Timing Options and Tradeoffs for Automation and Wide Area Measurement Systems – Timing Is Everything

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***Abstract*—Some form of "high-accuracy" timing has been considered a requirement in automation systems such as sequential events recording (SER) and digital fault recording (DFR) systems for many years. The advent of wide area measurements, as well as wide area event analysis, makes new demands on timing systems. Timing accuracy has evolved from the seconds range, a few decades ago, to the millisecond range, a few years ago, to the microsecond range of today.**

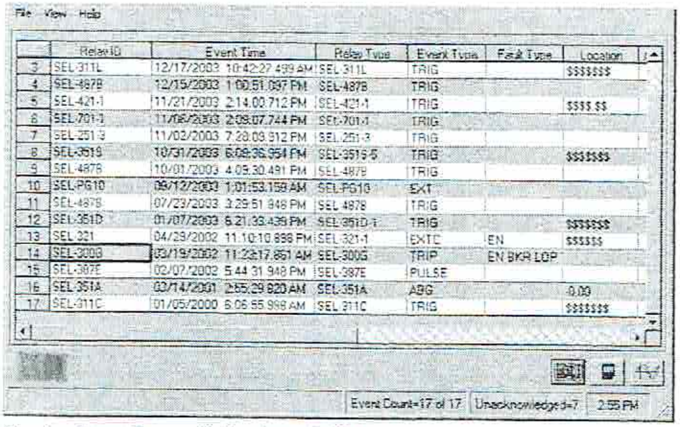
Troubleshooting system problems is simplified and improved by using SERs as a basis for information with very high-accuracy timing. Signal transmission times must be significantly more accurate than the millisecond range in order to determine cause and effect. Automated event retrieval and analysis systems become far less useful if high-accuracy timestamping is not included in the report format.

This paper explores the accuracy requirements for different power system applications and the different timing sources available for meeting those applications. It also discusses how time signals are distributed to the measurement devices and how that impacts accuracy. The economic tradeoffs of different installation options and their impact on application devices are also examined in this paper.

Examples from installations and power system events are included for illustration with root cause analysis to demonstrate how timing has become vital to the automation of today's power delivery systems.

I. INTRODUCTION

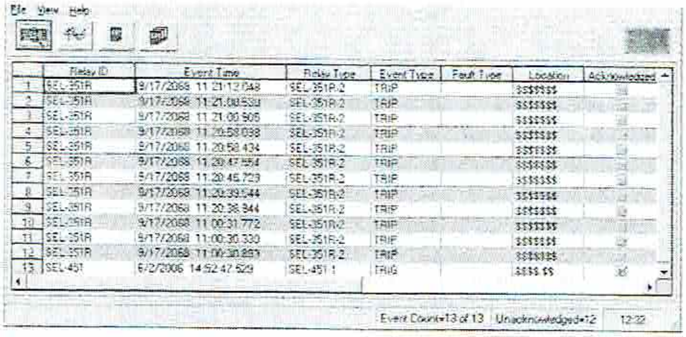
Determining the root cause of system problems is key to correcting those problems. The most basic factor in distinguishing between the cause of a problem and its effect is determining which happened first. This is one of the primary reasons that SER and automated event collection systems exist and why they have proven useful on numerous occasions. The key to this usefulness lies in the time tagging associated with the different events. Consider the portions of the event report collections in Figs. 1 and 2.



	Relay ID	Event Time	Relay Type	Event Type	Fault Type	Location
3	SEL-311L	12/17/2003 10:42:27.499 AM	SEL-311L	TRIG		$$$$$$$
4	SEL-487B	12/15/2003 1:00:51.097 PM	SEL-487B	TRIG		
5	SEL-421-1	11/21/2003 2:14:00.712 PM	SEL-421-1	TRIG		$$$$.$$
6	SEL-701-1	11/06/2003 2:09:07.744 PM	SEL-701-1	TRIG		
7	SEL-251-3	11/02/2003 7:28:09.912 PM	SEL-251-3	TRIG		
8	SEL-351S	10/31/2003 6:08:36.954 PM	SEL-351S-5	TRIG		$$$$$$$
9	SEL-487B	10/01/2003 4:09:30.491 PM	SEL-487B	TRIG		
10	SEL-PG10	09/12/2003 1:01:53.159 AM	SEL-PG10	EXT		
11	SEL-487B	07/23/2003 3:29:51.848 PM	SEL-487B	TRIG		
12	SEL-351D	01/07/2003 6:21:33.439 PM	SEL-351D-1	TRIG		$$$$$$$
13	SEL-321	04/29/2002 11:10:10.898 PM	SEL-321-1	EXTC	EN	$$$$$$
14	SEL-300G	03/19/2002 11:22:17.861 AM	SEL-300G	TRIP	EN BKR LOP	
15	SEL-387E	02/07/2002 5:44:31.948 PM	SEL-387E	PULSE		
16	SEL-351A	03/14/2001 2:55:29.820 AM	SEL-351A	ABG		0.00
17	SEL-311C	01/05/2000 6:06:55.998 AM	SEL-311C	TRIG		$$$$$$$

Event Count=17 of 17 | Unacknowledged=7 | 2:55 PM

Fig. 1. Event Report Collection—Different Dates



	Relay ID	Event Time	Relay Type	Event Type	Fault Type	Location	Acknowledged
1	SEL-351R	9/17/2008 11:21:12.048	SEL-351R-2	TRIP		$$$$$$$	☐
2	SEL-351R	9/17/2008 11:21:00.530	SEL-351R-2	TRIP		$$$$$$$	☐
3	SEL-351R	9/17/2008 11:21:00.905	SEL-351R-2	TRIP		$$$$$$$	☐
4	SEL-351R	9/17/2008 11:20:58.098	SEL-351R-2	TRIP		$$$$$$$	☐
5	SEL-351R	9/17/2008 11:20:58.434	SEL-351R-2	TRIP		$$$$$$$	☐
6	SEL-351R	9/17/2008 11:20:47.554	SEL-351R-2	TRIP		$$$$$$$	☐
7	SEL-351R	9/17/2008 11:20:46.729	SEL-351R-2	TRIP		$$$$$$$	☐
8	SEL-351R	9/17/2008 11:20:39.544	SEL-351R-2	TRIP		$$$$$$$	☐
9	SEL-351R	9/17/2008 11:20:38.344	SEL-351R-2	TRIP		$$$$$$$	☐
10	SEL-351R	9/17/2008 11:00:31.772	SEL-351R-2	TRIP		$$$$$$$	☐
11	SEL-351R	9/17/2008 11:00:30.330	SEL-351R-2	TRIP		$$$$$$$	☐
12	SEL-351R	9/17/2008 11:00:30.893	SEL-351R-2	TRIP		$$$$$$$	☐
13	SEL-451	6/2/2006 14:52:47.529	SEL-451-1	TRIG		$$$$.$$	☒

Event Count=13 of 13 | Unacknowledged=12 | 12:22

Fig. 2. Event Report Collection—Different Times

In a collection of relay events such as those shown in Fig. 1, even though the time is shown to the millisecond, it could be argued that only the date matters. Because no two events happened on the same day, it is only important to distinguish between days to determine which event happened first.

In Fig. 2 we see 12 events in a 21-minute time span with several events happening within a half a second of each other. In this situation, timing data are necessary to order the events.

We can gain significant experience from the blackout investigation of August 14, 2003, regarding practical requirements of a large event analysis. "More than 800 events occurred during the blackout of August 14. The events included the opening and closing of transmission lines and associated breakers and switches, the opening of transformers and associated breakers, and the tripping and starting of generators and associated breakers. Most of these events occurred in the few minutes of the blackout cascade between 16:06 and 16:12 EDT. To properly analyze a blackout of this magnitude, an accurate knowledge of the sequence of events must be obtained before any analysis of the blackout can be performed" [1].

Additional examples of event reports, discussed later in this paper, show critical time differences in the millisecond or even microsecond range.

Different applications and circumstances mandate different levels of timing precision. Examining how to achieve this precision leads to a number of different requirements.

II. TIME INPUTS

There are a number of different methods for providing the time (and date) to protective relays and other IEDs within a substation. These include manual input, remote communications, such as DNP time distribution, and satellite-synchronized clocks either directly connected to an IED or through a communications processor.

A. Manual Time Input

The simplest and possibly most common time input method is to type the date and time using a connected computer. Given anticipated events such as those shown in Fig. 1, this would seem to offer sufficient precision for many circumstances. Experience shows otherwise. Again, from the August 14 blackout investigation, "…not all of the time-stamps were synchronized to the National Institute of Standards and Technology (NIST) standard clock in Boulder, CO. Validating the timing of specific events became a large, important, and sometimes difficult task" [1]. Anecdotally, many of the event reports that were used as part of the investigation were off by several days.

The question then arises, how does an internal clock in an IED get that far off? Consider a typical IED timing accuracy of 10 ppm [2]. With 86400 seconds per day, this equates to roughly one second of possible timing drift per day. Therefore, to drift one day off of a set value would take 86400 days, or 236 years. Clearly, a factor other than timing drift is involved.

If set correctly, IEDs cannot be expected to experience a time drift from manual settings that would account for the observed number of IEDs that had time-synchronism errors; then the most likely cause is that the time was not set correctly in the first place. Consider what needs to be done to manually set the time in an IED, typically a multistep process [3].

After going to the appropriate communications access level in the IED, the date display and recording must be set to the desired format, either month-day-year (MDY), year-month-day (YMD), or day-month-year (DMY). The operator then inputs the command followed by the date in the appropriate format. For example, let us use the command "DATE 04/09/2007." Here we already have two serious sources of potential error. The date given in the example can be either April 9, 2007 or September 4, 2007, depending on the format selected. If the two settings are not done at the same time by the same person, there is a reasonable chance that the "correct" date input will be understood by the IED incorrectly.

Another source of error is that the date is just typed in wrong. In a nonpower system-related incident, a stockbroker meant to offer one share of stock at a price of 610,000 yen. Instead, he typed in 610,000 shares at one yen. The resulting error cost his company over 27 billion yen ($225,000,000). Because of the very serious consequences involved in this and other similar occurrences, there have been numerous studies conducted regarding errors in typed information. One collection of studies gives error ranges from 0.5% per zip code (following error correction) to 7.4% per word for trained secretaries typing nonsense words [4]. Given the limited possibility of error correction in typing a date into an IED, the higher end of this range would seem reasonable.

Another example is very relevant to the power industry: "Prof. Alan Hedge, Cornell University, found typing accuracy depends on room temperature. At 77°F employees had a 10% error rate. At 68°F speed slowed by almost half, and error rate rose to 25%" [5]. Considering that substation control houses and remote IEDs, such as recloser controls and voltage regulator controls, are very likely to be in the lower temperature range rather than the higher temperature range, a character string could readily have at least a 10% chance of being entered incorrectly. If we add the probability of either the time or date having an error in the input string, then we have roughly a 20% chance of a significant error.

From this it can be concluded that if any time accuracy (even to the day) is required, there is a need for some automated time input to the IEDs on a power system.

One example of this need was on a recloser control returned to a factory with severe burns and even partial cabinet melting, as shown in Fig. 3.

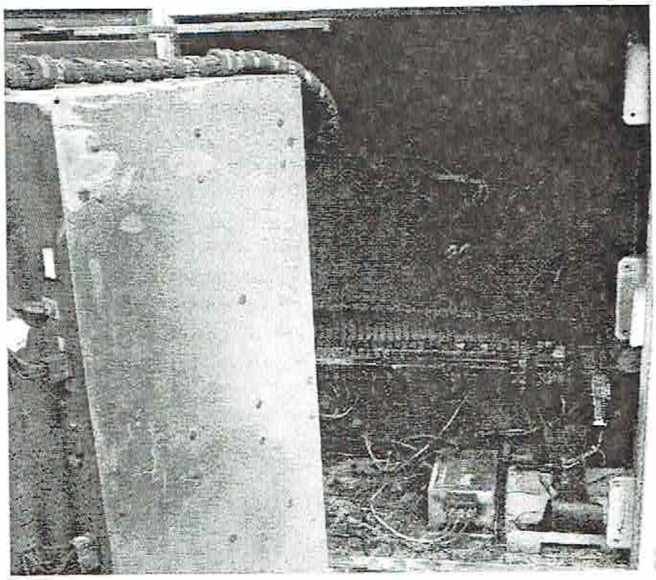


Fig. 3. Burned-Out Recloser Control

The electric utility wanted to know what had happened in order to make sure their corrective actions were appropriate. Even though the power supply was destroyed, the memory of the control was intact, and the last event was downloaded. The record showed that the last event in memory occurred on the 10th day of the month. The utility responded that the meltdown occurred on the 12th, so the last event must have been lost in the surge and fire. More work was done to try and recover later events but none were found. The utility was told that on the 10th, the control had issued a trip command, reclosed into a fault, and issued a second trip command with the interrupter not operating before the end of the record. The utility responded that this appeared to be the failure sequence that happened on the 12th. The date in the recloser was off by two days, causing hours of extra work at the control factory and utility to clarify what could have happened. Accurate date and time at the recloser control would have been very beneficial to avoid the extra work to identify the last event.

B. *Communications-Based Timing*

Supervisory control and data acquisition (SCADA) protocols have the ability to send a time signal to connected devices. Even though the SCADA master can be connected to a high-accuracy clock, there is a loss of accuracy in transmission time to connected remote units. Typical time-tagging accuracy in late 1970s systems was between 5 and 15 milliseconds [6]. While this signal could be transmitted to individual IEDs, it is more practical to use a communications processor at a substation that retransmits the time to connected devices in the form of an IRIG-B protocol. Of course, no accuracy is gained through this DNP to IRIG conversion, but it is an improvement, on many levels, to using a wristwatch and typing.

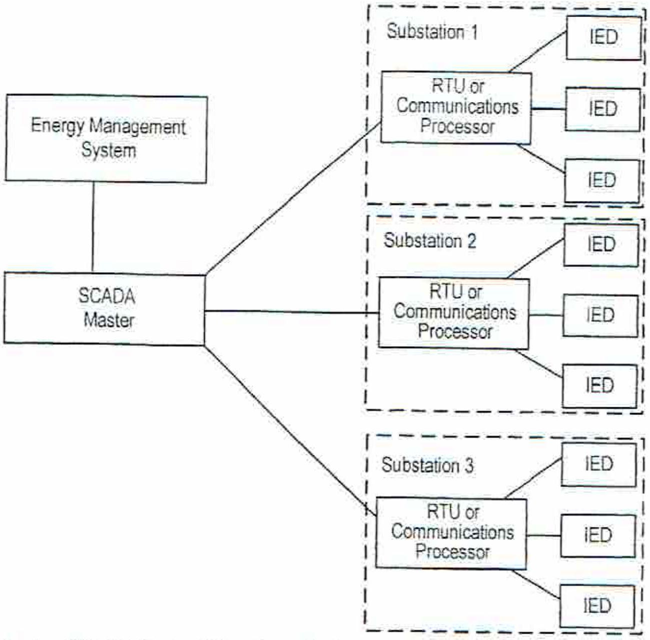
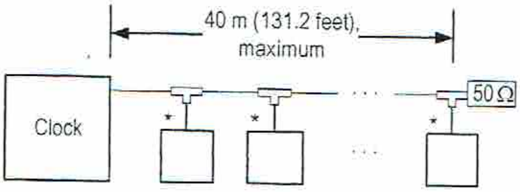


Fig. 4. SCADA System Time Distribution [7]

The timing distribution in Fig. 4 has the advantage of using a single, centralized time source to provide the time to many connected devices. The disadvantage, as discussed in the next section, is the loss of accuracy as compared to individual time inputs at each location.

C. *Local Clock Time Inputs*

The best method of providing accurate time to IEDs is to use a directly connected time source. A single, local clock in a substation can be used to distribute time to many connected devices, as shown in Fig. 5.



* Keep this connection as short as possible.

Fig. 5. Connection of Multiple IEDs to a Single Clock Output

Establishing guidelines for distributing the time signal is critical to achieving the benefits of a local clock. Proper connections are needed to ensure that an adequate time signal is received at the IED. A perfect square wave cannot exist in a real system, but time-signal receivers compensate for that by using thresholds, as shown in Fig. 6.

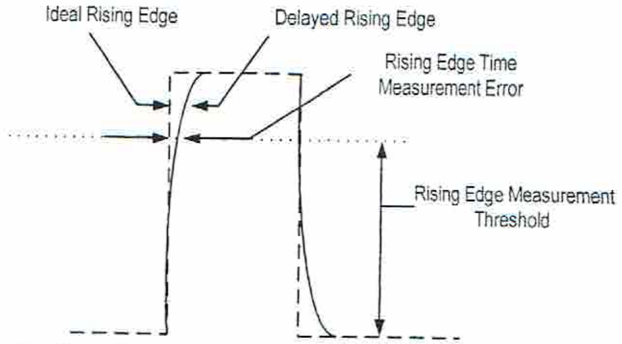


Fig. 6. Time-Signal Waveform

The importance of using proper terminations and connections can be shown by using a test circuit, as shown in Fig. 7.

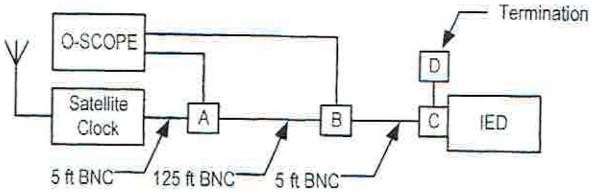


Fig. 7. Timing Wave Test Circuit

By measuring the signal at Points A and B we can assess the need for proper terminations.

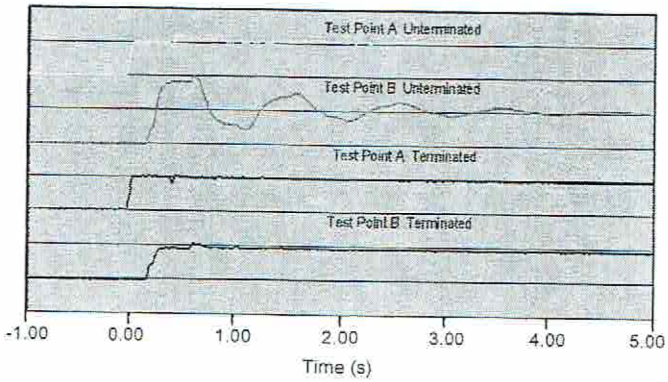


Fig. 8. Waveform Test Results

It can be seen from Fig. 8 that to set a threshold at Point B on an unterminated system with multiple IEDs would be very difficult if not impossible. It is also clear that terminated wiring provides a very high-quality signal even at the maximum lengths used.

III. TIME CORRECTION METHODS

Event reports, especially those collected automatically, come in with whatever time tag is assigned by the initiating IED. When these reports are evaluated, it is critical to put them on the same time basis. Different methods can be used, depending on the precision of the time alignment required to properly analyze the event.

A. Reference Subtraction

Fig. 9 illustrates a system example with an event requiring a moderate amount of time alignment.

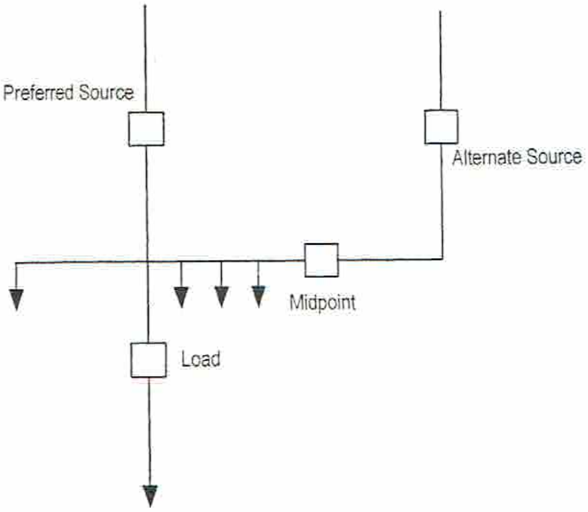


Fig. 9. Recloser Network Feeding Industrial Loads

In the event under analysis, the preferred source, midpoint, and load reclosers all locked out, blacking out a large industrial facility. Because there was an automatic throw-over scheme from the preferred to alternate sources, and no permanent faults were identified, it was thought that a coordination problem was the root cause of the power loss. This followed an initial fault on the source side of the system that lowered the voltage, resulting in an attempt to switch to the alternate source. In all the recloser controls, however, the time had never been set. In addition to comparing events between reclosers, it was also desirable to compare reclosing shots with loss of power at the industrial load points and motor inrush.

To begin the event and coordination analysis, an engineer looked at the time on each recloser. Because they were all fully functional, he was able to compare the recloser "apparent" time with the true local time. The results are shown in TABLE I.

TABLE I
TIME CORRECTION FOR RECLOSER CONTROLS

	Preferred Source	**Midpoint**	**Load**	**Alternate Source**
Recloser Time	5:35:00 AM	6:57:25 AM	5:42:56 AM	6:21:54 AM
Local Time	9:25:00 AM	10:50:00 AM	9:35:00 AM	10:06:00 AM
Time Correction	3:50:00.000	3:52:35.000	3:52:04.000	3:44:06.000

Using the time correction values from TABLE I, the engineer imported the event reports into a spreadsheet with a section for each recloser control, as shown in Fig. 10.

In order to see this a little clearer, refer to the enlarged sections in Fig. 11, showing just two rows of data from two controls.

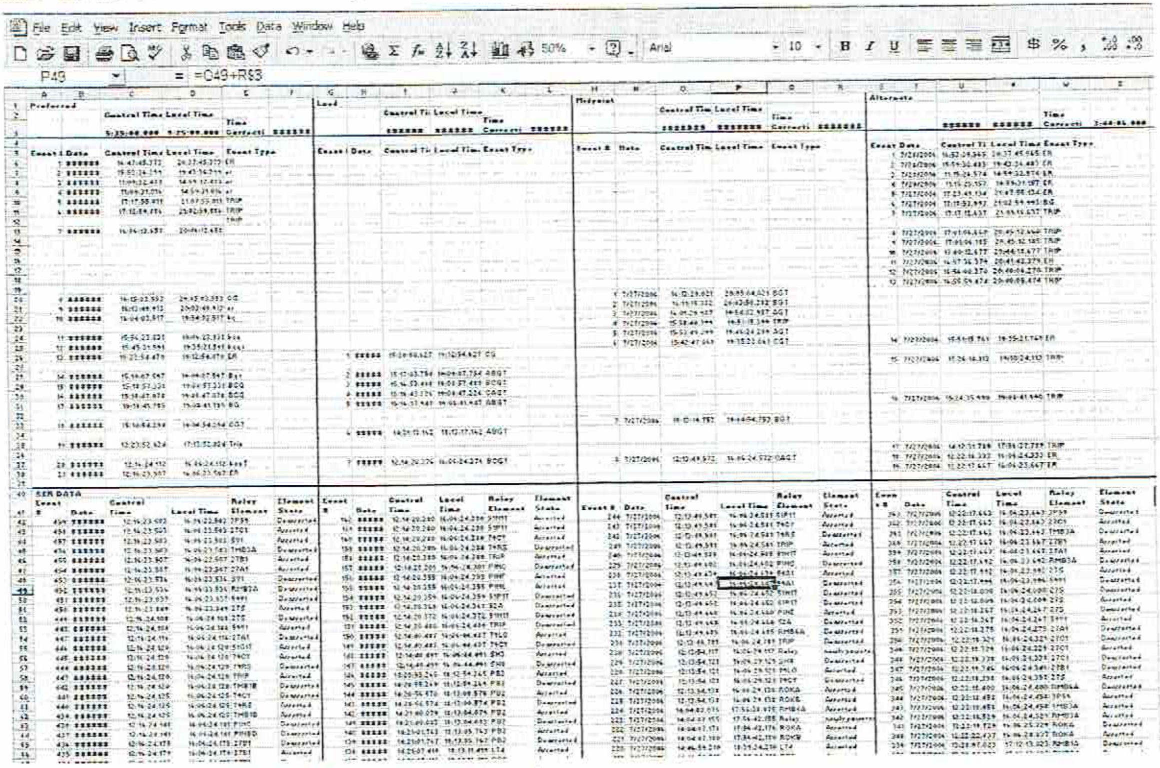
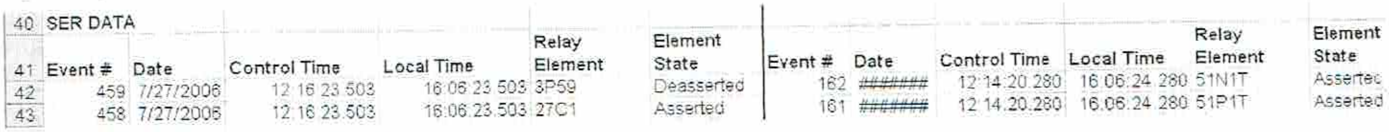


Fig. 10. Spreadsheet With Time and Events From Each Recloser Control



40	SER DATA										
41	Event #	Date	Control Time	Local Time	Relay Element	Element State	Event #	Date	Control Time	Local Time	Relay Element	Element State
42	459	7/27/2006	12:16:23.503	16:06:23.503	3P59	Deasserted	162	#######	12:14:20.280	16:06:24.280	51N1T	Assertec
43	458	7/27/2006	12:16:23.503	16:06:23.503	27C1	Asserted	161	#######	12:14:20.280	16:06:24.280	51P1T	Asserted

Fig. 11. Enlarged Sections of Spreadsheet Rows

The control only "knows" its own time, referred to here as control time. However, once the data are imported into a spreadsheet, a column can be added to give the local time. Note that the control times in the two sections in Fig. 11 differ by more than two minutes, while the local times (as corrected using the factors from TABLE I) differ by less than one second.

Using this methodology, the engineer was able to time-align the hundreds of internal events from each control that made up the end result of a blackened industrial site. Once the events were lined up, it was determined that the coordination between controls and some details of the transfer system were not appropriate for the current levels involved.

It is interesting to note a comment from the engineer doing the analysis. "The time alignment took four solid days of work and it will take it again the next time lightning strikes. It would be a whole lot easier if there were clocks to synchronize the controls."

B. Common Observation Quantity Alignment

Because multiple IEDs will experience the same event on a power system, the record of these events can be used to time synchronize the different devices to a high level of precision. To see how this works, we can look at the waveform captures in Figs. 12 and 13, which show the initial drop in voltage from the preferred and alternate sources in Fig. 9.

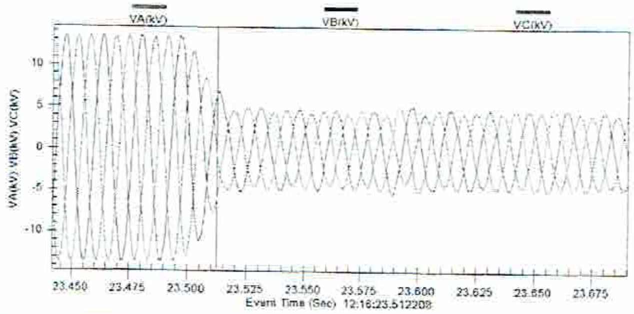


Fig. 12. Preferred Source Voltage Drop, Uncorrected Event Report

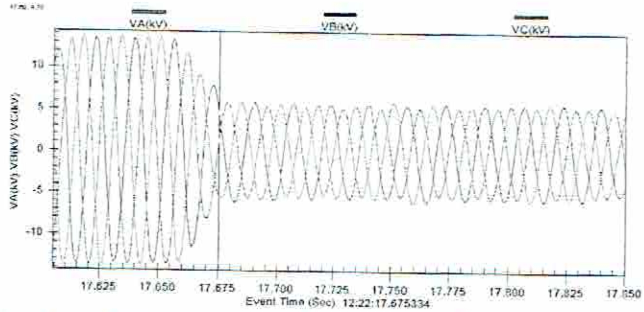


Fig. 13. Alternate Source Voltage Drop, Uncorrected Event Report

There are a few key pieces of timing information to look at in these reports. First, this is relative information only. We can see that from the vertical line, which marks the event time in each report, there are 5 minutes and 54 seconds between the two reports. This corresponds to the difference in the two times from TABLE I, but it does not include the roughly three hours necessary to bring the control time to true local time.

The real advantage of using an oscillographic record is in the precision that can be gained when compared to a simple clock difference check as done for TABLE I. Noting the event times, we can subtract the two times to have (1):

$$12{:}22{:}17.675334 - 12{:}16{:}23.512208 = 5{:}54.163126 \quad (1)$$

The result of (1) should be modified in two ways before using it to correct the time in the events. First, recognition of the sampling rate should be considered by discarding the last three digits. While there are some devices that may use microsecond accuracy, a recloser control is not one of them. The second modification is to recognize that the event line does not cross the same wave point in the two reports. This is because synchronous sampling is not done in the two devices. If the two IEDs had synchronous sampling, such as is provided with a synchrophasor-equipped device, then the points would have been lined up perfectly with no need to estimate the time between two samples. To move the alternate source event line to the left to match the same point on the voltage wave as the preferred source, we should subtract about three milliseconds from its time. This gives us the corrected result in (2):

$$5{:}54.163 - 0.003 = 5{:}54.160 \quad (2)$$

In other words, by subtracting 5 minutes, 54 seconds, and 160 milliseconds from the alternate source time, it will line up with the preferred source to about one-millisecond precision.

In the reclosing example, one millisecond is considerably more precise than is needed for correcting a coordination problem involving, perhaps, a few tenths of a second. Other applications make those few milliseconds critical. Consider the system in Fig. 14 with connected relays forming a bus protection scheme.

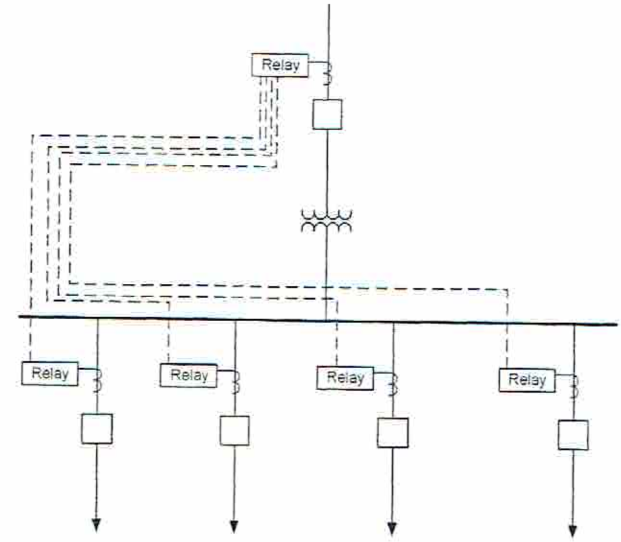


Fig. 14. Bus Protection Using Combined Feeder Relays

In this system, operation of any of the feeder relays blocks operation of the main relay. This can speed operation for bus faults, while maintaining security against tripping the bus for faults only involving one feeder. In a new installation of this scheme, the main breaker appeared to trip for a bus fault.

In this case, the relays involved used a time source that gave an accuracy of about ±5 milliseconds. When the event reports from the main breaker relay and the faulted feeder relay were combined on one screen, the results (only showing digital inputs and outputs) were as shown in Fig. 15.

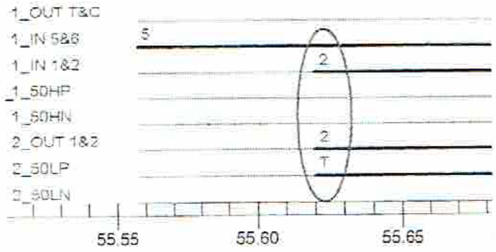


Fig. 15. Digital Inputs and Outputs With Uncorrected Time

Feeder Relay 2 (the bottom three traces) is shown tripping and sending a block signal to Main Relay 1 (the top 5 traces) at a time equal to 55.62 seconds. At exactly the same time, Main Relay 1 received a trip input. Any contact input to a relay takes some amount of time before it is recognized due to processing considerations and debounce timing requirements. In this case, a simultaneous block sent by one relay cannot be received as a trip input by another relay, so the false trip must have been caused by something else.

Because both of the relays saw the feeder fault, it was possible to use the fault-current jump as a time-alignment tool as in the previous example. With this alignment precision, the contact outputs were seen as shown in Fig. 16.

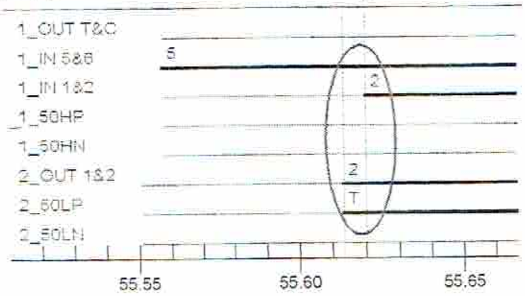


Fig. 16. Time-Aligned Inputs and Outputs

Notice that there is now a seven-millisecond difference between the output of the feeder relay and the trip input of the main relay. This is perfect for the case where the blocking input was incorrectly wired to the trip instead of block, which is what technicians found when they examined and tested the actual wiring.

While the difference of a few milliseconds did not matter in a recloser coordination system, when looking at the timing between inputs and outputs that amount made all the difference.

IV. PRECISE-TIME APPLICATIONS

In the recloser control coordination example in Fig. 9, a timing accuracy of one second was sufficient to identify the relative operating time sequence. In the interconnection wiring example in Fig. 14, a shift of seven milliseconds made clear a cause and effect relationship that was impossible with "uncorrected" time. The key is that the time error must be small compared to the minimum timing of interest.

Because communications timing (or even the proper setting of protection scheme values) is frequently critical to analysis, it is interesting to note the range of times for different communications systems, as shown in TABLE II [8].

TABLE II
COMMUNICATIONS TIMES FOR DIFFERENT SYSTEMS

Device	Max Baud Rate	Time
Multiplexer	19200	2–4 milliseconds
Audio Modem	9600	12 milliseconds typical
Spread-Spectrum Radio	38400	4 milliseconds
Fiber Modem	38400	< 1 millisecond
Leased Digital Phone Line (CSU/DSU)	64000	5–20 milliseconds

These times are typical for a range of communications systems that also include Ethernet protocols and microwave systems. In order to have a time precision significantly smaller than the time of interest, it is clear that a minimum accuracy of one millisecond or less is required.

Phase angle measurements add another level of accuracy requirement to timing systems. This is brought about by the timing resolution required to measure phase angles and the differences in phase angles that can cause major system disturbances. Consider a test system such as the one shown in Fig. 17 [9].

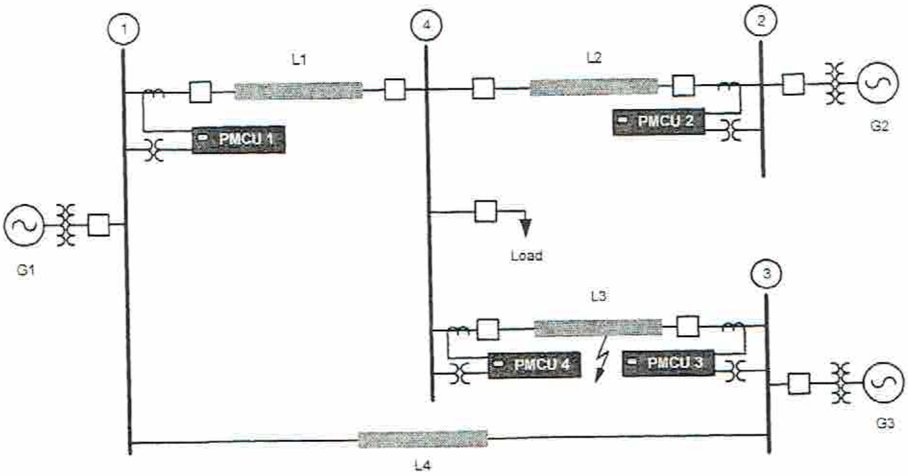


Fig. 17. Test System for Phase Angle Measurement of Stability

As the load on Bus 4 is increased, the system becomes less stable when a fault occurs on Line 3. This loss of stability is independent of fault-clearing time on the line. The increasing load can be seen as a prefault angular difference between Bus 2 and Bus 4. Following a fault on Line 3, the system will experience an oscillation that will either decrease (stable) or increase (unstable). The graphs in Figs. 18 and 19 show this happening.

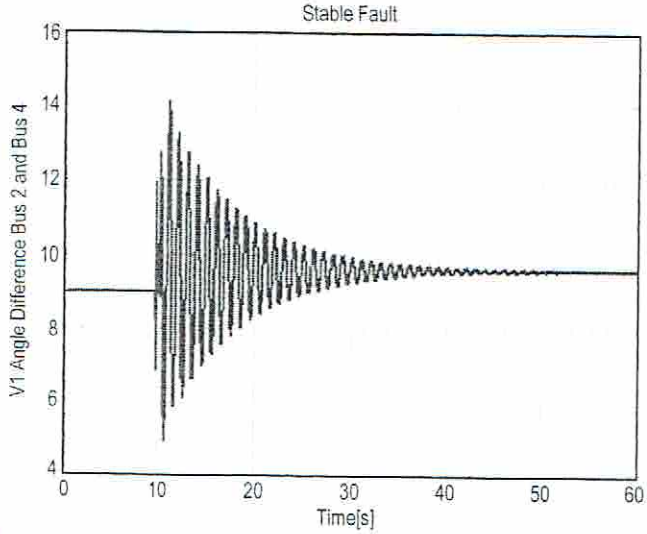


Fig. 18. Voltage Angle Between Bus 2 and Bus 4 Before and Following a Stable Event

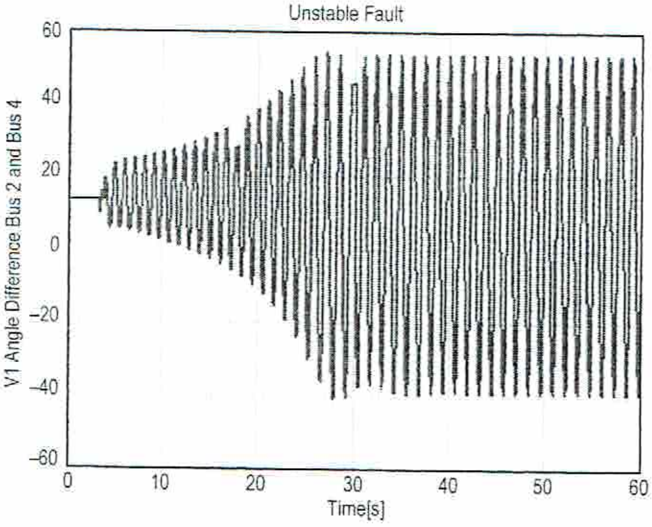


Fig. 19. Voltage Angle Between Bus 2 and Bus 4 Before and Following an Unstable Event

It can be seen from Figs. 18 and 19 that a prefault angle of 9 degrees results in a stable system following a fault, while a prefault angle of 14 degrees results in an unstable system.

On a 60-Hz system, this 5-degree difference is the equivalent in time of 230 microseconds as shown in (3).

$$1 / 60 \text{ cps} / 360° \text{ per cycle} \cdot 5° = 0.00023 \text{ s} = 230 \text{ µs} \quad (3)$$

Here we see that a difference of just a few degrees changes the system response completely. A timing accuracy of one electrical degree at 60 Hz is 46 microseconds. If we want the timing accuracy to be an order of magnitude smaller when compared to one degree, then a net IED accuracy of ±5 microseconds is desirable. Time accuracy can only degrade when the time signal goes from the input terminal in an IED to the internal processing. Therefore, to achieve ±5 microseconds at the outputs would suggest using a clock input with better than ±1-microsecond accuracy.

V. CONCLUSIONS

We see that timing has become an integral part of event analysis and, hence, any IED with a timed output. Because of the pressure on engineers to constantly improve operational efficiency, root cause analysis of all types of events is needed. When events are compared between IEDs in local or wide area applications, timing is the key to that comparison.

1. In order to be certain of any timing accuracy of an IED, it is necessary to have an automated time input.
2. On a case-by-case basis, time-alignment techniques can be used to overcome a lack of a time signal input; however, the cost in engineering time to perform this alignment generally exceeds the cost of adding a clock, making this approach a reasonable bandage, but an ineffective cure to the timing problem.
3. Timing accuracy requirements vary by application from seconds to microseconds. To be sure of meeting future needs, ±500-nanosecond accuracy should be used.

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VIII. BIOGRAPHIES

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