

Time Synchronization in Electrical Power Transmission and Distribution Systems

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Abstract

Synchronization of measurements in electrical power systems with Coordinated Universal Time (UTC) is expected to become mission critical worldwide over the next few years. This paper describes some of the applications for time-synchronized measurements, the requirements for accuracy and reliability, the ways timing information is received and distributed in electrical substations, and the risks which must be mitigated before the power system becomes reliant on time synchronization. It explains the need for alternative time synchronization sources redundant with Global Positioning System (GPS).

Time Synchronized Measurements

- not a new concept or application in electrical power systems
- as technology advances, the time frame of synchronized information has been steadily reduced from minutes to seconds, milliseconds, and now microseconds
- applications:
 - SCADA/EMS
 - disturbance monitoring/recording
 - fault location
 - synchrophasors
- multiple spatially distributed measurements which are synchronized to occur within a specified window of time
- transmitted and then collected at one or more locations and aligned in time
- increasingly being used in electrical power systems worldwide

Accuracy requirements

SCADA/EMS (state estimation):

- one to three seconds

Disturbance monitoring/recording:

- within 2 milliseconds of UTC
 - specified by the National Energy Reliability Corporation (NERC).
 - NERC is the U.S. regulatory agency for the energy sector

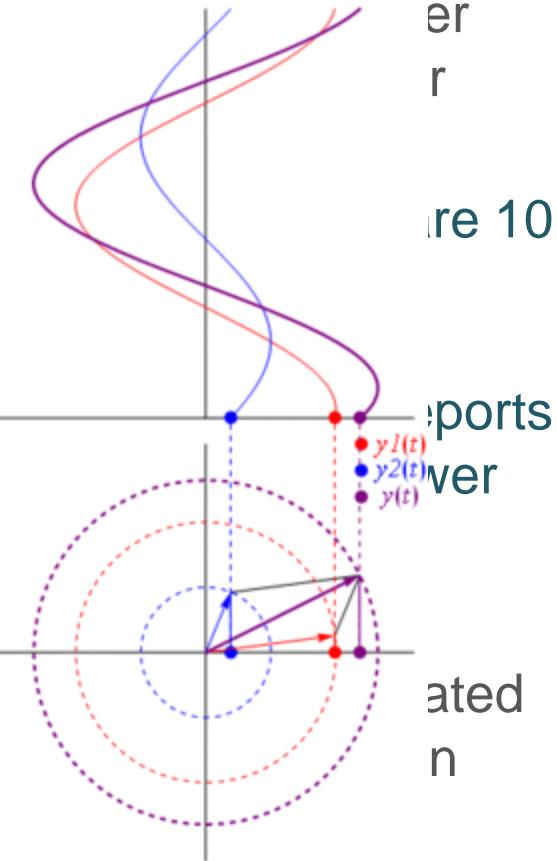
Fault Location Devices:

- less than about 1.7 microseconds
- travelling wave locators rely on the difference in clocks at either end of a fault.
 - fault signal travels at approximately the speed of light
- 1.7 microseconds equals about 500 meter uncertainty in the location of the fault

Synchrophasors

Phasor measurement units (PMUs) measure power system voltages and currents and estimate the synchrophasor of each phase

Synchrophasors are a polar or rectangular representation of the power system amplitude and phase compared to a theoretical signal at the power system nominal frequency synchronized to UTC



Synchrophasor accuracy

The maximum allowed error for PMU measurements is 1 % total vector error (TVE)

- PMU performance limits are specified by IEEE Standard C37.118.1-2011, revised by IEEE C37.118.1a-2014

The total vector error combines both the phase error and magnitude error into a single scalar value which is the magnitude of the vector between the measured synchrophasor value and the “true” value (the actual input to the PMU)

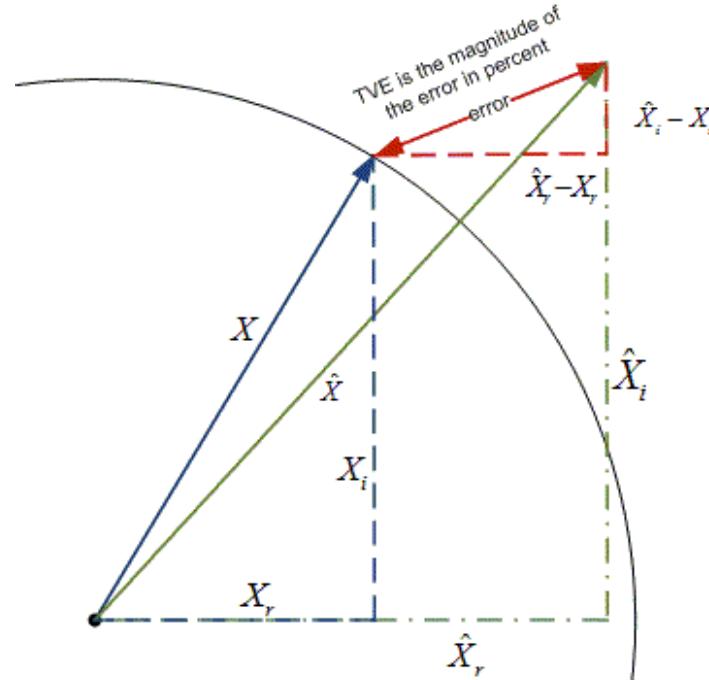
Equation 1: Total Vector Error [6]

$$TVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{(X_r(n))^2 + (X_i(n))^2}}$$

where:

\hat{X}_r and \hat{X}_i are sequences of estimates given by the PMU under test
 X_r and X_i are sequences of the theoretical values of the input signal

Figure 1: Graphical depiction of synchrophasor error



Effect of time accuracy on synchrophasors

For a 50 Hz or 60 Hz power system, a 0.573° (0.01 rad) error (with 0 magnitude error) would yield a 1 % TVE.

- A 0.573° phase error could be caused by a $26.53 \mu\text{s}$ time error for a 60 Hz system or a $31.83 \mu\text{s}$ timing error for a 50 Hz system
- This leaves no room for magnitude error

The recommended time accuracy for synchrophasors is $1 \mu\text{s}$ [4].

- All synchrophasor measurements at a particular time should be made within $1 \mu\text{s}$ of each other.
- The phase accuracy is a function of the frequency of the voltage or current being measured and the time accuracy.
 - For a 60 Hz measurement, a $1 \mu\text{s}$ error would yield a 0.377 mrad (21.6 mdeg) error, and for a 50 Hz measurement the error would be 0.314 mrad (18 mdeg)

Synchrophasors' future

The synchrophasor standard is being revised by a joint IEEE/IEC working group

- considering new applications
- expects to publish a joint synchrophasor standard: IEEE/IEC 60255-118-1 sometime before 2018
- applications which require better than 1 % TVE are being considered

A Department of Energy ARPA-E program is investigating applications for a “micro-PMU” (μ PMU)

- extremely precise time-stamping of measurements to allow comparisons of voltage phase angle down to small fractions of a degree
 - may be beneficial in distribution networks where the phase differences between nodes are smaller
- μ PMU technology is expected to discern angle differences to significantly better than ± 0.05 deg (aiming for ± 0.01 deg)
- the maximum timing error would need to be less than 0.463 μ s for a 60 Hz system or 0.557 μ s for a 50 Hz system

other synchrophasor timing requirements

A time-synchronous measurement device calibration system should be at least 10 times as accurate as the measurement system under test (20 times more accurate is preferable).

- A phase accuracy of 87 μ rad (0.005 deg) is the recommended target accuracy.
- The difference between the calibration system's time and the device-under-test's time must be small. If so, the time difference with UTC does not matter

Table 1: Phase error and TVE contribution of timing errors

| timing error | phase error (60 Hz) | TVE contribution |
|---------------|--------------------------|------------------|
| 26.53 μ s | 0.01 rad (0.573 deg) | 1% |
| 1 μ s | 0.3 mrad (0.022 deg) | 0.04% |
| 0.463 μ s | 0.17 mrad (0.01 deg) | 0.02% |
| 0.231 μ s | 87 μ rad (0.005 deg) | 0.01% |

Reliability requirements

NERC publishes reliability standards for the bulk electric systems of North America

- numerous standards which are required to be met by power system designers and operators.
- For many systems considered essential to the reliability of the bulk power system, redundant systems are required.
 - For example, in Standard COM-0011.1 – Telecommunications:

“Each reliability coordinator, transmission operator, and balancing authority is responsible to provide adequate and reliable telecommunications facilities for the exchange of interconnection and operating information.

Where applicable, these facilities shall be redundant and diversely routed”

At this time, there are no NERC requirements for redundancy in time-synchronization facilities

- Notably, requirement R2 of the NERC cyber security standards states:

“The (standards drafting team) understands that there may be some Cyber Assets where automated monitoring may not be possible (such as a GPS time clock). For that reason, automated technical monitoring was not explicitly required and a responsible Entity may choose to accomplish this requirement through manual procedural controls”

Time reception

GPS as Today's Only Option

- PMUs should maintain 1 μ s accurate synchronization with UTC and may be located almost anywhere in the world.
- satellite-based time synchronization is the only option available today, and GPS is the only system presently being used for timing. Other satellite systems are being developed. These include GLONASS, Galileo, and BeiDou.
- research is needed into the plausibility of using other sources of 1 μ s accurate UTC time to provide a redundant, diversely routed source of time signal.

In the United States, NERC creates standards for power system reliability, and power system operators must comply with the standards.

- most of the mission critical power system components are required to be redundant and diversely routed.
- PMUs today are not considered mission critical components of the power system.
 - however, demands on the system are changing with new loads such as electric vehicle charging and synchronous DC motors.
 - furthermore, new energy sources such as wind and solar power are becoming distributed across transmission systems and even across distribution systems which were not originally designed for bi-directional power flow.
 - based on synchronized measurements, PMUs are widely expected to become mission critical over the next 5 to 10 years.

Time distribution

Depending on the manufacturer and model of the device, the time-synchronizing source input may be:

- GPS antenna input,
- Inter Range Instrumentation Group (IRIG) standard 200-04 [11] input (sometimes also requiring a digital pulse per second (PPS) input)
- or for some newer equipment, an IEEE 1588 Precision Time Protocol (PTP) delivered via Ethernet as specified by the Power Profile

GPS Antennas and Splitters

- Many devices containing PMU functions include their own GPS receivers.
- input is often a coaxial cable directly from a remotely located GPS antenna or a GPS antenna splitter.
 - EMI, impedance matching, and cable delay are issues that can contribute to time synchronization errors or loss of lock.

Risks

Today's Risk is Low

- today's applications of time-synchronized power system measurements are not considered mission critical.
- applications in use today include:
 - power system base-lining
 - event analysis,
 - model verification,
 - transient analysis,
 - fault location,
 - restoration,
 - modal (oscillation) analysis, and state estimate verification.
- None of these applications is solely dependent on PMU data; as a consequence, a loss of PMU data is highly unlikely to contribute directly to a system outage or blackout.

Tomorrow's Risk is Uncertain

- time-synchronized measurement applications are being researched by power system operators, utilities and government laboratories.
- include:
 - real-time system protection applications,
 - real-time generator control,
 - real-time frequency and voltage control,
 - load shedding,
 - intentional islanding control,
 - many others.
- which of these applications may be implemented in the electrical system and the time frame is uncertain at this time
 - using time-synchronized measurements for the above applications could:
 - prevent large system outages
 - restore the system faster if outages do happen.
- these applications depend on PMUs:
 - failure or sabotage of the time-synchronizing source signal could introduce vulnerabilities that have the potential to degrade the grid operation or damage equipment.

Conclusion

Before time-synchronized measurement becomes mission critical on the power system, it is likely that measurement systems will be required to have redundant and diversely routed synchronizing time sources.

Thank you

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