Event Reconstruction Using Data from Protection and Disturbance Recording Intelligent Electronic Devices

Report of IEEE Power System Relay Committee Working Group I11
DRAFT 24 – Incorporated comments on September 19, 2007

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SECTION 1

1.1 Background

In the aftermath of the eastern blackout of August 2003, North American Electric Reliability Council (NERC) blackout investigators found that many of the various disturbance recordings were not synchronized, which made blackout analysis work significantly more difficult and time consuming. Because of this issue, NERC Regional Councils and NERC itself have been involved in strengthening the existing requirements regarding synchronizing, as well as creating new requirements. Some of the resulting documents are listed as references to this report. In particular, NERC Board of Trustees has approved, on August 2, 2006, important revisions to both PRC-002 and PRC-018. These are listed as References to this report and are available on the NERC public web site. These standards were scheduled to be revised beginning in June 2007 as NERC Project 2007-11.

1.2 Introduction

In this report, the Working Group examined the meaning of synchronization and the means to achieve it. Group I11 tackled the question of how accurate time synchronization needs to be and how accurately it can be done. It is fortunate that the synchronization accuracy required for event analysis can be achieved with reasonably priced equipment and careful engineering. NERC Standard PRC-018-1 states, in section R1.1. that "Internal clocks in Disturbance Monitoring Equipment (DME) devices shall be synchronized to within 2 milliseconds of the Universal Coordinated Time (UTC) time scale". It is possible to achieve this with available Global Positioning System (GPS) clocks and the proper attention to the engineering of the IRIG-B distribution network, as discussed in this report (1). The area which needs more investigation is the uncertainties and delays due to the various quantities brought to the DME, which are time synchronized, and due to the internals delays of the DME itself. In one field test, which is reported in the Northeast Power Coordinating Council (NPCC) SP-6 report, listed as a reference, the reported times for a system event range over 3 milliseconds. That is, the earliest reported time of 12 DME devices is 3 milliseconds before the last reported time. The simulation programs which are in use work in time steps of a quarter of a cycle. With this variance, the blackout investigation team would be able to place events in the proper time step. It appears reasonable to do this, if a correction factor could be developed which would characterize the average delay for a particular installation.

This report is organized into 4 Major Sections, which are as follows:

- Section 1 – Introductory Material (this section)
- Section 2 - Time Synchronization, Time Metrology
- Section 3 – Distribution of Timing Signals
- Section 4 - Event Time Correlation

A detailed list of references follows Section 4.

1.3 Other Working Groups

Recognizing the need for standardized methods to describe time synchronization accuracy and provide recommendations that will lead to improved consistency in time tagging, PSRC convened Working Group H3 in September 2006. This working group will develop an IEEE Recommended Practice in this area.

SECTION 2

2.1 The UTC Time Scale

The synchronization we are attempting to achieve is to the worldwide standard time scale, UTC, also termed either Coordinated Universal Time or Universal Coordinated Time. The abbreviation UTC results from a compromise with the term as expressed in other languages. UTC is based on measurements made by a "coordinated" group of some 80 standards laboratories throughout the world, all of which use atomic clocks to precisely measure each second. No clock is perfect; even the most advanced atomic clocks are not perfect; and it is necessary for all these laboratories to coordinate with each other to correct for errors which develop. The lead laboratory in this effort is BIPM, near Paris (see www.bipm.fr). The second

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[1] IRIG stands for American Inter Range Instrumentation Group

is now an "SI" unit which is precisely defined and is invariant, that is, the second is never adjusted; however, individual clocks may be adjusted.

Beside UTC, there are several other time scales being maintained, but these are mainly for astronomical use. It is important to mention the astronomical time scale "UT1" that is based on the rotation of the earth which is somewhat variable. UTC itself is not an astronomical time scale; however when UTC becomes deviated from UT1 by a certain amount, UTC is adjusted by the addition or subtraction of what is called a Leap Second. The last such adjustment occurred at the end of 2005.

UTC is disseminated in the USA by the Time & Frequency Division of NIST (National Institute of Standards & Technology) in many ways (see http://tf.nist.gov/). Particularly important for our purposes is that UTC is passed on to the US Department of Defense, which maintains its own time scale at the US Naval Observatory, and then in turn passed on to the GPS (Global Positioning System) which maintains its own time scale. The GPS (refer to Section 2.2 of this work) disseminates its internal time scale to receivers and it also disseminates the information necessary to convert the GPS time scale to UTC. As discussed in more detail elsewhere, this "UTC", which is available from a GPS clock, is deviated from UTC by an extremely small amount, and for purposes of the applications discussed in this work, can be considered to be UTC.

UTC is disseminated with no offset for local time zones and no offset for daylight savings time. When this is done, the letters UTC are sometimes put after the time, in the place where the time zone abbreviation would normally be. Perhaps we can interpret this as "raw" UTC, or UTC without any offset. This has led many to the erroneous impression that UTC is a Time Zone, but from the above material we can see that UTC is truly a Time Scale, and is not a Time Zone. An alternative would be Zulu Time which is the Time Zone centered on the prime meridian, and this terminology would avoid the confusion caused by appearing to use UTC as a Time Zone abbreviation. Refer to Section 2.5 on Time Zones in this work.

There are many more interesting details regarding UTC, but we have intentionally omitted these and have kept the above material to the essentials for this purpose, and direct the reader to the many references on this subject, particularly the listed references to this work.

2.2 The Global Positioning System

The Global Positioning System is a worldwide satellite navigational system used for determining the precise location of an object and providing highly accurate time reference almost anywhere on the earth. The GPS was developed and is operated by the United States Department of Defense, and was originally called Navigation System with Timing and Ranging (NAVSTAR).

The GPS consists of at least 24 satellites and a set of corresponding receivers on the earth. The satellites orbit the earth at approximately 20,000 km (12,000 miles) above the surface and make two complete orbits every 24 hours. The GPS satellites continuously transmit digital radio signals that contain data on the satellites' location and the exact time to the earth-bound receivers. The satellites are equipped with atomic clocks that are precise to within a billionth of a second.

Both GPS satellites and clocks are prone to timing errors. Ground stations throughout the world monitor the satellites to ensure that their atomic clocks are kept synchronized. GPS clock errors depend upon the oscillator provided within the unit. However, the errors can be calculated and then eliminated once the receiver is tracking at least four satellites.

Usually the GPS is able to provide a timing reference with an accuracy of 1 microsecond. In a power system with 60 Hz system frequency, a 1-microsecond corresponds to 0.0216 degrees in 60 Hz phase angle. Therefore, the timing reference provided by the GPS system should be accurate enough for most power system applications.

The GPS maintains its own internal system time scale, however correction factors are provided by the GPS so that a GPS clock can provide UTC Time Scale to the accuracy stated above. The GPS clock is also capable of applying various offsets to supply various local time zones. GPS clock manufacturers generally use the term “UTC” to describe the condition of no applied offset. Refer to Section 2.5 on Time Zones.

2.2.1 Other GNSS Systems

GPS is one of several existing and planned Global Navigation Satellite Systems (GNSS). Others include the Russian GLONASS, EU GALILEO, and China’s Beidou (Compass). All work on a similar basis as GPS, and all are potentially capable of providing accurate world-wide time, either independently or in conjunction with GPS; for example, in a combined GPS/GLONASS receiver.

Only the Russian GLONASS is presently operational. Originally developed under the Soviet regime, GLONASS was allowed to degrade after the breakup of the Soviet Union. The Russian government has renewed its commitment to GLONASS, and recent launches have restored its operational capabilities. GALILEO is presently under development, and the first on-orbit test satellites (GIOVE) have been launched. Operational capability is still many years away. Four experimental Beidou-1 satellites are on-orbit, but the operational Beidou-2 has not yet been deployed. While the Chinese government says the system will be operational in 2008, no Beidou-2 satellites have yet been built. China is also participating in the GALILEO system.

GPS’s large lead in deployment, and the free availability of its basic signals, has given it a near monopoly on end-user or ‘terminal’ equipment. GPS receivers are manufactured in large quantities as consumer commodities, which has driven the price down to the point where the economic attractiveness of alternatives has been reduced. However, there do exist some systems (though not for timing) which can receive signals from multiple systems, most commonly GPS and GLONASS. Over time, receivers (including timing) will probably be made available for the other GNSS. If past patterns are an indicator, this will likely start with high-end equipment used, for example, by national laboratories for test and comparison purposes.

2.3 Related Supervisory Control and Data Acquisition (SCADA) Data Time Synchronization

Time synchronization is also highly desirable on data from Remote Terminal Units (RTUs) transmitted to Energy Management System (EMS) systems. Technical Recommendation 15 from the NERC Transmission and Generation Performance Report Blackout of August 14, 2003 — Detailed Power System Forensic Analyses and Modeling, calls for synchronized time-stamping of RTU data:

TR-15a. "EMS hardware and software designs should be changed, over time, to accommodate time stamps recorded by remote telemetry units (RTUs) at the substation. Each substation should have GPS synchronization capabilities for both RTUs and DMEs."

One of the biggest problems presenting itself to the blackout investigative team was the lack of time synchronization of the large amount of data that had to be analyzed. Because of the widespread nature of the outage, data from multiple control centers had to be collected and analyzed. Depending on the type of data being analyzed, it came with varying degrees of quality, periodicity, and synchronicity such as:

- Remote telemetry unit, also commonly called remote terminal unit, data was generally time stamped when it came into the control center, or when the control center computer processed it. This data varied in scan rates from 2 seconds to 30 seconds
- EMS and SCADA alarm logs and breaker actions were time stamped when the control center computer processed them.

Some control center computers became overwhelmed with processing the myriad of alarms that resulted from the blackout, either completely failing, or skewing even their SCADA data by several seconds or, in some cases, minutes. Even the EMS computers were not necessarily time synchronized to UTC.

These time skews made determining the sequence of events difficult even for the slower, non-dynamic portion of the blackout sequence. During the high-speed portions of the outage, events have to be sequenced down to the millisecond to properly analyze them.

Time stamping of RTU data is beyond the scope of this paper. Although some types of RTUs have both protection and data collection/recording capabilities, this document makes no attempt to address the larger issue of RTU data time stamping. That work will be pursued by NERC and the IEEE.

2.4 GPS Clocks

GPS receivers are used to establish position and time information and can be used to synchronize devices provided by various manufacturers so that information or data can be correlated with respect to a fixed, industry recognized, extremely stable standard. Although receivers are also used to determine a position on the earth by calculating the time differences in signals received from various satellites and the earth located receiver, our focus is on the time signal only. The GPS satellites in orbit around the earth have cesium or rubidium based oscillators such that their time is kept to within three nanoseconds with respect to Coordinated Universal Time (UTC) Scale. A GPS receiver's internal clock may not be as accurate as the clock in the satellite. It was agreed to by the United States Naval Observatory and the National Institute of Standards and Technology that UTC time between the two organizations are to be maintained to within 100 nanoseconds.

Since manufacturers of modern protection and control equipment base their designs on a microprocessor platform, there are internal oscillators that can be used as timers or clocks for event recording and time stamping. Since cost is an important factor in the design of a product, the internal free running oscillator may not be as accurate as required to run independently of an external synchronization signal. This is where the GPS clock signal can be applied to "get the time back on track" within a piece of protection or monitoring equipment for extremely accurate time stamping.

There are two styles of GPS clock systems, embedded types that manufacturers place into their microprocessor based product designs, and stand-alone products that can be connected to multiple protective devices. The embedded GPS clock system normally provides at least two outputs. One is a 1 pulse-per-second output that can be synchronized to within 100 nanoseconds by knowing the inherent delays within the clock. The other output is serial data which can provide UTC time scale as well as other data. This serial data has to be requested from the protection device in many cases so a manufacturer has to understand both the hardware and software interfacing specifications to a GPS clock. A stand-alone GPS system may include these two outputs, but also includes an IRIG-B continuous output that is a widely used data input among protective relays and disturbance monitoring equipment (DME).

A protection and control equipment manufacturer must perform design tests to determine, by measurement, how data is acquired and what the system's inherent delays are. This is then compared with the 1 pps signal from the GPS clock. Aging of circuitry may also lead to drift in these acquisition delays, and many designs can compensate for this by routinely injecting internal "test" signals and measuring delays. The negative side of this approach is that the cost of a design can increase when additional circuitry and software overhead are added to perform such functions.

2.5 Time Zones

UTC time scale is disseminated with no offset for local time zones, and no offset for daylight saving time (DST). For purposes of scientific investigations, and international communications and transportation industries, it is conventional to express time without any offset. It would be appropriate to follow this practice for power system events reporting, particularly for wide area events, which can span time zones. Use of DST offsets invites confusion, particularly during the changes coming in the next few years, and also at the time of the shifts to and from DST. We recommend using UTC without offset for logging events and labeling event records. When using no offset, we recommend using an abbreviation UTC, Z, Zulu, or UTZ as the time zone abbreviation.

If local offset, or local DST offset is used in reporting times, this should be clearly identified by using a standards time zone abbreviation after the time digits. Examples are AST, EDT, CST, MDT, PST.

GPS clocks are capable of applying various offsets for local time zones, and are also capable of applying an offset for daylight savings time (DST) during a programmed time period. In some cases the DST offset function can be automatic. Users are cautioned however that the dates for DST changeover have been revised in the USA and Canada, and use of the new dates began in the Spring of 2007.

SECTION 3

Distribution of time synchronization within a facility is possible using wiring dedicated for the purpose of carrying a protocol such as IRIG-B, and network wiring (or fiber) carrying other data as well as time synchronization messages. Both are covered in this section.

3.1 IRIG-B Time Code

The de-facto standard for time distribution is the IRIG-B code, originally developed by the US/NATO military to replace dozens of incompatible time codes. This time code, used properly, meets many needs of the power industry for time synchronization. Accuracy at levels of 100 µs is achievable with care, and any distribution system providing a valid IRIG-B signal should allow local clock synchronization at better than one millisecond accuracy.

3.2 IRIG-B Time Code Formats, and Accuracies.

To support different communication and storage technologies, three different formats are specified for the IRIG-B signals:

(a) "DCLS" for "DC Level Shift" (also called "unmodulated"), IRIG-B0xx which transmits the 100 bit/sec IRIG-B data frames as a NRZ logic level pulse train (typically 0V and 3V to 6V). The transitions are very fast (< 100ns typical) allowing sub-microsecond timing accuracies.

(b) "Modulated, IRIG-B1xx", for Amplitude-Modulation of a 1 kHz sinusoidal carrier. This format was provided to allow a timing signal to accompany the recorded data. The zero-crossings of the 1 kHz signal are much slower so accuracies of 10 to a few hundred microseconds are to be expected.

(c) "Modified Manchester, IRIG-B2xx," is a more recent format (requested by the IEEE 1344 syncrophasor standards WG) to provide the accuracy of (a) whilst providing the dc-balanced feature of (b) (for transmission over ac-coupled fiber links).

IEEE Standard 1344 (now replaced by Standard C37.118) also added extensions to the basic IRIG-B time code (using the Control Function (CF) bit field in the IRIG-B code) which were desirable for real-time, continuous applications. These include the year of century (IRIG-B has only day of year); local time zone offset; and flags for time quality, leap seconds, and summer (daylight saving) time changeovers. This additional information allows compliant devices, receiving the time code, to know the year; predict and follow 'jumps' in time caused by leap seconds and summer time; convert from local back to UTC time; and monitor the operation of the IRIG master clock. The most recent version of the IRIG time code standard, IRIG 200-2004, has adopted the Modified Manchester modulation format and the optional year extension field of the IEEE-1344 recommendations.

The original use of the IRIG time codes was as a ‘time track’ to be recorded along with test data on multi-channel Instrumentation Tape Recorders (ITRs) at missile test ranges.

The IRIG-B code, with a 100 bit per second signaling rate and a 1 kHz sine wave carrier, was ideal for recording on voice-grade channels. Due to bandwidth limitations of these voice-grade channels (delay and phase shifts), the IRIG-B code was guaranteed only to provide one millisecond accuracy, equal to one period of the (1 kHz) carrier signal.

When the modulated IRIG-B code is transmitted over a direct connection (i.e. no ITR), channel bandwidth limitations are far less significant. It is relatively easy to build IRIG-B generation hardware with accuracy of one microsecond, and to demodulate the signal at an accuracy level of tens of microseconds. The challenge is to accurately generate and detect the carrier phase angle. Most decoders use simple zero-crossing detectors, which are generally adequate although the signal slew rate has an inflection point (caused by the change in signal level) at the on-time mark. For most applications using the modulated IRIG signal, this level of performance (tens of microseconds) has proved adequate.

Since the modulated IRIG signal is basically an audio signal, like a telephone signal, similar techniques may be used for distribution. The input impedance of a typical decoder is several kiloOhms, so a low source impedance driver (tens of Ohms) can drive hundreds or even thousands of loads – in theory at least. Line termination is generally not required.

Unlike the audio-band modulated signal, the unmodulated or level-shift IRIG-B time code must be transmitted over a channel with dc continuity, which generally means a direct connection. So, this code was not widely used by the missile range community, who therefore were not particularly concerned with its potential performance.

Observe that the unmodulated IRIG-B signal is a digital signal. Its accuracy is usually the same as the clock’s one pulse-per-second output, since both signals are typically generated using similar drivers. This means that the IRIG-B unmodulated signal can easily be generated with the fundamental accuracy of digital logic: a few tens of nanoseconds.

Most substation “Intelligent Electronic Devices” (IEDs) that accept the unmodulated IRIG time code use an optically-isolated input. This prevents ground loops, making possible direct connection throughout a control room without excessive concern for grounding and potential differences. Such optocouplers only require a few milliamperes of input current, making it possible to connect many loads to a single IRIG-B driver. The optocoupler output is normally connected via a pulse-conditioning circuit to a logic input (a timer-counter, for example) which measures the time of arrival and width of each IRIG pulse. The accuracy of this process is also quite good: easily better than one microsecond, and potentially a few tens of nanoseconds.

3.3 Unmodulated (Level-Shift) IRIG-B Time Code Wiring

Unmodulated or level-shift IRIG time code is generally developed by a system clock at a level of approximately 5 volts peak, i.e. the "high" level is approximately +5V and the "low" level approximately zero volts. This signal is normally distributed using copper wiring, which may be either coaxial (typically the common RG-58 types) or shielded twisted pair. Most drivers are unbalanced and the clock outputs are often BNC connectors.

For applications requiring sub-microsecond accuracy, issues such as cable delay (1 to 1.5 nanosecond/foot or 3 to 5 ns/meter) and ringing caused by the fast rise and fall times of the signal coupled with imperfect line termination (which causes reflections) must be considered. For such applications, it is customary to use direct coaxial connections with one load per driver, and lines are generally terminated at either the source or load to reduce ringing if the line length exceeds a few feet. Since the characteristic impedance of coaxial cable is typically 50 (sometimes 75 or 93) Ohms, compared with the input impedance of the optocoupler circuit of around 1000 Ohms, overloading of the driver often precludes more than one load being used per output when the load includes a 50 Ohm termination. However, in most applications such measures are fortunately not required. It is usually possible to connect an unmodulated IRIG driver to numerous IEDs, using pretty much any reasonably-clean setup of either coax or twisted-pair lines. For accuracies at the level of one microsecond and up this is generally sufficient, providing that the IEDs themselves are properly designed (see later section) and the cable lengths not excessive. In general, an IRIG-B unmodulated signal, when reliably decoded, will provide clock setting accuracy sufficient for 1 ms time tagging requirements.

3.4 Modulated IRIG-B Time Code Wiring

As mentioned in the introduction, the modulated IRIG signal is similar in many ways to a voice-grade audio or telephone signal, and it can be distributed with similar methods. The rise and fall times of the signal are low, and the decoders generally use an automatic gain-control amplifier to compensate for varying input signal levels, so there are no significant considerations with respect to reflections or signal loss. Similarly, delays are small compared with the typical accuracy of 50-100 microseconds, so cable delays are not an issue. IED inputs are normally transformer-isolated, so ground loops will also not be a problem.

The best practice for a modulated IRIG signal is to use shielded twisted pair cable to connect the IEDs to the clock. Choice of cable type, gauge, stranding etc. is pretty much up to the station designer based on other considerations, such as ease of routing and termination, and minimizing costs.

3.5 IED Considerations

To ensure adequate performance in the substation environment, certain practices should be followed in the design of the IED. These include the following.

Modulated IRIG Inputs

Inputs for modulated IRIG signals should:

1. Provide galvanic isolation (typically a telephone line transformer with 2500 Vrms minimum isolation) and immunity to C37.90 transients
2. Compensate for signal level variations from a few hundred mV pp up to perhaps 10 Vpp, to allow for different clock output levels and potential attenuation by system cabling
3. Determine zero-crossings to better than 50 microseconds

Unmodulated IRIG Inputs

Inputs for unmodulated IRIG signals should:

1. Provide galvanic isolation (typically an optocoupler with 3750 Vrms isolation) and immune to C37.90 transients
2. Tolerate reflections and other non-ideal behaviors caused by imperfect signal routing
3. Tolerate signal level variations, perhaps from 3 V to 6 V peak for proper operation
4. Accept peaks and transients of >10 V repetitive (ringing and overshoots) and several hundred volts minimum (in normal mode) due to C37.90-type transients without damage or mis-operation

Remember that a time code signal, unlike a data signal, is highly repetitive and redundant, and has well-known characteristics (pulse shape, repetition rate etc.). These characteristics may be used to advantage to design inputs resistant to common system integration problems, while still delivering excellent performance. For example, ringing and overshoot on an IRIG signal can easily be handled by recognizing that the pulse width (high or low) is always at least 2 ms, so any "earlier" transitions are either noise, or ringing and overshoot. Visual observation can easily identify these on a scope display, and it is possible to design a pulse conditioning circuit and firmware that will do likewise. An IED that fails to do this reliably will present system integration problems to the customer.

3.6 General Considerations for IED Clock Synchronization

Each IED should have its own internal clock that is synchronized by the incoming time code signal through firmware algorithms. Older IEDs sometimes used the incoming IRIG signal directly, specifically the 1 kHz 'sliced' carrier signal of a modulated IRIG signal, as a time base. This gives up many potential improvements that can be had with a slaved local clock.

This local clock does not need to be anything spectacular. It can be the existing processor clock, driving a counter-timer chip. What it must do is provide a local time reference that will run continuously in the absence of any synchronizing input. This local clock may, of course, be far off if it has never been set.

The local clock, and the firmware controlling it, should do the following things:

1. It should operate independently of the external time-code reference.
2. Its time should be compared to the time code, when available, and the local clock time updated ONLY if there is a persistent, fixed offset between "local" time and "'time

code" time. This is called an "error bypass" and it is made possible by the redundancy of the time scale. The error bypass is normally 3 to 5 seconds, which prevents undesired time jumps caused by time code errors and transients.

3. It should control local time updates in a predictable manner. This may depend on the application: it may be desirable to reset time immediately, despite any "jump" it might cause in recorded data (thereby reducing the number of subsequent, incorrect time tags) or it may be desirable to "slew" local time to match system time at a controlled rate. Either choice may be appropriate, as may a "hybrid" choice (slew for small errors, jump for large errors). The important thing is that this is a design choice, which should be appropriate to each IED and not left to chance.
4. In normal operation, it should track the reference time code (or other control input) using a control loop, driving the static error to zero and thereby compensating for local clock offsets, ageing, and drifts.
5. It should monitor its own operation; including status (locked to external time code; unlocked but time has been set and is now drifting; never locked, etc.).
6. It should provide an estimate for how far off its time might be, based on known characteristics of the IED clock oscillator and the length of time the IED has been without a synchronizing input.
7. It should manage multiple sources of synchronization, if they are available. Examples might be: set from the front panel; set remotely by SCADA or system operator; set from a local battery-backed real-time clock; set by IRIG time code; set by NTP (Network Time Protocol), set by IEEE 1588; etc. Each of these potential sources of synchronization has strengths and weaknesses, and these must be managed by the control firmware since multiple sources of synchronization might be available simultaneously. Example: "What do I do if I get an NTP tag or SCADA update which is greatly different from the time I'm getting from the IRIG input?"
8. It should be aware of so-called 'non-sequence events,' such as changeovers from winter to summer time, and leap seconds.
9. It should be able to provide time outputs (tags) in whatever form the user application requires.
10. Unless some particular system consideration requires otherwise, modern IEDs should use unmodulated, optically-isolated IRIG B time code inputs. They are lower in cost and higher in performance than modulated inputs.

3.7 Considerations for Sampling or Time Tagging

There are two basic methods for sampling the inputs to an IED. The first is to sample with a free-running clock, and then time-tag each point. The second is to use the local clock to generate sampling signals at known points in time.

Many (perhaps most) older IED designs used the first of these methods. Depending on the accuracy of the tagging process, this can introduce significant errors. These errors can easily be the largest errors in the data acquisition system. Where the IRIG 1 kHz signal is used directly for time tagging, resolution is limited to 1 millisecond at this step alone. With this method, the errors of both processes (sampling and time tagging) contribute to overall performance and both must be considered.

The second method is to use the local clock to generate sampling signals. These signals can be generated at known points in time (since the clock is synchronized), with little or no additional error. Then, the reported event times can be accurately known, limited only by the performance of the IED's signal processing firmware. This performance can then be optimized for best performance. New designs for IEDs should use this approach.

3.8 Time Code Grounding Considerations for IED and System Design

From time to time, there is a discussion about how and where (and if) grounding of the time-code signal lines is required. IED designers can be tempted to use a non-isolated input in their device to save a little money. Best engineering practice generally requires any signal line to be grounded (earthed) at some point. For most analog signals, including time-code signals, this is normally the signal source.

Since ground loops are to be avoided, it is important to ground each signal at one point only. This must be the source if there is the possibility to have multiple loads attached to a given source. Therefore, time-code inputs in such a system must provide galvanic isolation.

There is also the system cost issue. Floating time-code outputs can be built, but require (costly) floating power supplies, whereas an isolated input requires no power supply. Compare a simple system having four IEDs driven by a clock: system A has one output, driving four optically-isolated IED inputs in parallel; and system B has a clock with four isolated outputs, each driving a single, grounded IED input. Clearly system A will have a lower equipment cost, since system B requires (in addition to optical isolators) floating power supplies for each independent output.

For these reasons, it has become best industry practice to ground time-code outputs from clocks, and use galvanic isolation of time code inputs to IEDs.

3.9 Fiber-Optic Distribution

No discussion of time-code distribution would be complete without mention of fiber optics. Fiber-optic cables have the advantage of immunity to electromagnetic interference. They can be used to distribute time codes in severe-EMI environments. However, while substations may reasonably be considered high-EMI environments, the expense of fiber-optic cable and drivers is generally not justified for most connections, particularly between clock and IEDs in the same rack or control room.

This is because the galvanic isolation provided at the IED input also provides great immunity to damage from substation surge voltages. The occasional transient signal propagated to the optical isolator or transformer output is easily dealt with by the pulse-conditioning or demodulation circuits, and even if a transient is detected by the counter-timers, it is easily identified and ignored. As a final protection, error bypass in the local clock guarantees continuous and accurate operation.

There are applications for distribution of time codes, particularly between substations or control houses, where the length of the link makes copper connections undesirable. For these applications, where lengths can be many kilometers and losses require an ac-coupled signal, IRIG time code may be transmitted using modified Manchester encoding. This was first defined by PES-PSRC in IEEE Standard 1344-1995 (annex F) and later adopted by IRIG itself in IRIG Standard 200.

However, the cost of such systems must be weighed against the alternative of placing an additional GPS clock at the remote location. In almost all cases, the cost is lower, and reliability and flexibility greater, when a second GPS clock is used instead of a long fiber-optic link.

3.10 Network Time Synchronization

Computers and IEDs connected to the Internet or other network can be synchronized to a timeserver. Network timeservers use several standard timing protocols defined in a series of RFC (Request for Comments) documents. The three major network time service protocols are the Time Protocol, the Daytime Protocol, and the Network Time Protocol (NTP). Timeservers are continually “listening” for timing requests sent by client servers or network IEDs using any of these three protocols. When the timeserver receives a request, it sends the time to the requesting server or IED in the appropriate format. To provide accurate time, the timeserver must be connected to a source of accurate time, such as GPS source.

The protocol that is used depends on the type of client software used. Most client software requests that the time be sent using either the Daytime Protocol or NTP. Client software that uses the Simple Network Time Protocol (SNTP) makes the same timing request as an NTP client but does less processing and provides less accuracy. Table I summarizes the protocols and their formats.

Software programs are available that provide a method for synchronizing the clock of a client computer/IED using messages transmitted over the Internet from a remote timeserver. The principles are appropriate for other types of connections, e.g., a dial-up telephone modem connection, provided that the delay through the network connecting them is symmetrical on average.

All synchronization algorithms start from the same basic data—the measured time difference between the local machine and the remote device and the network portion of the round-trip delay between the two systems. Delays in the remote device are usually not a problem because they are either small enough to be ignored or they are measured by the timeserver and removed by the client. These data are processed to develop a correction to the reading of the local clock. The usual approach is to use the measured time difference after it has been corrected by subtracting one-half of the round-trip delay. This model is based on the assumption that the transmission delay through the network is symmetrical so that the one-way delay is one-half of the measured round-trip value. This corrected value may be used to discipline the local clock directly, it may be combined with similar data from other servers to detect gross deviant points that are statistically irrelevant, or it may be used to compute a weighted average time difference that is then used to steer the local clock.

The corrections are made in either time steps, which adjust the local clock by a fixed amount, or frequency steps, which adjust the effective frequency of the local clock oscillator and thereby retard or advance the time.

This approach is better suited to computers and servers that can run software programs. Protection and control IEDs are more likely to operate on imbedded software (firmware) that would require special or unique code to perform the time synchronization function.

Reported accuracies [1] using this type of approach are as low as 1 ms. More frequent synchronization is required to maintain this level of accuracy, which adds to the communications burden on the computer, server, or IED. Variations in network loading can cause variations in round-trip delay that increases the potential for error. Unbalanced network traffic loading, as well as physical routing differences, cause communications delay asymmetry, which is also a source of additional error. Synchronizing a device clock via a network timeserver so that it is correct to the nearest second is easily achievable. Synchronizing the clock within several milliseconds is realistic but difficult.

The IEEE 1588 "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems" (13) specifies a Precision Time Protocol (PTP), designed to provide timing accuracies better than 1us for devices connected via a network such as Ethernet.

The PTP protocol allows excluding the non-deterministic delays through queues and protocol stacks by timestamping messages as close to the physical media interface as possible (typically at the Media Independent Interface (MII)). It also compensates for path delays by performing round-trip path delay measurements (based on an assumption that the path delays are symmetrical).

Software only PTP implementations have demonstrated timing accuracies of 10 to 100 us (similar to NTP in a small local area network); in contrast, hardware assisted PTP implementations typically show timing accuracies of 20 to 100 ns. Note that to achieve timing accuracy of less than 10 us in a network, all devices have to run hardware assisted PTP implementations. Chips with PTP hardware assist are available from a number of vendors. The number of commercially available devices supporting PTP is growing.

At the time of writing this report (June 2007), a revision of the IEEE 1588 standard for PTP version 2 is going through an IEEE Sponsor ballot. A wider PTP acceptance by chips and equipment vendors is expected after publishing this new standard (2007). Industries are expected to produce their own IEEE 1588 profiles to suit their applications. To address this, a new Task Force has been formed by the Relaying Communication Subcommittee H (HTF1) to work on an IEEE 1588 profile for the Power Industry;. The IEC TC57 WG10 is also interested in such a profile, and harmonization is expected due to the two groups having several common members.

Reference: IEEE Std. 1588 – 2002 "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems", November 8, 2002.

TABLE I
INTERNET TIME PROTOCOLS

Name	Document	Format
Time Protocol	RFC-868	Unformatted 32-bit binary number contains time in UTC seconds since January 1, 1900.
Daytime Protocol	RFC-867	Exact format not specified in standard. The only requirement is that time code is sent as standard ASCII characters.
Network Time Protocol (NTP)	RFC-1305	The server provides a data packet that includes a 64-bit timestamp containing the time in UTC seconds since January 1, 1900 with a resolution of 200 picoseconds. NTP provides accuracy of 1 to 50 ms. NTP client software normally runs continuously and gets periodic updates from the server.
Simple Network Time Protocol (SNTP)	RFC-2030	The data packet sent by the server is the same as NTP, but the client software does less processing and provides less accuracy.

[1] IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 16, No. 4, July 1999, “Time Synchronization of the Internet Using an Adaptive Frequency-Locked Loop,” by Judah Levine.

SECTION 4

4.1 Delays and Distortion in Input Circuits

Modern recording systems have the ability to record signals appearing at their inputs with great accuracy. While many times there is little control over the distortion of these signals; nevertheless, it is important to recognize the effect ct, pt, and cabling on the accuracy of the measurements. Synchronized recorders have the ability to measure phase of input signals on the order of 0.02 degrees, which corresponds to a time error of 1 microsecond. Time delay introduced in the recorder due to filtering and a/d conversion can be corrected in the instrument itself.

However, input transducers, particularly Coupling Capacitor Voltage Transformers (CCVTs), can introduce phase errors (an equivalent delay) hundreds of times greater, particularly at off-nominal frequencies. Instrumentation cables do introduce delay, but this is not usually significant. These input signals are normally terminated in a number of devices for any given application (e.g. recorders, meters, relays). Each of these input terminations represents a substantial burden that introduces errors in the signal being measured. Typically, for example, large capacitors are inserted at the inputs to meet the transient/withstand specifications required of power system equipment. The overall circuit, transducer, cable, and load, can result in errors many times greater than the accuracy of the measuring instrument. This is particularly true during system transients and disturbances.

It is important to keep the realities of the measurement in mind when making any measurement. There are methods to minimize these effects. These include limiting the number of burdens on a given vt, ct circuit and using optical vts and cts. For applications requiring high accuracy it may not be feasible to use a relay-connected ct or vt circuit, but rather a dedicated transducer may be required. Significant work has also been done in modeling and correcting distortions in the input circuitry.

4.2 Timing of System Events

There are a number of different times that may be associated with a power system event or disturbance. Some of these are; trigger, fault inception, current-zero, and clearing time. It is important when sharing information with others that the times reported be clearly identified. Recognizing that many disturbance records will include pre-trigger or pre-fault information and post-trigger or post-fault information, it is important that the information provided within the event or disturbance record, or provided as a supplement with the record, should permit the user to accurately determine the record starting time, ending time, and the time of any selectable sample or data point within the record. The disturbance record and any supplemental information must provide the accurate time of at least one identifiable point in the record and the means to accurately determine the time of any other point in the record, either prior to, or following the identified point.

It is also equally important that the data type be specifically identified to assure that any event record comparisons are accurate. For example, some event records may contain filtered data, while others may contain unfiltered data. Data filters have associated delays that result in analog data phase shifts. To assure accurate comparison of analog data, unfiltered event data should not be compared with filtered event data.

A. Record Initiation Time

Any triggered event record will have a trigger time associated with it. This may be a point where the monitored analog quantity either exceeded or fell below a trigger threshold, or where a digital point picked up or dropped out. The record should also include information about sample intervals that can be used to accurately determine the time of first and last data relative to the specific time associated with the trigger point. Often trigger time or file start time will be part of the file name, or somehow linked to the file record. Within the recorded data, the initial trigger time should be identified. These times are useful in identifying the records related to an event as it is the approximate time of the event.

B. Fault Inception Time

When analyzing a fault record there are several significant times. The first is the fault inception, or the time at the beginning of the fault. When there is a breakdown of insulation or a sudden phase to phase or phase to ground contact the current level will usually increase abruptly and there will be a phase angle shift from primarily resistive current to inductive current. To capture the beginning of the fault, the recorder should be set to record several cycles of pre-trigger/pre-fault voltage and current waveform. Occasionally the current will build up gradually to a point where it activates an overcurrent trigger. In such a case there probably will not be sufficient pre-trigger in the record to identify the fault inception.

C. Current-Zero Time

To support simulations for event reconstruction, it is helpful (if not essential) to accurately identify when current interrupting devices interrupted the fault or power swing current. If the recording device is directly monitoring the current on the interrupting device, the time the current went to zero may be easily identified. Therefore, it is important that monitoring devices be applied on all critical circuit breakers and switching devices that may operate due to faults or significant system disturbances. Event records from remote recording devices often cannot be used to accurately identify when the fault current was interrupted because they may still be carrying current after the interrupting device opened and interrupted fault current. If a current-zero time is reported, it is important to identify which phase it is associated with. The time difference between phase zero crossings is approximately 2.8 milliseconds on a balanced 60 Hz three-phase system. Unbalanced faults will cause phase shift between phases that will change the time between successive phase current zero points. Additionally, when comparing current zero times across a wide area, the phase shift across the system will introduce a time difference. A one millisecond time difference represents a phase shift of 21.6 degrees at 60Hz.

D. Clearing Time (Fault Duration)

The clearing time, i.e.,fault duration, is the time span from fault inception to fault current-zero. Transmission protection schemes are typically designed to have a maximum clearing time of six cycles or less (protective relay time plus breaker current interrupting time). Backup or secondary zone clearing time may be much longer, typically 20 to 60 cycles or longer, depending on the system protection design. Event records should capture the fault inception time and the fault interrupting time so that the clearing time, or total fault duration can be determined. For long time events, it may require that multiple event records be used to capture both the beginning and end of the event. If multiple records are provided, accurate time tags must be provided with each record so the total fault duration can be easily determined.

E. Non-Fault Events and Wide Area Disturbances

In reporting circuit outages for wide area disturbances such as a blackout, the most precise time to use for the circuit interruption may be the current-zero. This assumes that a record is triggered which captures the last phase current-zero. It further assumes that if a disturbance recorder is used, it’s recording the current waveform and not just an RMS signal; though the current-zero on the RMS record will be fairly accurate. This also assumes that sampling and recording rates are sufficient to provide the desired accuracy. A recording rate on the order of 720 Hz (12 samples per cycle at 60Hz) should provide sufficient accuracy; while recording rates as low as 240 Hz (4 samples per cycle) have proven to be useful for event reconstruction many times in the past.

If all three phases are available, then the last phase to go to zero should be reported. If only one phase is recorded and it's the first phase interrupted, then the time reported would be for the phase recorded. In either case, the report should include an indication of whether it is the last phase or the only phase available. Using the current zero method also requires analysis of each record, and assembly of a sequence of events from these records.

It may be possible with many EMS/SCADA systems to record Sequence of Events (SOE) times at a central location. However, these times will be based upon breaker auxiliary contacts or auxiliary relays that introduce additional delays and time reporting variations. If SOE data are recorded, it should include the time that the device actually operated, not the time that the EMS/SCADA system polled the status point. Polling time and polling sequences can significantly skew the recorded breaker operating times.

4.3 Event Inputs (Contact Inputs)

Event inputs are usually added to the disturbance recorder data in addition to, or instead of, the sequence-of-events recorder data. Although this input can be a simple contact, it is deserving of considerable attention, because of the importance it can assume in the analysis process. Some of the items to be considered are:

1. Interposing Relays: All interposing (auxiliary) relays introduce some time delay into the record. The amount can vary from relay to relay (microswitch to HFA/MG-6 which ranges from microseconds to 100 milliseconds). The amount of operate time is not as important as the fact that it exists.
2. The pick-up time and drop-out time can be added to the data on the oscillogram, just as ct ratio and vt ratio are added. (In some applications the contact drop out time is also an important consideration. The time at which a contact opens does not necessarily correspond to the time when the event ceased to cause an operation to occur)
3. Open vs. Close Contacts: It is usually clearer to indicate deviation from normal (breaker trip, low air pressure, hot spot temperature, loss of station service, etc.). In analyzing the data, it is helpful to know that going from normal to abnormal is the same for all event inputs. Some manufacturers allow the user the option of selecting an open or a closed contact, but other manufacturers specify which it shall be.
4. Wet vs. Dry Contacts: This is the statement of who will supply the voltage to the event logic. The "wet" contact has voltage supplied from the user. The "dry" contact has voltage for the logic supplied from the recorder.
5. Logic Sensitivity (current requirements): With "dry" contact logic, the amount of current required for a closed contact multiplied by the number of logic circuits determines the size of the manufacturer's power supply. Heat dissipation can also become a problem.
6. For "wet" contacts, a ground on the battery (dc supply) should not cause a false indication. In the case where the substation battery is being used, the requirements should include "battery on overcharge". Another consideration should be "wet" cables. The current required to operate the logic input should be greater than the current that will flow between the cables going to the switchyard.
7. Contact Bounce: Contact bounce occurs whenever contacts close. It is the result of two contacts approaching each other, touching, and sliding (contact wipe) to their final

location. From “contact first touch” to “contact at rest” may be a very short time, but the current flow may be interrupted “hundreds” of times. It is important that the contact bounce be ignored. Current should flow for a predetermined time period to be considered a closed contact. This time must be coordinated with the event resolution time of the recorder.

8. Event Resolution Time: This is the time from event input to output. This time can include or not include the anti-bounce time.
9. Minimum pulse for Event Input Recognition: An interposing relay requires a pulse of a minimum duration in order to close its contacts long enough to produce an output. Pulses less than this minimum will not produce an output and hence may have occurred without any indication.
10. Event Input Delay or Extension: Some event inputs may be connected to sources that have pulse delay or extension. An example would be receipt of direct transfer trip. The DTT receiver may have “trip extension” which provides a minimum duration of as much as 100 ms rather than the actual receive trip signal. While this is the actual signal that is used to trip locally, it is not the same duration as the send duration at the remote location.

4.4 Disturbance Recorders

Various recorders have been installed at substations of different voltage levels for the purpose of monitoring the power system. Commonly used recorders are illustrated as follows.

Digital Fault Recorder (DFR) is intended to record the voltage and current waveforms, and breaker, teleprotection channel and relay digital signals pre-ceding, during, and after a fault for power system fault analysis. Usually the timestamp of the sampled points is available.

Digital Relay is designed to protect the intended circuit element. Beyond protection functionality, some digital relays may also be capable of recording certain period of voltage and current waveforms and certain digital signals. The timestamp of the sampled waveforms may not be available. Normally, digital relays have lower sampling frequency and less storage capacity than DFRs.

Sequence of Event Recorder (SER) is intended to record various status events such as breaker and relay status chronologically and is able to provide the timestamp of the events.

Dynamic Disturbance Recorder (DDR) is intended to record the long term and slow response information required for power system stability analysis. DDR saves the calculated values of concerned quantities such as the voltage, current, phase angle, power, and frequency, instead of the instantaneous values.

Remote Terminal Unit, or called Remote Telemetry Unit (RTU) is intended to report (transmit) calculated values for voltage, current and power, report breaker, alarm and relay status, and may also record sequence of events. RTU is usually intended to be part of a Supervisory Control and Data Acquisition (SCADA) system.

Serving different purposes, different types of recorders may provide different types of data at different locations in the system, and may also require special considerations for configuration and interfaces.

4.5 Synchronized Fault Recorder Testing Methodology - Overview

The following test proposal is intended for type testing, qualification testing, and performance evaluation of fault recorders. Expensive test equipment is required, which is normally only found at manufacturers, large utilities, and third party test labs. This procedure is not intended for routine field tests.

The method is to create a known signal and then measure it with the Device Under Test (DUT). Sources of error in the DUT are analyzed statistically. The result is a report characterizing the DUT's performance as a distribution of phase angle (time offset) errors, possibly including such measures as mean error, standard deviation, peak error etc. Tabular and graphic formats of presentation can be used as appropriate.

4.5.1 Synchronized Fault Recorder Testing Methodology - Procedure

1. Set up a synchronized source having known 50 or 60 Hz output phase relationships of voltage and current, relative to an absolute time reference such as UTC. Typically this would be a three-phase signal, but it could be whatever is wanted. This could be done with a three-phase test set synchronized with a GPS clock.
2. Command the recorder to take a record (a series of point-on-wave measurements), with time tags, and analyze the result using a Fourier transform to determine fundamental phase angle. This could be an FFT but a DFT would work as well, since all we care about is fundamental phase (and possibly magnitude).
3. Calculate the difference between measured and expected phase angle.
4. Repeat steps 2 and 3 for a specified number of times, for example 100 or 1000 repeats.
5. Perform a statistical analysis of the results of step 4 to determine, for example, mean phase error, standard deviation, and peak errors. This could include plotting a histogram of the measured values, which could give some insight into potential causes of measurement offsets, if any. Any uncertainties in the test standards should be accounted for as well.

This test could be repeated, if desired, for other frequencies than nominal and at various input levels, values of influence quantities etc. at the operator's discretion.

A similar test could be performed for digital inputs by using, for example, a GPS clock with a programmable-pulse output to generate pulses at known times and use them to trigger the input of a DFR. A similar analysis of the time differences could be performed.

4.6 Simplified Time Synchronization Testing

Two simplified methods are proposed for testing/validating the time synchronization of sample data (analog and digital) captured by IEDs such as Digital Fault Recorders, and modern protective (Numerical) relays with the IRIG-B output of GPS clocks. It is expected that the results will permit the “end-users” to account for any “time stamping” inaccuracies and facilitate correlation of data from different devices (IEDs) for the same power system event. The two test methods follow:

4.6.1 Correlation of Transmission Line Fault data with Lightning Stroke data

It is possible to correlate the location and time of lightning strokes that cause transmission line faults with the data in fault records captured by DFRs and IEDs. One utility has reported a one millisecond time difference between the time of a lightning stroke (from their lightning data service) and the time of ground fault inception as recorded by a GPS synchronized DFR.

One of the benefits of this approach is that data for this type of analysis already exists in utility company records. One does not have to arrange for special test equipment nor does one have to wait for a lightning stroke and fault to occur.

A secondary benefit of "mining" this type of data is that it is possible to compare the time stamping accuracy (or determine the skew) of all the IEDs that captured analog sample data for a power system fault that can be attributed to a recorded lightning stroke.

Note that representatives of two utilities have already been approached with respect to reviewing their lightning and DFR records to determine the time skew between the data from their lightning systems and IED fault records.

4.6.2 Using GPS Clock IRIG-B AM and TTL Output Signals as a Test Source

By connecting the IRIG-B modulated (AM) output to the voltage inputs of an IED and the IRIG-B unmodulated (TTL level) output to the digital inputs of the same IED it is possible to determine the accuracy of the time stamping of both the analog and digital sampled data recorded by the IED. The IRIG-B "bit patterns" captured by the IED can be decoded (manually or by software) to correlate the time from the GPS clock with the time stamp information associated with the data samples stored by the IED.

If an internal GPS receiver is used to generate an IRIG-B signal that is recorded to ensure accuracy, the recording/timestamp must be compared against and external signal.

At least one DFR manufacturer imbeds the IRIG-B data from the GPS clock in the digital event data to ensure highly accurate time stamping of the recorded analog and digital input sample data.

This proposed test method is relatively simple, provided that the IED under test (DFR, Numerical relay, etc.) has voltage and digital inputs that can be scaled / programmed to directly accept the output levels from a GPS clock. Note that the IED under test must sample at a rate greater than 2 kHz (34 samples/cycle at 60 Hz) because of the modulation of the 1000 Hz signal modulation in the modulated IRIG-B output (remember the Nyquist frequency/limit).

4.7 Event Time Correlation

Having accurate and precise knowledge of the time intervals between events during a disturbance is vital to a proper reconstruction and analysis of the disturbance. During a high-speed cascade (such as August 14, 2003), events may be separated only by milliseconds.

Illustrations of the importance of accurate and precise timing in event reconstruction are presented in this section. Some techniques for identifying the time of unsynchronized data recordings are also discussed.

Reconstruction of events, as described by this document, ultimately serves the purpose of event analysis to understand what actually happened, when it happened, and, ideally, why it happened. For example, an event analysis may find that a phase to ground fault was caused by a lightning strike and subsequently determine the location of the fault. Event analysis provides valuable input to engineers for developing remedial action plans to restore the normal operation of the system and precautionary steps to prevent future occurrence of similar events. A complete discussion of event analysis is beyond the scope of this document, but the reasons for event analysis should be kept in mind during the course of event reconstruction.

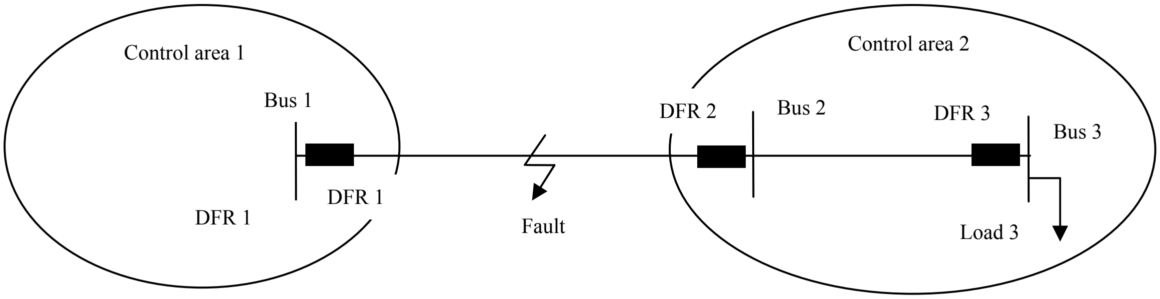
4.8 Reconstructing an Event, Sequence of Events (SOE)

When an event occurs on the power system, recorders installed at different locations may be triggered at different moments to record specific information that reflects different aspects of the same event during the course of the event. Normally, the records obtained by different recorders can be transferred to a central control office for further analysis.

If different recorders are synchronized to the same time reference, then the records provided by different recorders may be correlated with each other to reconstruct the event and thus provide a clearer and more complete picture of the entire event.

The input data that may be needed for analyzing the event usually include both analog data such as phase currents, residual current, phase voltages, and residual voltage and digital data such as primary and backup relay trip, breaker open/close position, breaker failure contact, carrier start, and carrier received contacts, etc.

The following is an example of using the records from different recorders to reconstruct an event. A sample power system is shown as follows, in which control area 1 is exporting energy to control area 2 at a rate of 500 MW. DFRs are installed at bus 1, 2 and 3. Distance relays are installed at each bus. An underfrequency relay is installed at bus 3.



Suppose that a fault occurred on the tie line between bus 1 and 2, and the digital fault recorders had the following information:

DFR 1
The distance relay at bus 1 tripped at 13:20:03.011 (13:20, with seconds 3 and milliseconds 11)
The breaker at bus 1 opened at 13:20:03.071

DFR2
The distance relay at bus 2 tripped at 13:20:03.014
The breaker at bus 2 opened at 13:20:03.085

DFR3
The underfrequency load shedding relay at bus 3 tripped at 13:20:08.030
400 MW of Load 3 at bus 3 is shed at 13:20:08.050

Based on the records, it can be determined that the following sequence of events occurred:

- A fault occurred on the tie line
- The distance relay at bus 1 tripped at 13:20:03.011, and the breaker at bus 1 operated correctly and opened the line after 60 ms after receiving the tripping signal.
- The distance relay at bus 2 tripped at 13:20:03.014, and the breaker at bus 2 operated correctly and opened the line after 71 ms after receiving the tripping signal.
- Since the imported power is cut off, control area 2 has a shortage of power. The underfrequency load shedding relay at bus 3 tripped at 13:20:08.030, and 400 MW of Load 3 was shed at 13:20:08.050 to maintain the system normal frequency.

By taking advantage of the voltage and current waveforms, the time taken by the relay to issue a tripping signal from the fault inception moment can also be calculated, which can be used to evaluate the relay performance. The recorded system frequency locus during the event can also be used to evaluate the performance of the underfrequency load shedding relay.

4.9 Simulating an Actual Event

An event can be reconstructed using the available recorded data. To perform the reconstruction, the event may be simulated or replayed using specific simulation techniques. This type of simulation study enables us to better understand the cause of the event, verify the model, and develop any appropriate remedial actions.

To simulate an event, the initial power system model is built first. Depending on the type of disturbance, power system models corresponding to different abnormal conditions as obtained by the event reconstruction may also be built, and/or dynamic models for the power system components may also be included. Numerous simulation tools exist; two widely used programs are Power System Simulator for Engineering (PSS/E) and PSLF. The simulation is then performed using the models to estimate quantities of interest such as the voltage and current magnitudes and angles. The simulated quantities can then be compared to the values directly obtained from the recorders or calculated from the recorded data. Significant discrepancy between simulated and recorded data, if any, may indicate inaccuracy of the system model or wrong interpretation of the event. Correspondingly, either the system model is modified, or the sequence of events is further analyzed and adjusted. Then the event can be simulated again using the new system model and/or new sequence of events. This process can be iterated until a close match between the quantities obtained from simulation studies and those obtained from the recorded data is obtained.

An alternate approach to simulating an actual event involves the use of a low-level test set that allows playback of event recorder files into a protective device and monitor the device's response. Using application software, a COMTRADE or similar format file can be played back into the test system. The outputs of the system (three-phase voltage and three-phase current) are at signal levels (0 - +/- 10 volts). If the protective device has provisions for accepting a low-level input signal, the test system can repeatedly provide the device with waveform playback and monitor its output contacts. Multiple protective devices could be connected to the test system to compare performance and timing under the same fault event sequence. Although this is a more hardware specific approach, it can be seen that similar results can be obtained by playing back either a simulation created event file or an actual event recorder file.

4.10 Event Reconstruction – Powerflow vs. Dynamics Modeling

In performing a reconstructive simulation of a power system disturbance, it is important to identify the type of analysis that is to be performed. There are two broad categories of such analysis: powerflow and dynamics. However, the dynamics category can be further subdivided into transient stability and mid-term dynamics.

Powerflow analysis is used to analyze disturbances which evolve relatively slowly, with events being separated by minutes. Under these conditions, a constant real and reactive power load model is usually used. A comparison of power flows with facility ratings can be performed to assess the causes of many types of events, such as the contribution of line sag to ground faults and certain relay actions.

If the disturbance is characterized by transient instability, a dynamics (transient stability) program is a useful tool for the replication. Such programs are generally intended to represent a time period of about 30 seconds after the initiating event. Discrete events in this type of disturbance are separated only by milliseconds. A static load model may be used, or a model which represents load dynamics (particularly motors) can be included. The appropriate load model to use depends on the disturbance being studied; a dynamic load model is likely to be more accurate but may be computationally prohibitive for large scale disturbances.

Mid-term dynamics describes a disturbance which evolves more slowly than transient instability but which is dynamic in nature and hence cannot be adequately represented with powerflow analysis. Voltage collapse is a classic example of such a disturbance; powerflow models of a system in voltage collapse will not converge, but the dynamics of such a system have time constants on the order of 30 to 60 seconds. To model such disturbances, a long-term or mid-term stability program is the ideal tool. However, the data requirements for such a program are enormous, and much of this data is not readily available. To get around this problem, a transient stability program is often used, with additional models added or other adjustments applied to approximate the behavior of dynamics that have longer time constants and are not explicitly modeled (such as LTCs).

Occasionally, some of these additional models may be desirable to add to a transient stability simulation as well. For example, a model of turbine dynamics which represents the loss of mechanical power after a unit trip while the generator is still electrically connected to the grid may be needed to represent certain observed phenomena.

Regardless of the type of reconstructive analysis performed, benchmarking of the starting powerflow model to observed conditions is vital for a meaningful analysis of the disturbance. Voltages, line flows (real and reactive), generator outputs (real and reactive), shunts, phase angle regulator settings, and transformer taps all need to match their actual values on the power system at the start of the event as closely as possible in order to derive value from the simulation, particularly when "what-if" questions are modeled. Needless to say, both network and dynamic model parameters also need to accurately reflect the characteristics of the power system.

4.11 Determination of Event Times from Non-synchronized Disturbance Monitoring Equipment

Because of the rapid pace at which events occur when the power system becomes unstable, precision in event time resolution is critical for a proper analysis of the resulting cascade. However, many dynamic recording devices on the power system are not GPS-time synchronized. In order to precisely calculate event times using data from these recorders, a means of computing the time skew between the recorder clock and the actual time needs to be developed.

For stations with disturbance monitoring equipment near events of interest, recordings can be first selected based on the raw, unsynchronized time. A frequency trace can then be calculated from the voltage in these recordings by measuring time between zero crossings. The frequency trace provides a rough indication of the time the recording was actually made. In general, a steady 60 Hz frequency indicates a recording from a stable period prior to a high-speed cascade, whereas significant frequency fluctuations of 0.5 Hz or more indicate data taken during or possibly after a cascade. A frequency that is relatively steady, but not near 60 Hz, indicates a post-cascade recording.

This frequency information can be compared with frequency traces from other station recorders showing events of known times to more accurately determine the time of the recording. If available, the frequency in a dynamic simulation may also be used to assist in identifying the recording time. Since frequency tends to be relatively uniform over a broad area, comparisons of frequency are possible among recordings from multiple stations, obtained by DMEs such as DFRs. Additionally, real and reactive power line flows can be calculated for some recordings using the voltages and phase currents in the data (particularly DFRs). These power flows, along with the voltage, provide another means to identify the approximate time frame of a recording. The availability of voltage and current from all three phases in such data records greatly enhances the ability to make such comparisons.

The derived frequency plots from DFR recordings often show spikes. These spikes have been found to correspond to discrete events such as line and generation trips. Step changes in voltage and current are also observed in many recordings, indicating events. In many cases, a DFR at one end of a line that trips will record the line trip, making it easy to identify the cause of the frequency spike in that recording. This spike can then be identified in DFR recordings from other stations in the area by comparing the frequencies and other quantities. However, in some cases, a line trip will not be directly observed by a DFR at either end of the line. In these cases, some deductive reasoning needs to be applied to determine the event that is being observed, often using data from multiple dynamic recorders.

The timing of the spikes and accompanying voltage and current changes can be used to establish a precise synchronization between disturbance recordings from different stations after performing the general frequency match described above. The time duration between spikes precisely indicates the elapsed time between two events. By finding an event of known NIST time in the disturbance recordings, other event times can be calculated by measuring the time difference between events.

REFERENCES

A web page is being maintained by the Working Group which contains all the references which can be displayed without copyright violation. The address of that page is: http://www.pes-psrc.org/i/ITF2report.html

(1) The Perfect Time: An Examination of Time Synchronization Techniques, Ken Behrendt and Ken Fodero, presented at 2006 Protective Relay Conference at GA Tech, May 3–5, 2006.

(2) NPCC SP-6 Report, Synchronized Event Data Reporting, February 9, 2005, Technical Revision - March 31, 2005, available at address: www.npcc.org/

(3) IRIG Serial Time Code Formats, IRIG Standard 200-04, public document.

(4) Analysis of Oscillograms, Jack Chadwick, from 2000 Fault & Disturbance Analysis Conference, by permission.

(5) Time Scales and Time Zones (PPT), Jim Ingleson, from 2006 Fault & Disturbance Analysis Conference, presented at 2006 Fault and Disturbance Analysis Conference at GA Tech, May 1-2, 2006. Background material document for this PPT is available from the author.

(6) A. G. Phadke, "Synchronized phasor measurements", IEEE Computer Applications in Power, April 1993, p.p. 10-15.

(7) NERC "Glossary of Terms Used in Reliability Standards," November 1, 2006, available at www.nerc.com

(8) NERC Standard PRC-002-1, "Define Regional Disturbance Monitoring and Reporting Requirements," adopted by NERC BOT on 08/02/06 and effective on 05/-2/07, available at www.nerc.com.

(9) NERC Standard PRC-018-1, “Disturbance Monitoring Equipment Installation and Data Reporting,” adopted by NERC BOT on 08/02/06 with effective dates phased in over four year period beginning 08/02/06, available at www.nerc.com.

(10) NPCC Document B-25, “Guideline to Synchronization of Substation Equipment,” dated August 21, 2006, and available at this address: www.npcc.org/

(11)NPCC Document B-26, “Guide for Application of Disturbance Recording Equipment,” dated September 6, 2006, and available at this address: www.npcc.org/

(12) Time and Frequency Measurements Using the Global Positioning System, Michael Lombardi, Lisa Nelson, Andrew Novick, Victor Zhang, Time and Frequency Division. National Institute of Standards and Technology. Available at address: tf.nist.gov

(13) IEEE 1588 Standard for a Pecision Clock Synchronization Protocol for Networked Measurement and Control Systems

Some Useful Links Relating to the subject:

www.webopedia.com/TERM/G/GPS.html

www.answers.com/topic/global-positioning-system

tf.nist.gov

ieee1588.nist.gov