Methods of Time Synchronization

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***Abstract*—Time synchronization is critical to modern electrical power systems. Based on the lessons learned from the postdisturbance analysis of the August 14, 2003, northeast blackout, NERC (North American Electric Reliability Corporation) recommendations place a high priority on implementing time synchronization in data-recording devices. This eliminates or reduces the effort involved in comparing event information from distributed intelligent disturbance recording devices. Accurate device time is required for disturbance analysis in order to correlate individual device event reports and is also essential for synchronized system control and synchrophasor applications. Many different time-synchronization methods currently in use provide time using different physical dissemination methods and deliver varying levels of accuracy. In many cases, these time-synchronization methods are untested, yet they are assumed to be sufficiently accurate.**

This paper explores some of the most commonly used synchronization methods, identifying the strengths and weaknesses of each. Measured accuracy for each method is identified, and a determination is made regarding the suitability of each method for event correlation, synchronized system control, and synchrophasor applications. Methods tested include:

- **Direct IRIG-B to an intelligent electronic device (IED).**
- **DNP3 to an IED via a communications processor receiving IRIG-B.**
- **DNP3 over radio via a communications processor receiving IRIG-B.**

Conclusions are presented regarding which timing method is preferred for different applications. Tables are provided to allow direct comparisons of application methods to assist in applying the best method of this important technology.

I. INTRODUCTION

Albert Einstein once said, “The only reason for time is so that everything doesn’t happen at once.” In modern power systems, it can sometimes appear that everything is indeed happening all at once. Protective relays and power circuit breakers can open and close a transmission line so fast it is nearly imperceptible to the human eye. Sometimes the only indication end users have that anything happened is the proverbial blinking VCR. However, once analysis begins, it becomes strikingly clear that these events have a distinct chronology. Because this timeline is condensed to such a small time scale, it can be very difficult to decipher. Today’s power systems are overwhelmingly more complex than those of yesteryear. Analysis of a single feeder fault might include data from a pole-mounted recloser control, voltage regulator control, feeder relay, bus differential relay, transformer differential relay, and station main breaker relay—and that is just for starters.

On average, it takes the human eye 300 milliseconds to blink. The typical protective device event report is 15 power system cycles, or 250 milliseconds. Imagine the nightmare presented if all of the devices mentioned above were set to different times.

Various means of synchronizing these devices have been developed over the years, and new ones are still emerging. However, not all of these methods are created equal.

II. THE NEED FOR TIME SYNCHRONIZATION

Modern power and control systems are complex and extensively interconnected. Events at a single location in the system can have diverse trickle-down effects in other areas of the larger system. This complexity can make it difficult to analyze and diagnose system events and problems.

Fortunately, in today’s systems, a plethora of intelligent electronic devices (IEDs) are recording and storing even the minute details of system operations. These may include protective relays, communications processors, digital fault recorders (DFRs), remote terminal units (RTUs), voltage regulator controls, programmable automation controllers (PACs), and recloser controls, to name a few. The IEDs log and time-stamp data from the power system, including analog waveforms, contact status, internal device binary states, trip and reclose signals, and many more. While all of these data aid in analyzing and improving system performance, this is true only if the data can be extracted from the IEDs and organized in an intelligible manner.

Each IED places time stamps on data items relative to some internal time source. Thus, the accuracy of the internal time source is critically important if the recorded data are to be useful in a larger system analysis. The East Coast blackout in August 2003 helped highlight the criticality of accurate time sources.

> The analysis portion of the investigation began with the development of a sequence of events. The initial focus was on the critical events leading up to the power system cascade. The task was painstakingly arduous due to the large volume of event data and the limited amount of information that was precisely synchronized to a national time standard. Assembling the timeline to the level of accuracy needed for the remaining areas of investigation was analogous to completing a jigsaw puzzle with thousands of unique interlocking pieces. [1]

It should be noted that the accuracy of an IED time source can be thought of mainly in two parts. The first facet is the accuracy of the internal time source in terms of drift or error per unit of time. A device might have an internal time-source drift or error of up to 1 second per month. The second part of the error is not a function of the internal time source itself but rather the time-synchronization method. In other words, how closely is the internal time source synchronized to a time standard? For example, an IRIG-B time source might synchronize the internal time source to within 500 nanoseconds of GPS (global positioning system) time. Hardware latency can also be a small contributor to overall time-stamp error. There is some period of time that elapses between the occurrence of an event and the device detection of that event. Typically, this is a fairly fixed value related to the processing interval of the device.

For the purpose of this paper, it is assumed that synchronization of the internal time source occurs frequently enough that the synchronization method is the only significant contributor to time error. Internal time-source drift will be ignored.

III. TIME-SYNCHRONIZATION ACCURACY NEEDS

When examining IED time-synchronization needs, the question may be asked, how accurate does it need to be? The answer is dependent on a few factors.

A. IED Time-Stamp Resolution

It is important to understand the difference between accuracy and resolution when considering devices with time-stamped data. “Accuracy is the degree of absolute correctness of a measurement device; resolution is the smallest number that the device can display or record” [2]. Thus, accuracy is a measure of how close the device time stamp is to an absolute reference (or how close the device relative time is to the true or absolute time). Resolution refers to the smallest increment of time allowed by the time stamp.

IED time-stamp resolution varies from manufacturer to manufacturer and from device to device. Time-stamp resolution is typically given down to the millisecond. This means that as events occur through inputs, outputs, and logic, they are time-stamped to the millisecond of when it was detected that they occurred. Another important factor to note is the accuracy of the given time stamp, which is based upon the processing interval of the product. Depending on if it is a relay, PAC, or SCADA (supervisory control and data acquisition) device, the accuracy of the 1 millisecond resolution time stamp can vary by ±1 millisecond to ±4 milliseconds. When viewing time-tagged data from multiple sources, great care should be given to use the accuracy of the device and not the resolution.

B. Power System Characteristics

Because ac power systems are sinusoidal and operate at a (more or less) fixed frequency (typically 50 or 60 Hz), some timing accuracy needs are fairly concrete. In a 60 Hz system, a single power cycle is approximately 16 milliseconds in length. Thus, time synchronization needs to be accurate to some level less than 16 milliseconds. Most power system IEDs process analog signals every one-quarter cycle or faster. This aligns well with the typical 1 millisecond time-stamp resolution.

C. Power System Complexity

If a power system is extensively interconnected and complex, many events can occur within a short time frame. In these situations, constructing an accurate timeline of events may be difficult if time synchronization is not adequate. In contrast, a simple radial feeder with only a few connected IEDs could be easy to analyze even with inaccurate time stamps.

IV. IED TIME-SYNCHRONIZATION METHODS

Until the introduction of the first digital relay in 1984, recording capabilities of power system devices were limited or nonexistent. Thus, these devices did not require and were not capable of time synchronization. Early oscillographs, such as the hospitalier ondograph shown in Fig. 1, provided a means to record system analog signals and disturbances but did not provide time-synchronization capabilities.

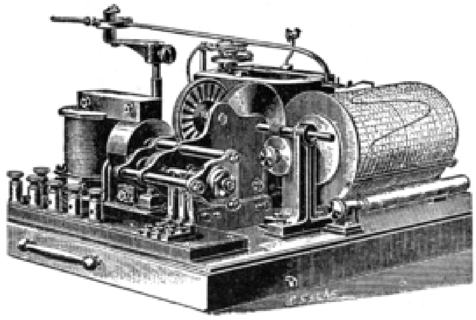

Fig. 1. Hospitalier ondograph

With the advent of digital devices and recording capabilities, time synchronization became important. Over time, many methods of synchronizing device time have been developed.

A. The Wrist Watch

Many power system IEDs have their time set manually via computer or front-panel interface. While this method obviously yields poor results in terms of accuracy, it is still widely used today. Many of the devices analyzed during the August 2003 East Coast blackout were set in this manner, and many were not set at all. Some of the devices were not even set with the correct date.

B. Computer Software

Many modern devices provide computer software tools for use in setting and commissioning the device. Some of this software allows users to synchronize the device time to the computer time. While this is more accurate than the manual method described above, it operates on the assumption that the computer time is synchronized to an accurate source. Most of the software tools do not specify the accuracy of their time-synchronization routine. Also, because many devices are set and commissioned in the field using laptop computers not connected to an external time source, their time synchronization will be of dubious accuracy.

C. SCADA Protocols

Many popular SCADA protocols like DNP3 include provisions for synchronizing device time through existing communications media. While some consider this purely a time-setting mechanism versus a form of synchronization, some provisions are made to account for delays in the communications channel. For example, DNP3 calculates message latency and accounts for this time in its time-synchronization message.

D. IRIG-B

In 1956, the TeleCommunication Working Group (TCWG) of the American Inter-Range Instrumentation Group (IRIG) created a standard format for the distribution of synchronized time signals. This resulted in a standardized set of time-code formats documented in IRIG Document 104-60. The standard has been revised several times over the years, with the latest publication being IRIG Standard 200-04.

As fully described in IRIG Standard 200-04, IRIG-B is a popular format for distributing time signals to IEDs. Time is provided once per second, in seconds through day of the year, in a binary-coded decimal (BCD) format, and optional, binary seconds of the day count. The format standard allows a number of configurations designated as "Bxyz," where *x* indicates modulation technique, *y* indicates counts included in the message, and *z* indicates interval. The most commonly used forms for general time synchronization are B122 and B002. B122 has seconds through day of the year coded in BCD format and is amplitude-modulated on a 1 kHz carrier. B002 has a level-shift format that also has seconds through day of the year coded in BCD format [3].

V. TESTING EQUIPMENT

Test setups and results are discussed later in Sections VI through VIII. Each test was conducted on three test devices and one control device. The control device has a known and constant input assertion latency. All results shown in this paper are normalized using this known latency value.

A. Device 1

- Protective relay
- Input sampling: 0.0625 cycle (~1 millisecond)
- Time-stamp resolution: 1 millisecond

B. Device 2

- Protective relay
- Input sampling: 0.0625 cycle (~1 millisecond)
- Time-stamp resolution: 1 millisecond

C. Device 3

- PAC
- Input sampling: 1 microsecond
- Time-stamp resolution: 1 microsecond

D. Control Device

- PAC
- Input sampling: 1 microsecond
- Time-stamp resolution: 1 microsecond. The control device has a constant contact assertion latency of approximately 100 microseconds in each test conducted. In order to account for any delay in the clock output closure, all time errors are normalized to use the control device as a zero time reference.

E. Clock

- GPS-disciplined clock
- Clock accuracy: ±100 nanosecond average, ±500 nanosecond peak
  (to coordinated universal time [UTC])
- Contact pickup time: 92 microseconds

F. DNP3 Master

- Communications processor
- DNP3 master device

VI. DIRECT IRIG-B TIME SYNCHRONIZATION

For direct IRIG-B time-synchronization testing, the device under test (DUT) is connected directly to an IRIG-B clock output, as shown in Fig. 2. The clock output contact is connected to a DUT input using an appropriate voltage source. The clock output contact is closed at a known time, and the resulting DUT input assertion time stamp is compared to the known time of the event and normalized using the control device time stamp. Results of the testing are shown in Fig. 3 and Table I.

This configuration is common in substations and remote devices where an IRIG-B output from an accurate time source is available for connection to an IED.

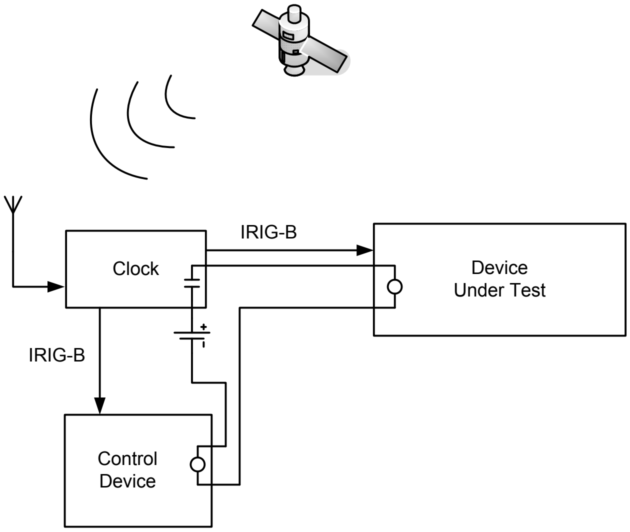

Fig. 2. IRIG-B time-synchronization test configuration

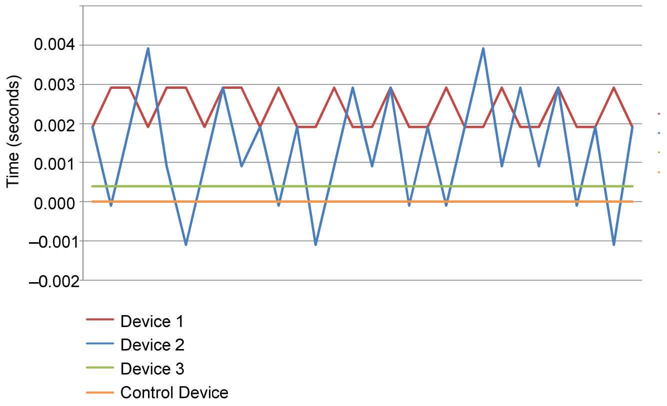

Fig. 3. Direct IRIG-B time-synchronization results

TABLE I
DIRECT IRIG-B TIME-SYNCHRONIZATION ERROR RESULTS

Error (s)	Device 1	Device 2	Device 3
Maximum Positive	0.002901	0.003900	0.000401
Maximum Negative	0.001899	–0.001100	0.000399
Average	0.002333	0.001333	0.000400

VII. DIRECT SERIAL DNP3 TIME SYNCHRONIZATION

For direct serial DNP3 time-synchronization testing, the DUT is connected directly to a serial DNP3 port of the DNP3 master device, as shown in Fig. 4. The DNP3 master is connected to an IRIG-B clock output. The clock output contact is connected to a DUT input using an appropriate voltage source. The clock output contact is closed at a known time, and the resulting DUT input assertion time stamp is compared to the known time of the event and normalized using the control device time stamp. Test results for this method are shown in Fig. 5 and Table II.

This application can be found where a large, installed base of SCADA-connected devices is in place. GPS clocks or other IRIG-B signals may be available only in limited locations. Rather than incur the expense of adding time sources in all locations, time synchronization is attempted via existing SCADA links and protocols.

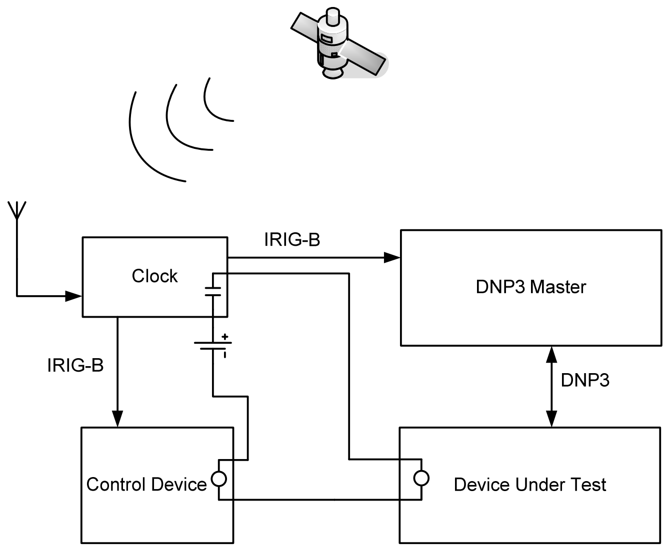

Fig. 4. Direct serial DNP3 time-synchronization test configuration

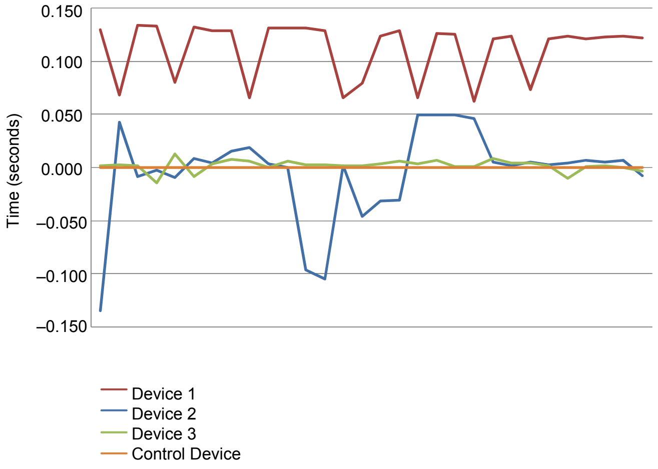

Fig. 5. Direct serial DNP3 time-synchronization results

TABLE II
DIRECT SERIAL DNP3 TIME-SYNCHRONIZATION ERROR RESULTS

Error (s)	Device 1	Device 2	Device 3
Maximum Positive	0.134	0.050	0.013
Maximum Negative	0.062	–0.134	–0.014
Average	0.112	–0.004	0.002

VIII. SERIAL RADIO DNP3 TIME SYNCHRONIZATION

A. Point-to-Point Radio Link

For serial radio DNP3 time-synchronization testing (shown in Fig. 6), the DNP3 serial port of the DUT is connected to a 900 MHz spread-spectrum radio. A second radio is connected to the DNP3 serial port of the DNP3 master device. The DNP3 master is connected to an IRIG-B clock output. The clock output contact is connected to a DUT input using an appropriate voltage source. The clock output contact is closed at a known time, and the resulting DUT input assertion time stamp is compared to the known time of the event and normalized using the control device time stamp. Test results for this method are shown in Fig. 7 and Table III.

This application can be found where a large, installed base of SCADA radio-connected devices is in place. GPS clocks or other IRIG-B signals may be available only in limited locations. Rather than incur the expense of adding time sources in all locations, time synchronization is attempted via existing SCADA links and protocols. These conditions might commonly exist with pole-mounted or other remote devices, such as recloser controls, sectionalizers, equipment monitors, voltage regulator controls, or capacitor bank controls.

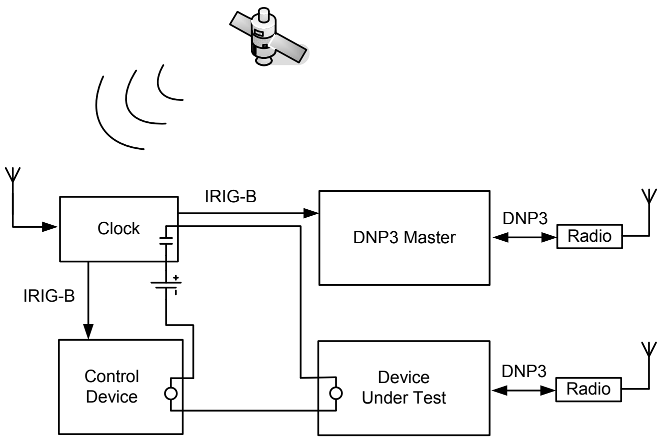

Fig. 6. Serial radio DNP3 time-synchronization test configuration

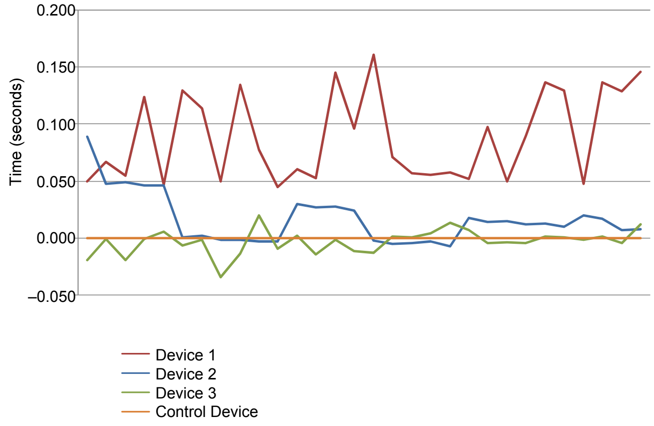

Fig. 7. Serial radio DNP3 time-synchronization results

TABLE III
SERIAL RADIO DNP3 TIME-SYNCHRONIZATION ERROR RESULTS

Error (s)	**Device 1**	**Device 2**	**Device 3**
Maximum Positive	0.161	0.089	0.020
Maximum Negative	0.045	–0.007	–0.034
Average	0.089	0.016	–0.003

IX. METHODS COMPARISON

A. Device 1

Fig. 10 compares the results of all testing methods for Device 1. Device 1 results from the serial DNP3 were poor, indicating that while IRIG-B synchronization yields an accuracy of better than one-quarter cycle, DNP3 synchronization yields results as poor as 8 cycles of error. Surprisingly, the radio DNP3 test results showed some improvement over a direct serial connection.

Results from all DNP3 time-synchronization methods were erratic and unpredictable. If the accuracy error was constant, as with the control device, automated measures could be used to compensate for it. However, because automated methods are not feasible, if this method was employed, any system analysis would involve a large amount of manual data manipulation and alignment. In some cases, analysis might not be possible if no landmark data points can be identified.

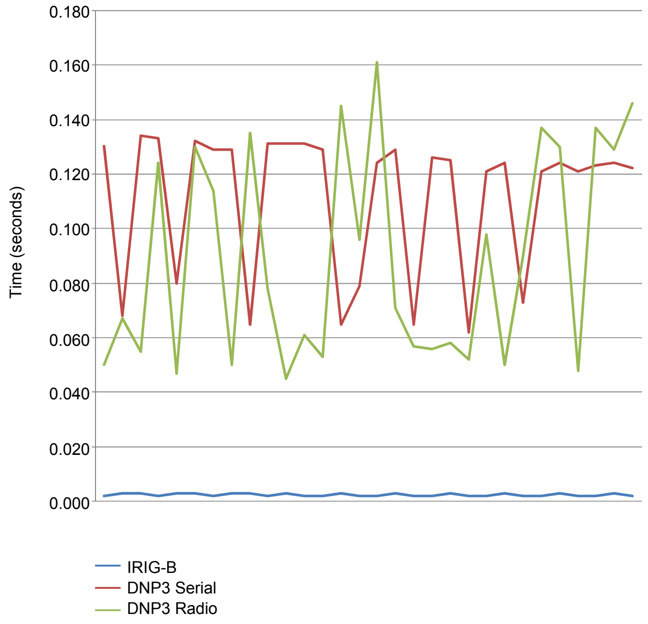

Fig. 10. Device 1 time-synchronization methods comparison

B. Device 2

As noted for Device 1, only IRIG-B synchronization yielded consistent and accurate time synchronization for Device 2. These results are shown in Fig. 11. Device 2 performance under direct serial DNP3 and radio configurations was better than Device 1. The direct serial DNP3 error was 8 cycles with the addition of radios pushing it beyond that level. The Device 2 testing results clearly illustrate the variation in synchronization accuracy. With any non-IRIG-B method tested, it is impossible to determine the time-stamp error of a device in the field, which makes system analysis difficult or impossible.

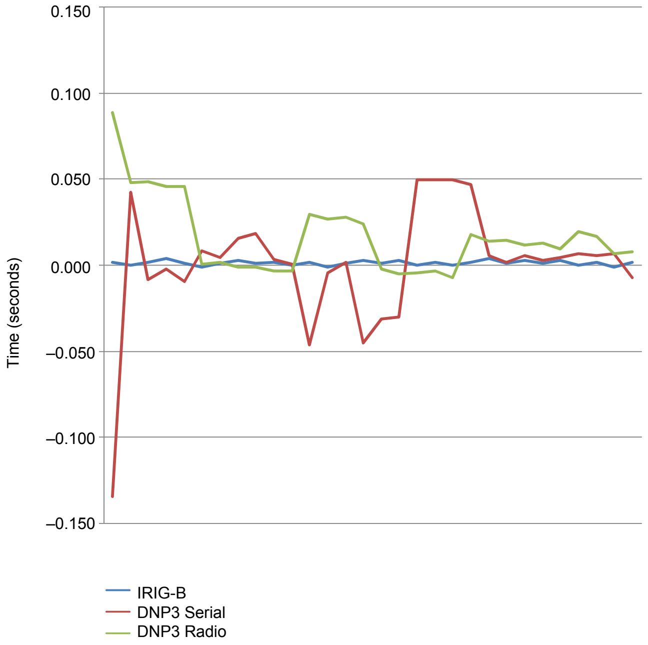

Fig. 11. Device 2 time-synchronization methods comparison

C. Device 3

Although the results shown in Fig. 12 for Device 3 show a noted improvement over Devices 1 and 2, with error in the radio configuration topping out at 2 cycles, there is no notable improvement in consistency or predictability. The time error is still an incalculable quantity, necessitating manual data manipulation where possible.

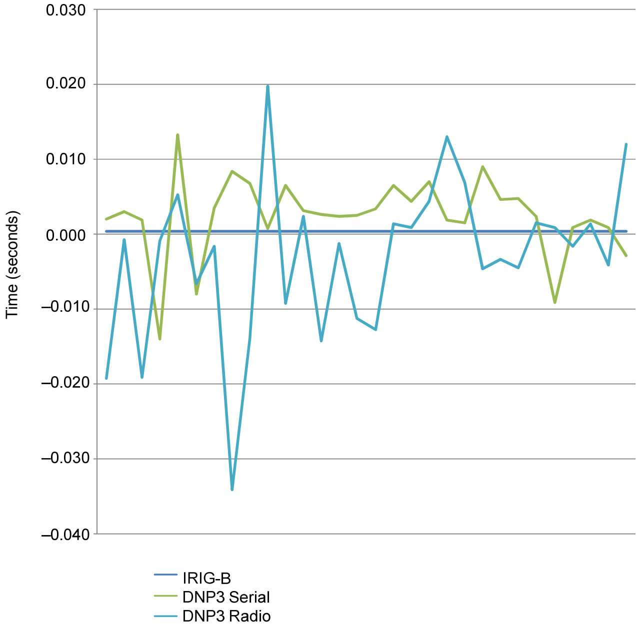

Fig. 12. Device 3 time-synchronization methods comparison

X. NEW TECHNOLOGIES

New time-synchronization technologies are being developed, while some are already seeing limited applications in industry. Chief among these is the IEEE 1588 standard that defines the Precision Time Protocol (PTP).

> This standard defines a protocol enabling precise synchronization of clocks in measurement and control systems implemented with technologies such as network communication, local computing and distributed objects. The protocol supports system-wide synchronization accuracy in the submicrosecond range with minimal network and local computing resources. The standard includes mappings to UDP/IP, DeviceNet and a layer-2 Ethernet implementation. The standard permits synchronization accuracies better than 1 ns. [4]

While PTP offers exceptional time synchronization over an existing communications path, it is not compatible with legacy devices already installed in the infrastructure. Most of these devices do not have Ethernet communications. Even if they do have Ethernet ports, it is unlikely that older devices will provide PTP support. Use of PTP will likely be a long adoption process as new products are developed, accepted, and installed.

XI. CONCLUSIONS

Most electric power system operators include a modern form of time synchronization in new system installations and designs, usually a GPS clock. This provides good device synchronization moving into the future. However, a large number of existing installations have not been updated. In some cases, the technology is too old (i.e., electromechanical relays) to support time synchronization without complete equipment replacement. In these cases, cost can be an inhibiting factor.

Not having a time-synchronization system in place greatly increases system operating costs; it increases the labor required to perform postdisturbance analysis and system troubleshooting and maintenance. NERC states, "All digital fault recorders, digital event recorders, and power system disturbance recorders should be time stamped at the point of observation with a precise … GPS synchronizing signal" [1]. While stated as a recommendation at the time, future mandates could make the addition of GPS clocks a requirement, perhaps imposing financial penalties for failure to comply.

For systems with equipment that supports time synchronization but not originally designed to include it, there are economical ways to add this capability. Not only does this reduce the overall system operating costs, it also improves operating efficiency. GPS-synchronized clocks capable of supplying highly accurate time synchronization to a dozen devices or more are readily available, starting as low as $550. In most cases, this costs less than replacing even a single existing device and is more than recovered in operating cost savings.

While using existing SCADA communications links for time synchronization may seem attractive due to their low cost, they have proven to be inaccurate and inconsistent. Time-synchronization accuracy varies erratically from interval to interval, resulting in timing accuracy with a low level of confidence. Additionally, these methods rely on communications paths that may have additional unreliability (i.e., poor availability) of their own. These methods are not sufficient to reduce or eliminate the need for intensive manual data manipulation in system disturbance and troubleshooting analysis.

Of the timing options readily available in today's market, IRIG-B solutions provide the consistent accuracy required for modern power system applications. While some of the emerging technologies (IEEE 1588 PTP) promise exceptional performance, they are not yet widely applicable and will rely on a communications path that may have less than acceptable reliability.

XII. REFERENCES

[1] "Technical Analysis of the August 14, 2003, Blackout: What Happened, Why, and What Did We Learn?" Report to the NERC Board of Trustees, July 13, 2004. Available: http://www.nerc.com/filez/blackout.html.

[2] J. Lehman, "Accuracy Versus Resolution in Analyzing System Errors," December 2008. Available: http://www.techbriefs.com/component/content/article/3458.

[3] K. Behrendt and K. Fodero, "The Perfect Time: An Examination of Time-Synchronization Techniques," proceedings of the 60th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 2006.

[4] *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, IEEE Standard 1588.

XIII. BIOGRAPHIES

Eric Sagen received his BS in electrical engineering from Washington State University in 1997. He worked for General Electric in Malvern, Pennsylvania, as a product engineer before joining Schweitzer Engineering Laboratories, Inc. as a distribution product engineer in 1999. Shortly thereafter, he was promoted to lead distribution product engineer. He transferred to the time and communications group in 2006, where he is currently a lead product engineer. He is certified in Washington as an engineer in training (EIT).

Kenneth Workman received his BSEE and MSEE from New Mexico State University in Las Cruces, New Mexico. After graduation, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as a product engineer, working with recloser and other control products. He has also worked as the product manager for SEL time and communications products. Currently, he works as a power systems instructor for SEL University. He is a member of IEEE and a certified information systems security professional (CISSP).

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