. To correct this, the time leaving Wallops Island is advanced this same amount so that when the signal arrives, it is on time to within a few milliseconds. For further correction to sub-millisecond accuracies, there are two approaches.

The first approach is to further correct for average path delay. This is done by using charts supplied by the manufacturer or using a simple computer program. Internal switches are set so the IRIG-B code comes out within approximately ±300 US of UTC (NBS) in the western United States. This is the approach taken by True Time Instruments on the Model 468DC Satellite Synchronized Clock.

There is another approach used by other manufacturers, Arbiter Systems, Inc. and Trak Systems. They build what is called a "smart" clock. In this approach, the internal microprocessor reads the satellite position from the down code. Knowing the satellite position and the latitude and longitude of the clock, an exact propagation delay figure is computed and used to control the IRIG-B code out.

Recently, the budget for orbital maintenance of the GOES system has been reduced. With this reduction, the satellites drift more and the orbital position information is not as accurate. What this means is that even if your receiver-clock states that it is accurate to ±10 US of UTC, the transmitted satellite position information may be inaccurate such that your local received time may differ from UTC (NBS) by ± 100 US. The ± 100 US is just meant to be a typical number. The actual figures vary from day to day in a seemingly stochastic process. Actual GOES performance is monitored in Boulder, Colorado, by NBS. (13)

Another interesting point is that if your average propagation delay receiver-clock has a propagation delay switch in the hundreds of microseconds range, the performance of this clock versus a smart clock <u>may</u> be very similar a large percentage of the time.

There are several advantages and disadvantages in the use of satellite synchronized clocks. Among the advantages are:

1. They are small, lightweight, easy to install, and easy to set up. The only installation problem is mounting the 10-pound antenna. Typical installation time is 1 to 2 working days.

2. The price is reasonable, ranging from $3,800 to $4,500, depending on options.

3. Knowing your latitude and longitude, you can easily set the internal switches and obtain time code outputs accurate to less than 1 millisecond. Recent performance typically runs 100-300 US (peak-to-peak) back to UTC. (18)

4. All installed clocks are up and running. We have had no failures.

5. If one clock were to fail, we only lose synchronization at that substation.

6. We are not putting all our eggs in one basket. There are three satellites in orbit (East, West, and spare).

7. All clocks have their own internal oscillator (1 x 10^6 or better) so that if all satellite lock is lost, the clock accurately flywheels on its own. The clock also tells you if it could be off time by asserting bits in the Prt550 region of the IRIG Code.

8. The IRIG-B code output is clean and stable. Equipment such as a Hathaway 280 IRIG-B decoder has no trouble locking in. (See Section Six.)

9. A parallel BCD or RS-232(c) option is available so that other equipment can be totally synchronized.

10. The downlink frequency is high, namely 468 MHz. With this high carrier, a high frame rate code can be used to provide high time resolution.

11. Satellite lock can be easily obtained in a substation. I pointed the antenna through the Curecanti 230-kV bus and through the control house roof at Shiprock (both SLCA substations) and had no problem achieving satellite lock. I do not recommend this in the long term. Move the antenna a few meters.

Some of the disadvantages are:

1. If you choose to operate your True Time clock in "Auto" mode so that the clock can automatically switch between satellites, the propagation delay is different from the East satellite to the West satellite. You could be off by ±4 ms. This problem can be bypassed by looking to the East (or West) satellite or, monitoring satellite lock as we can do at Ault Substation. (19) This problem has been solved with their Advanced Performance Option. Other GOES clocks do not have this problem.

2. The frequency broadcast from the satellites down to the ground (downlink) is in a frequency band that is shared with land mobile

services. In a large urban area full of mobile radios, you might lose satellite lock occasionally.

The Choice:

The final decision on whether to use a microwave channel or GOES equipment depends on the propagation path you are used to and prefer. The microwave channel goes through the lower atmosphere and many repeaters. The satellite channel is mostly in free space (vacuum). What type of geometry do you like? For an excellent further discussion, see references 11 or 12.

SECTION FIVE
EQUIPMENT DETAILS

Now that we have an IRIG-B (or parallel BCD) on your substation doorway, what do you do with it? If you are still awake, we will discuss some experiences and recommendations on how to time each piece of equipment. This Section is intended to be a helpful list of my experiences over the past several years (1982-1986). The various manufacturers may have changed the details by now. Let's discuss oscillographs first:

Sangamo RA-5 Systems (Phoenix District) This oscillograph is the type where you have two large magnetic tape recorders (transports), one running at a time. In the past, a locally generated unsynchronized IRIG-B time code was written on channel 1. To synchronize, just take the IRIG-B from the microwave or satellite clock and write the synchronized IRIG on channel 1. It is possible to synchronize the existing time code generator (16), and use this as a back-up.

Hathaway RS-9, RS-9/30, RS-32, RS440, etc.
These older Hathaway oscillographs are seen in the Phoenix and Montrose Districts and, I believe, in the Billings Area of Western. The clock on these machines is typically some sort of rotating dial that is flashed on the end of the run. If you can space one channel, just input IRIG-B to that channel. IRIG-B is like an audio signal and is designed to be read off an oscillograph or magnetic playback trace. You may need the communications technicians to install a telephone-type line driver amplifier to boost the IRIG-B up to higher amplitude. The Phoenix relay crew and I have done this successfully. Run the oscillograph for better than a second so that you always get a full frame of IRIG-B.

Hathaway AD or SD 544 Systems
Hathaway has heard the siren call of being on time and designed a circuit to make IRIG-B compatible with their oscillograph clock. Specifically, this Hathaway Model 280 IRIG-B Decoder (a mere $1,900) takes IRIG-B as input and output pulses that are compatible with their Model 255 or 257 clocks. These pulses reset the seconds counter to zero once each minute and the minutes counter to zero once each hour. If there is a spare (analog) channel on the oscillograph, I have recommended that the incoming IRIG code be written on a channel directly. With direct writing, you gain accuracy and have a back-up and an estimate of any time error. (17)

Hathaway, Fault Monitor or SER 6000

In this new combined oscillograph-sequential recorder (SER) approach, the clock in the SER does the equipment timing. Hence, we need to synchronize this clock to UTC. One method is to order (or retrofit) your fault monitor with "clock Option C." This addition of one printed circuit board allows the SER clock to accept a multi-bit parallel BCD which keeps everything (days, hours, minutes, and seconds) in lock step. If you have a satellite clock, have your satellite clock refitted with the parallel BCD option. If your time comes from the microwave system and is not corrected for delay, order a TCG with the BCD option. This black box takes IRIG-B in, corrects for delay, and outputs parallel BCD. Connect the BCD to "clock option C."

Rochester Instrument Systems (RIS)

The sequential event recorders produced by RIS can be synchronized via an option BCD input. The IOM3 modification is needed. The RIS transient recorder (a high performance digital "oscillograph") accepts IRIG-B. RIS also packages a combined SER-transient recorder combination. Here both parallel (BCD) and serial (IRIG-B) time information is required. I hope that in the future only IRIG will be required.

Dranetz Technologies

Dranetz is another manufacturer of SERs. These can be synchronized in two different ways. First, their SER comes already equipped with a 50-pin BCD input point that accepts seconds-through-hours information. Unfortunately, days information is not used. The second method is to purchase their option "Trak-Pack" internal time code generator. This option is a small package that converts an IRIG-B input to BCD for the Dranetz.

One disadvantage of the Dranetz approach is that the days are not synchronized. A nice feature is that if the external time base is lost or is performing poorly, the Dranetz will automatically switch to its internal time, then re-lock to the external signal when the information is stable.

SECTION SIX
APPROACHES TAKEN BY AREAS WITHIN WESTERN

In this section, we discuss the approaches taken by the different Areas to date. No endorsement or disapproval of any equipment is intended or implied. Any opinion expressed is that of the author.

Boulder City (Phoenix). In this Area, timing signals are received from the GOES satellite at Phoenix Dispatch and at Mead and Liberty Substations. At Phoenix Dispatch, the BCD output from the clock is used to provide a backup to the time display in Dispatch.

At Mead Substation, a satellite clock is presently synchronizing three newly-installed fault monitor type oscillographs.

Plans are to eventually take IRIG from Phoenix to Parker and Davis Dams, down to Gila Substation, and finally up to Mead. At Mead, the satellite clock will back-feed the microwave system upon the loss of an incoming IRIG signal. Please note that presently there is no correction for propagation delay. It would be easy to add time code generators (like those we have discussed earlier). Recently, the engineers in the Phoenix Office are considering going to satellite clocks instead of a microwave system approach.

Loveland-Ft. Collins Area. In this Area, the microwave system is presently under construction, but there was a real and rapid need to obtain accurate timing on the oscillographs. System breakups were going through this Area. I recommended and management gave the go-ahead to purchase eight rack-mounted and one field-portable True Time satellite clocks. Seven rack-mounted clocks were for the Loveland Area and one for the Montrose District (Curecanti Substation). To date, clocks have been installed in northern Colorado, western Nebraska, and throughout Wyoming.

Sacramento, California. Presently, this Area within Western has four GOES clocks at the following locations: the Sacramento Control Center, and Elverta, Tracy, and Keswick Substations.

Salt Lake City (Montrose). In my field office (Montrose, Colorado), we have installed a hybrid timing system. Western operates its own microwave communications system throughout the upper Colorado River basin. Where the microwave system reaches a desired substation with a light beam oscillograph or transient recorder, a synchronized time code generator was installed. Where there was no microwave channel, True Time 468 DC satellite clocks were installed. These clocks have been retrofitted with the Advanced Performance Option.

In Montrose at the power system dispatch and control center, an Arbiter Systems Model 1057 Power System Time and Frequency Standard is used for the central site source of IRIG-B. Other signals from the Arbiter feed power system frequency and time difference to the SCADA system. From the Arbiter, IRIG is run through a distribution amplifier then to:

1. a large time display in the control center.

2. a simple time code generator to synchronize an HP 1000 computer.

3. two microwave system voice-grade channels which connect to the remote substations. A party-line channel configuration is used.

4. a Dranetz SER used to monitor transmission line transfer tripping signals.

At each substation, the remote TCGs were set to run on their internal oscillator upon loss of the incoming IRIG-B or the detection of control bit PR+550 on the IRIG-B code. Such bit would indicate loss of lock at the central site. The TCGs were manufactured by KODE, Inc. Several special options were added including a 5 VDC input. We used 130 VDC to 5 VDC converters made by Lambda. It was necessary to increase the propagation delay from a maximum of 1 millisecond to 10 milliseconds (the manufacturer chose to go to 100 milliseconds). (18)

A GOES satellite clock has been installed at Curecanti Substation near Montrose and is connected directly to an oscillograph analog channel. At Curecanti Substation, we write IRIG-B directly on one analog channel and feed a Hathaway 280 IRIG-B decoder. The oscillograph is a Hathaway Model 544 AD. A Rochester Instruments Model RA 2800 SER has been added. The one pulse-per-hour (PPH) signal was taken from the 280 decoder and fed to the 1 PPH input on the SER. This hybrid synchronization appears to be working well.

For a period of one year in 1984, we had satellite clocks on both ends of a critical 230-kV line. We had two system disturbances. Both times the incident fault currents showed the same millisecond time at both ends of the lines. We were also able to time the transmission and reception of direct transfer trip signals between the relay terminals. A satellite clock will be installed at Midway Substation, near Colorado Springs, Colorado.

SECTION SUMMARY

As you can see from this paper, 1 millisecond resolution is not hard to achieve. Accurate 1 millisecond time base, all your geographically-scattered power system monitors will be combined into a multi-state disturbance monitoring system.

We have seen that there are basically two methods of getting an accurate time signal to the equipment in the substation or dispatch center. One approach uses a high reliability, high accuracy "time central" and microwave channels to distribute the coded time information. At each site, the signal is adjusted and made useful to whatever equipment you have.

The other approach is to locate a stand-alone time source--a satellite clock for a noisy substation--at each site. Each substation clock is set up to operate independently and output the needed codes or pulses. Of course, a combination of the two approaches is possible.

I have built and operated both a microwave and a satellite timing system. The microwave approach costs about equal to twice as much as satellite clocks and typically involves several divisions of an organization. The time transfer results appear to be very similar.

SECTION SEVEN
ADVANCED APPLICATIONS

So far, we have been discussing large area timing in the 1 millisecond accuracy range. With better time accuracies available, other applications occur:

100 to 20 microseconds:

The function of a relay or protection engineer is to ensure the electromechanical or solid-state equipment he or she maintains works with reliability as close to 100 percent as possible. At high voltage, short circuits (or faults) occur due to lightning strikes or equipment breakdown. With the tremendous amounts of energy available to supply a short circuit, it is very important that any faulted portion of the electric power system be isolated very quickly.

Conversely, you do not want your equipment misoperating or over reacting for no one likes to be in the dark.

To this end, relay engineers have specialized test equipment called relay test sets. Before a new relay system is placed in service, it is desirable to simulate a fault. This is done at safe levels inside the substation. It would be best to have a relay test set at each end of a transmission line and using two timing pulses start the test within, say, 100 microseconds of each other. In this way, the total performance of the relay system could be evaluated before the system had to protect an actual high voltage (or EHV) transmission line. Problems could be found before any misoperations.

On the other hand, if a relay system did misoperate, we want to know why. Industry leaders are discussing the advantages of the following test procedure. First, from a modern high sample rate digital disturbance recorder, obtain a record of the fault that caused the relay misoperation. Store this real life data in a floppy disk or other media. Now, play this data back through your relay test set, using the test set as an amplifier. Trigger each end with your timing system.

Some relays that protect series compensated transmission lines detect a fault by the traveling wave front it produces. To test this type of relay, perhaps greater timing synchronization accuracies are needed to simulate the differences in arrival times.

Twenty microseconds:

The electric power system, like any other system, can be characterized by its state variables. A possible set of state variables would be (real) power flow, reactive power flow, voltage magnitude at substation buses (nodes), and voltage phase angle. Historically, the first three quantities have been easy to monitor. Voltage phase angle has been very hard to measure in the past. Typically, the magnitude of the voltage phase angle difference between major substation buses lies between 5 and 30 degrees. At a normal power system frequency of 60 Hertz, 1 degree equals approximately 43 microseconds.

The basic idea of measuring voltage phase angle is to compare the zero crossing of the voltage from a substation bus with a reference quantity (angle) that is invarient across the geographical area of interest. Recent activity in voltage phase angle measurement has been concentrated in Utah (20) and Quebec (15).

As pointed out very well by D. T. Hansen and C. P. Dalpraz, to solve large scale transient electrical network problems, engineers are looking for a more global approach to system protection. To adequately access system stability (or fitness), we need to ensure quantities over a multi-state area. A uniform time base, invariant to about 20 or 30 microseconds, is the means by which to measure voltage phase angle. System voltage phase angles is a good early-on indicator of stability problems because it is the driving force behind AC power flows. (20) Recent equipment developments have brought this quantity within financial reach. The GPS system of satellites is used in manufacturers realization with a price of about $17,000.

One microsecond. The main power system application of a large geographic 1 microsecond time base is in determing the location of short circuits. These short circuits can be either temporary in nature, such as a lightning strike causing an arc to ground, or permanent in nature, such as caused by a phase conductor laying on the ground. In either case, there is a need to know the location of these problems.

If a utility determines that knowledge of the location of power system faults is economically justifiable, there are two ways of obtaining this information automatically. One method uses impedance measurements while the other uses a time domain technique and a 1 microsecond time base.

The impedance method has recently been developed by several authors and manufacturers. (21, 22) This method uses pre-fault values of current and voltage along with measured fault currents and voltages to obtain a good estimate of the distance to the problem. Typical results obtained in field tests and operating experience have an accuracy in the 1 to 2 percent of the transmission line length. Accuracy can be improved with various techniques, typically requiring a measuring unit at each end of the transmission line. (23) Typical costs of each measuring unit are about $8,000 per unit.

In the western United States and Canada, our transmission lines are long (as discussed in the section on stability). Also, the typical distance between transmission line towers is about 300 meters, or about five structures per mile. With a 100-mile long line and a fault locating accuracy of 1 percent, your estimate of a problem area can span five towers. If the problem is intermittent and with modern high speed relays removing any problem in two to three electrical cycles (32 to 50 milliseconds), not much evidence of a fault is left behind. (This is good because equipment damage is limited, but "bad" because problem areas are hard to physically locate.) The point is that other techniques must be used if one-tower accuracy is required.

The second technique of fault location uses the fact that electrical information travels at about 300 meters per microsecond. If you could time the arrival time of a fault-induced electrical transient at each end of a transmission line to an accuracy of 1 microsecond, the location to the fault can be obtained. (19, 24)

Of course, life is not this simple. There are many other questions such as the speed of response of the instruments that transform the high-voltage electrical transients to safe working levels, the speed and stability of the electronic measuring package, etc.

Historically, the BPA has operated a true domain fault locating system. (24) One of the problems with operating such a system is the necessary housekeeping to maintain a 1 microsecond time base. Recently, BPA commissioned a National Bureau of Standards study on how to best provide such a time base. (25)

Wide-Area Relaying and Control

In the western United States and Canada, relay and control engineers are beginning to look at a standard time base as a key piece of information. If a reasonably priced, low maintenance, dependable time base can be established, maintained, and believed in, then the applications will grow. Few managers are going to use or base key tripping decisions on a timing system that may or may not be in service or accurate.

A very attractive feature of an automatic time base is that it can be a broadcast service. This means that someone else can operate the service and maintain its accuracy to within stated limits. Most utilities do not want to get involved in managing a time service when this is best done by others. Most utilities simply want to set a few switches and then use the service. This means that measurements can be made simultaneously, then all data communications problems of exchanging information between equipment can be dealt with.

SECTION EIGHT
SUMMARY

The idea of time synchronizing various clocks within the electric power system has recently been fully accepted. In western Canada and the United States, the regional coordinating organization has recommended synchronization to within 8 milliseconds. This limit and a limit of 1 millisecond can be technically adhered to at reasonable costs by individuals who are not PTTI experts. Such commonality of time base makes system operations and post-disturbance much more exact. More information on the actual performance of our protection and operations systems can be analyzed and connected, if needed.

Electric power systems typically cover large geographic areas and affect almost all citizens. Traditionally, utilities have been able to manage and control local problems. Through a common time base and other power system measurements, regional group of utilities can measure global quantities. With this wider picture of the state of the electric power system, in the future we can use computer technology to provide more reliable, economical service.

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LIST OF ABBREVIATIONS

BCD - Binary coded decimal

GOES - Geostationary Operational Environmental Satellites

EHV - Extra High Voltage

ms - millisecond

NBS - National Bureau of Standards

PTTI - Precise Time and Time Interval

SER - Sequential Events Recorder

TCG - Time code generator

UNSO - United States Naval Observatory

UTC - Coordinated Universal Time

us - microsecond

WAPA - Western Area Power Administration, U. S. Department of Energy

Western - Same as WAPA

APPENDIX A

ESTIMATING MICROWAVE RADIO PROPAGATION DELAYS

It is possible to estimate propagation delays through a microwave multiplex system.

- First you have to find the (back-to-back) propagation delay for your microwave multiplex system (ask the microwave engineer). Typical values I have heard of are: 300 US for older systems (150 US for encoding, 150 US for decoding). In Montrose, the new Collins MX-108 MUX has 1450 US of delay.
- 1 US for a remodulating radio repeater.
- 5.28 US/microwave path mile (statue) of free space (or air).
- and .75 US/1000 feet of cable, either coax or paired.

In the Western office at Montrose, Colorado, we took a four-wire multiplex circuit from Montrose to Flaming Gorge, Utah. At Flaming Gorge, we "looped" the circuit back to Montrose.

One way of measuring propagation delay is by use of a Hewlett-Packard (or equivalent) "Transmission Impairment Measurement Set (TIMS). The microprocessor-controlled instrument can measure envelope delay, noise levels, jitter, dropouts, etc., on a microwave system. The function I used was the envelope delay. Envelope delay is a differential delay measurement and an alternate way to characterize the frequency response of a microwave channel.

The (audio) frequency of the TIMS was set to 1 kHz. Next, the output of the TIMS was connected to its input and the "Delay Zero" function was pushed. Next, the output of the TIMS was connected to one "side" of the loop-back to Utah, the input to the other. Then the delay was read in microseconds.

The calculated delay to Utah was (on loop-back) 5390 US. The TIMS measured between 5385 US and 5390 US with a one unexplained value at 5364 US. The median was 5386 US. These observations were taken between August 1984 and March 1985. If your organization does not own a TIMS, there are methods of measuring delay using two time code generators.

These observations are limited. First, the tests were run on only one channel for a short period of time. Second, this was a loop-back test. In a broadcast mode, the channel may behave differently. Third, when a time code is placed on the same channel, the time code generators may behave very differently. The results do lend credence to the above guidelines but probably not to the microsecond level. For a 1 millisecond time service, I have confidence.

The real and ultimate test lies in actually measuring propagation delay by use of a "flying clock" or highly accurate clock using GPS, say. At Western, we have not yet done this (as of 1986).

PROPAGATION DELAYS
FROM MONTROSE, COLORADO

Substation	Microwave Path in Miles	Propagation Delay in Microseconds
Flagstaff (AZ)	327	3180
Flaming Gorge (UT)	235	2690
Glen Canyon (AZ)	242	2730
Hayden (CO)	217	2600
Shiprock (NM)	201	2520
Vernal (UT)	241	2730

Figure 1

QUESTIONS AND ANSWERS

LUTE MALEKI, JET PROPULSION LABORATORY: I just wanted to mention to you that there was some work that George Lutes did with optical fiber systems for power applications at JPL with a number of other people in another group. At the time their interest was to use optical fiber systems in power distribution. I know that they have not been used widely, but if that ever happens it seems to me that a possibility for dissemination of time and frequency would be optical fiber systems.

MR. WILSON: Yes, if you can do it over a four state region. You could have optical fibers from Montrose, Colorado to Flagstaff, Arizona to Vernal, Utah etc. I think that the primary use of fiber optics will be within a substation for bringing a telephone circuit in because of the ground mat rise you can get during a fault. It would be a way to electrically isolate equipment. Or, if you are going from one switch yard a mile over to another one, the non-metallic conductor would help. I think that it is coming and I agree with you.

MR. MALEKI: At any rate, you requirements of milli-seconds and micro-seconds are very easy to realize in a system like that.

MR. WILSON: It is easy for you, but out in the dirty, nasty world its been a job.