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Uses and Limitations of Advanced Analog Quantities

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SUMMARY

The new IEEE C37.118 phasor measurement standard includes values that traditional SCADA, Protection, or EMS systems do not provide. These values, which include rate of change of frequency and phase angle, are within synchrophasor messages. The standard also provides new information that can be transmitted to operators and provides values with or without a precise timestamp indicating when the measurement was taken. This paper highlights the use of such new measurements as time error, and especially Time Error Differential measurements.

The unique nature of these new measurements provides for new applications, but communication method, signal latency, and time criticality of the applications also produce limitations. This paper discusses the impact of the time-based nature of each quantity and how communication-related limitations affect possible applications. But for the lack of instantaneous communications, ideal analog filtering, and perfect accuracy, one could use mathematics to apply these new quantities for control automation or power monitoring applications. One must, instead, recognize the previously discussed limitations in any application.

This paper discusses the following applications:

- Islanding detection—high-speed algorithms and visualization methods
- Close angle supervision—preventing excessive loop flow on line closing
- Remote synchronization—breaker close time supervision for zero-angle closing

The paper discusses communication methods for different implementations of each scheme as well as how communications restrictions impact scheme performance.

KEYWORDS

Wide Area Measurement, Time Error, Time Error Differential, Synchrophasor, High-Accuracy Timing, Rate of Change of Frequency, Islanding

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INTRODUCTION

Synchrophasor measurements offer operators a knowledge of system conditions far superior to what was previously available. For example, NERC studies have shown that the phase angle between Western Michigan and Cleveland had increased steadily for hours before the August 14, 2003 cascading blackout, as shown in Fig. 1. Had this information been available at the time, there would have been more than sufficient time for operators to have taken action to prevent this cascade.

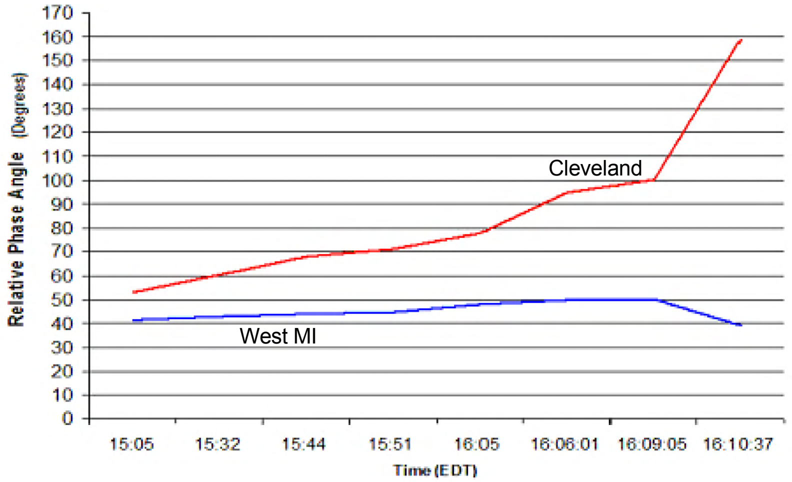


Fig. 1 Phase angle preceding August 14 blackout [1]

It is not enough to state hypothetically that this new information will help operators maintain stability. Operators can only act on the information if it is time aligned and formatted. The information may be valuable enough for one to consider purchasing a new broadband communication system, but system installation, maintenance, and integration may be impractical in the short term.

The challenge, then, is how to use existing communications and integration systems to bring synchrophasor data to operators in a usable form.

COMMUNICATION SYSTEM CONSTRAINTS

Although many consider broadband communications an ideal, this paper assumes a slower system such as that used in most SCADA systems. The limitations associated with a typical SCADA communications architecture are slower data transmission and a reduced number of data points that the system can transmit. Scan rates for SCADA systems are generally between two and ten seconds, with five seconds the typical rate. Practical data transmission rate limits make a significant change in this scan rate difficult.

POWER SYSTEM CONSIDERATIONS

To understand better the system status information that operators need to receive, consider the power swing shown in Fig. 2. This swing was recorded by an IED during the August 14 blackout in the Northeastern United States between a utility that ended up in the "blackout zone" and another utility that separated its system from the blackout area and maintained service.

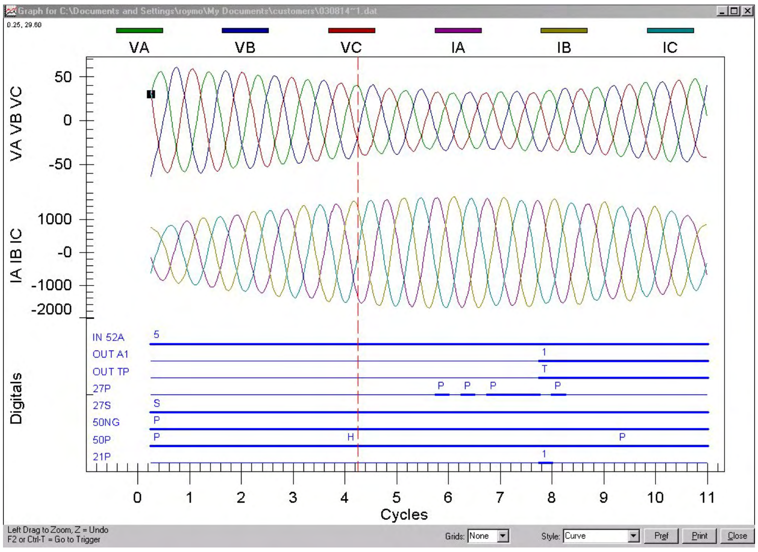


Fig. 2 Out-of-step event

In this actual system disconnection, we can see from the event report that the period of oscillation is about 11 or 12 cycles, or 0.2 seconds (60 Hz system). Any data transmission slower than one-fifth of a second will have a problem communicating system status during such an event. Traditional use of phasor measurements has always involved direct comparison of an instantaneous power system phasor, voltage or current, with a time-dependent reference wave. Because the reference wave is only a function of time, it is the same at all locations in a power system. By comparing the measured phasor at multiple locations with the reference phasor, we can relate any number of phasors at any number of locations. For this process, phase measurements must occur simultaneously. With synchrophasors, we can send measurements from a phasor measurement unit (PMU) at rates from 1 to 60 times per second. Applying synchrophasor technology within protective relays provides a method for widespread and low-cost installation [2]. A problem that arises is how to develop an operator-viewing methodology to deal with fast-moving events when the communication system (SCADA or other) sends a status message only once every five seconds or so.

TIME ERROR

Time error (TE) is a measurement not traditionally in use for state visualization. One might ordinarily see this measurement in use for generator dispatch of a power system to ensure the accuracy of frequency-based clocks or in balancing power schedules within a control area. Time error is the difference between a time period a high-accuracy clock measures and the same period another clock measures through use of the measured system frequency as a time standard. For example, if we started measuring TE at midnight and operated a power system at 60.01 Hz, we would have a time error of 10 ms after 60 seconds.

$$\begin{gathered}60\text{ s} \bullet 0.01\text{ cycles/s (frequency error)}\\ \bullet\ 1/60\text{ s/cycle (at nominal frequency)}\\ = 0.01\text{ s (or 10 ms)}\end{gathered} \tag{1}$$

This TE would increase by 10 ms every minute as long as the power system frequency remained unchanged. For a connected system, the TE at different locations varies as the system frequency varies. Load and generation throughout the day cause frequency variations.

Traditional TE measurement for generation dispatch purposes is accurate to tenths of a second. Modern devices serving as PMUs can measure TE to significantly greater accuracy and precision. This greater accuracy of TE measurement provides a new capability known as time error differential measurement. At an accuracy level of tenths of a second, TEs are very large compared to the ac waveform of a power system. There are modern PMUs however that can measure TE to an accuracy of ±5 µs. This high accuracy makes it possible to use time error differential (TED) to compare phase angles between two locations. TED between two areas equates to a phase angle shift. In a 60 Hz system, a 360-degree shift (or a slip cycle) equates to a 16.67 ms TED. Measuring TE to an accuracy of ±5 µs provides for a phase angle measurement accuracy of ±0.108 degrees.

For example, we can measure TE at two different locations on a power system, such as illustrated in Fig. 3. We illustrated the concept by using a precision relay test set to compare the response of two different PMUs to slightly different frequencies.

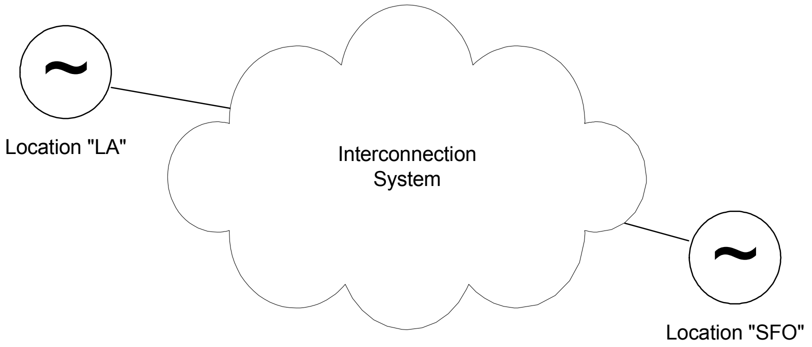
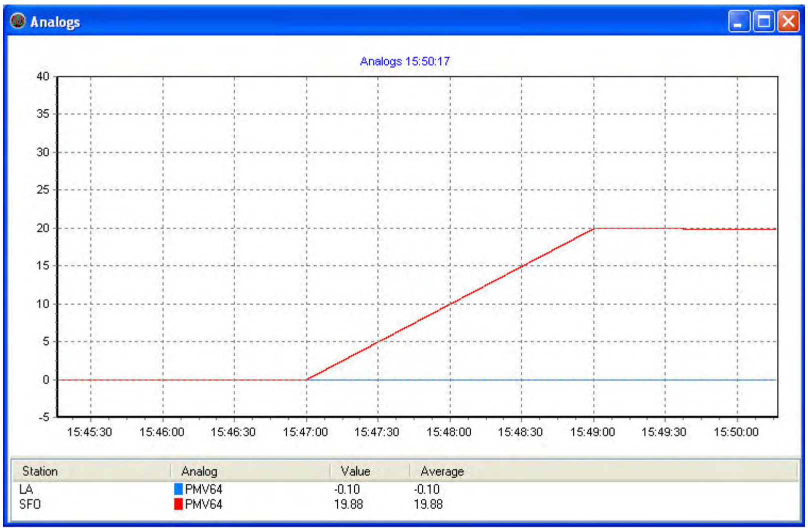


Fig. 3 General interconnected power system

One of the PMUs ran at a steady 60 Hz, while the other started at 60 Hz but then ran 120 seconds at 60.01 Hz. For every second that a clock ran at this higher frequency, it developed a time error of 0.16667 ms, as shown in equation (1). This equates to an angular difference between the two systems of 3.6 degrees per second. The PMU must detect the TE and make it available in a form accessible to intelligent electronic devices (IEDs) outside the PMU for either direct differential measurement or transmission to a central location for comparison with the time error measured at other locations.

The PMUs in the example were protective relays with logic available to perform analog comparisons or to place the time error into a register for direct reads by SCADA masters.

In the graph of Fig. 4, the output was a math variable equal to the TE and read from the relay register every cycle. The graph shows the TE increasing from zero to 20 ms during two minutes of operation at off nominal frequency.



Station	Analog	Value	Average
LA	🟦 PMV64	-0.10	-0.10
SFO	🟥 PMV64	19.88	19.88

Fig. 4 Output of time error differential measurement

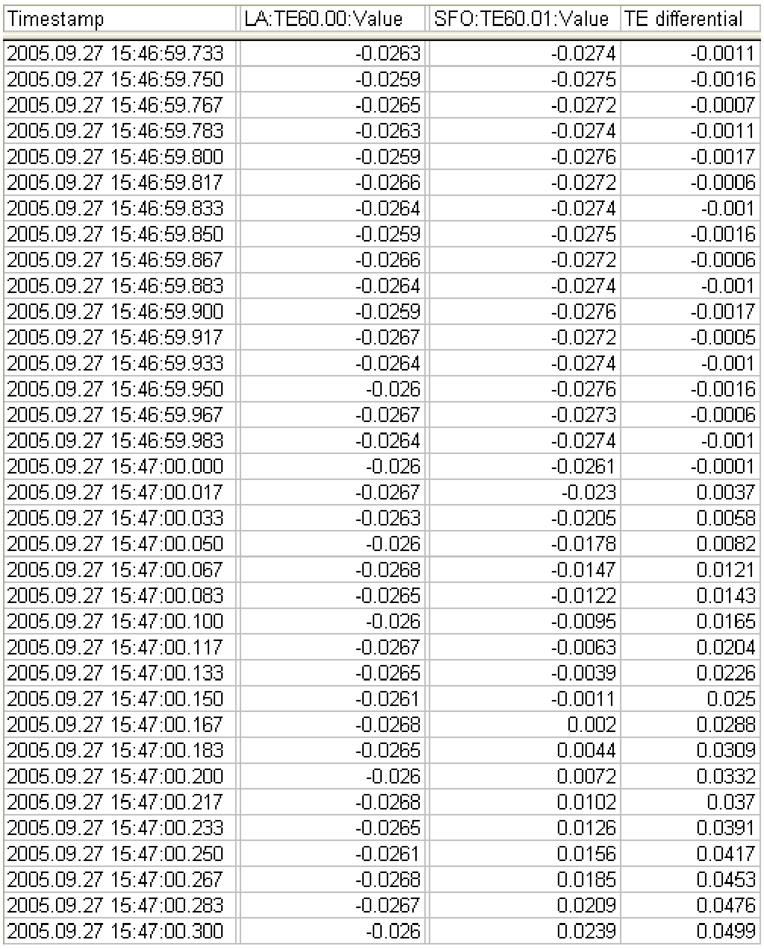
We collected the TE data as part of a synchrophasor message according to the definition in IEEE C37.118. This standard provides for the transmission of optional analog and digital information along with traditional phase angle data. To obtain the maximum resolution possible, we set an analog math variable within the PMU to the TE times 1000.000000. We transmitted the data 60 times per second, the maximum rate of the PMU. The standard provides for data transmission in either floating or fixed-point format. For maximum resolution, we selected floating-point format.

While we selected an IEEE 37.118 message format for use in this illustration, other possibilities are available. The paper discusses these formats later. In any transmission format, programmable math variables provide for flexibility with high-speed data availability.

Before we use differential time error measurement as a representation of accumulated phase angle difference, remember that the accuracy and resolution of TE we retrieved from the PMU are sufficient.

Table I displays a segment of the TE measurements and synchrophasor time stamps from the PMUs we used for the graph of Fig. 4. We obtained these data before and after the start of the frequency difference shown at the “ramp” (at about 15:47 in both the figure and the table). By using Table I data from before the start of the frequency difference, we can see the level of significant data within each point shown in the figure graph.

TABLE I
TIME ERROR ANALOG DATA



Timestamp	LA:TE60.00:Value	SFO:TE60.01:Value	TE differential
2005.09.27 15:46:59.733	-0.0263	-0.0274	-0.0011
2005.09.27 15:46:59.750	-0.0259	-0.0275	-0.0016
2005.09.27 15:46:59.767	-0.0265	-0.0272	-0.0007
2005.09.27 15:46:59.783	-0.0263	-0.0274	-0.0011
2005.09.27 15:46:59.800	-0.0259	-0.0276	-0.0017
2005.09.27 15:46:59.817	-0.0266	-0.0272	-0.0006
2005.09.27 15:46:59.833	-0.0264	-0.0274	-0.001
2005.09.27 15:46:59.850	-0.0259	-0.0275	-0.0016
2005.09.27 15:46:59.867	-0.0266	-0.0272	-0.0006
2005.09.27 15:46:59.883	-0.0264	-0.0274	-0.001
2005.09.27 15:46:59.900	-0.0259	-0.0276	-0.0017
2005.09.27 15:46:59.917	-0.0267	-0.0272	-0.0005
2005.09.27 15:46:59.933	-0.0264	-0.0274	-0.001
2005.09.27 15:46:59.950	-0.026	-0.0276	-0.0016
2005.09.27 15:46:59.967	-0.0267	-0.0273	-0.0006
2005.09.27 15:46:59.983	-0.0264	-0.0274	-0.001
2005.09.27 15:47:00.000	-0.026	-0.0261	-0.0001
2005.09.27 15:47:00.017	-0.0267	-0.023	0.0037
2005.09.27 15:47:00.033	-0.0263	-0.0205	0.0058
2005.09.27 15:47:00.050	-0.026	-0.0178	0.0082
2005.09.27 15:47:00.067	-0.0268	-0.0147	0.0121
2005.09.27 15:47:00.083	-0.0265	-0.0122	0.0143
2005.09.27 15:47:00.100	-0.026	-0.0095	0.0165
2005.09.27 15:47:00.117	-0.0267	-0.0063	0.0204
2005.09.27 15:47:00.133	-0.0265	-0.0039	0.0226
2005.09.27 15:47:00.150	-0.0261	-0.0011	0.025
2005.09.27 15:47:00.167	-0.0268	0.002	0.0288
2005.09.27 15:47:00.183	-0.0265	0.0044	0.0309
2005.09.27 15:47:00.200	-0.026	0.0072	0.0332
2005.09.27 15:47:00.217	-0.0268	0.0102	0.037
2005.09.27 15:47:00.233	-0.0265	0.0126	0.0391
2005.09.27 15:47:00.250	-0.0261	0.0156	0.0417
2005.09.27 15:47:00.267	-0.0268	0.0185	0.0453
2005.09.27 15:47:00.283	-0.0267	0.0209	0.0476
2005.09.27 15:47:00.300	-0.026	0.0239	0.0499

Note that from 15:46:59.733 to 15:47:00.0017 (the start of the frequency differential) there is a “float” differential error in the third digit to the right of the decimal. We can note two observations from these data.

1. There is no consistency to time errors below about 2 µs. This shows a minimum meaningful resolution of about 0.04 electrical degrees.
2. In the 60 seconds of identical frequency input to the two PMUs prior to the start of the frequency jump, there was no significant accumulation of TED. Because timer error is inherently an integral quantity, one must take care to avoid a systematic accumulation of error.

Once we increase the frequency in the PMU identified as SFO, we see the steady accumulation of TED displayed graphically in Fig. 5.

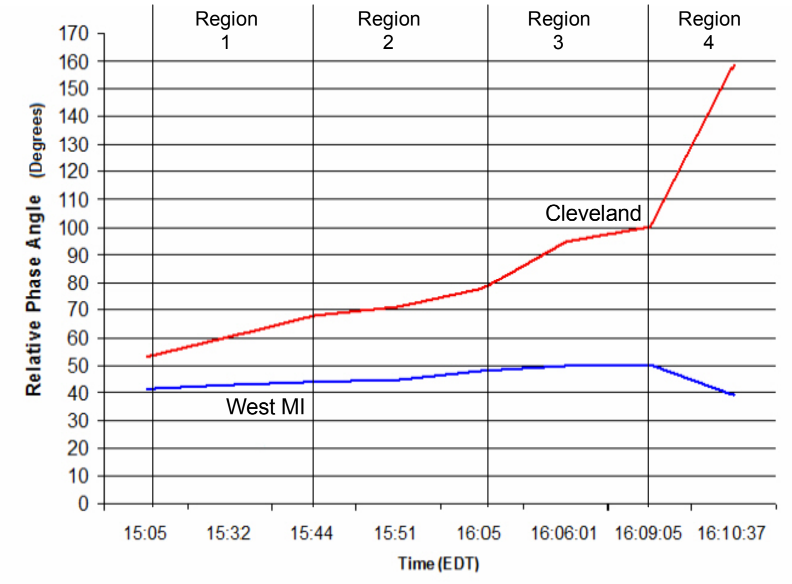


Fig. 5 Time periods for phase angle preceding the August 14 blackout

SYSTEM CONSIDERATIONS

We must consider critical power system operating conditions when determining the best method for giving operators information that will help them make optimal control decisions. There are problems that accumulate over time and events that change the system in a matter of cycles. Considering the graph of phase angles preceding the August 14 blackout (Fig. 5), we can see that phase angle varied at different rates over different periods of time. While we can consider no event of this magnitude to be typical, we can look at changing conditions and see how TED can be used to visualize the condition. The graph of Fig. 5 is not linear in time, but we can divide the graph into four basic periods and look at the rate of change of phase angle differential.

By dividing the graph into time divisions, we can see that there are very different rates of change of phase angle occurring at different times during the day. Putting the data into a tabular form, we can display the information as in Table II.

TABLE II
PHASE ANGLE RATE OF CHANGE

	Duration	Δ Phase ∠ Difference	Degrees Per Minute
Time Region 1	39 Minutes	12°	0.307
Time Region 2	21 Minutes	6°	0.286
Time Region 3	4 Minutes	20°	5.0
Time Region 4	1.5 Minutes	70°	46.7

From the table, we can see three different orders of magnitude in the available data. It is clear that a change in frequency of less than one degree per minute (as seen in time regions 1 and 2) is well within the parameters for human response. At this rate, in fact, one problem facing an operator might be that the data are changing too slowly to indicate the urgency of the situation. Historical trending displayed along with such instantaneous data would in this case make the information more useful.

In Region 3, the rate of change has accelerated significantly. Here, data display may be too fast for operator evaluation of the information, but enough time still exists for mitigating action before a system collapse.

In Region 4, the situation is clearly so bad that any action would likely have little effect. Unless there is action from a relay or pre-programmed automated scheme, it is unlikely that an operator could respond to the rapid change in the system indicated by the high phase shift.

Consider in any selection of a display method that the data must be in a simple, concise, easily viewable format. A combination of instantaneous and historical data might be advantageous, but such data could be too complicated for continuous display on a large system display.

One advantage of using TED instead of instantaneous data is the inherent "memory" function of TED. This "memory" action is a result of TED being, effectively, the integral of phase angle shift over time. The TED shown in Table I increases continuously as long as SFO has a higher frequency than LA.

This "memory" action becomes even more important during power swing events. Consider the event report shown in Fig. 6. This power swing is the result of a line fault on a bulk transmission system near an HVDC terminal. As we see in the event report of Fig. 6, the fault caused an out-of-step condition. The frequency of the power swing is very high and accelerates as the number of slips increases.

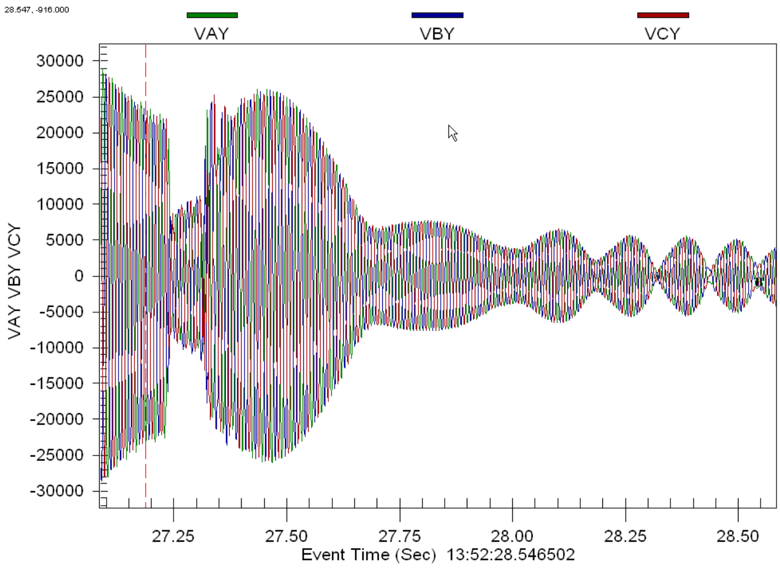


Fig. 6 Multicycle power swing with decreasing period

Through use of the microsecond time stamping available in the Comtrade event report, we can determine the exact slip frequency of each swing cycle. Table III displays this information.

TABLE III
SLIP PERIOD PER CYCLE

Slip Cycle	Slip Period
1	0.442 s
2	0.307 s
3	0.193 s
4	0.136 s
5	0.115 s
6	0.115 s

This swing has a slip frequency of about the same period as that of Fig. 2. A report to an operator of the phase angle between the systems on each side of this swing would have very little practical value to the real-time data, regardless of the reporting interval. At high data rates, the phase angle would change so fast as to be meaningless. At low data rates, the phase angle difference between the two ends of the system would be almost random.

1) *Time Error Differential Visualization*

For the power swing of Fig. 6 above, consider how to display the TE difference between the two sides of the swing.

Because we see display of only the TE *difference*, any variations in frequency common to the two systems are negated. The power swing happened to be on a 50 Hz system, which makes it easy to calculate the time error difference that the PMUs on each side of the swing will measure. Table IV lists the calculated differential time error per slip cycle.

TABLE IV
DIFFERENTIAL TIME ERROR PER SLIP CYCLE

Slip Cycle	Time Error Differential
1	20 ms
2	40 ms
3	60 ms
4	80 ms
5	100 ms
6	120 ms

Consider the display of TED during a power swing event. For any slip frequency, the display of TED would simply be the number of slip cycles multiplied by 20 ms for a 50 Hz system or multiplied by 16.67 ms for a 60 Hz system.

For heavy system loading that does not produce a power swing, the display of TED would be time corresponding to the phase angle between the two (or more) points being measured. For a 20-degree phase angle, for example, calculation of the TE difference would be as follows.

$$20^\circ/360^\circ \text{ per cycle} \bullet 16.67 \text{ ms per cycle} = 0.93 \text{ ms} \quad (2)$$

This value is well within the accuracy and resolution limits shown in Fig. 4 and Table I. It might even be possible with an intelligent display to convert TED to accumulated degrees.

2) Time Error Differential Control

As the application of synchrophasor-based quantities becomes more familiar, the use of these quantities for high-speed control will become more straightforward. There are some simple applications that could occur at high speed without need for system studies.

Islanding detection is one application that lends itself to TED comparison. IEEE standard 1547, Interconnecting Distributed Resources with Electric Power Systems, requires the following under 4.4.1 Unintentional Islanding: “For an unintentional island in which the DR energizes a portion of the Area EPS through the PCC, the DR interconnection system shall detect the island and cease to energize the Area EPS within two seconds of the formation of an island.” The standard provides no information regarding how to accomplish the island detection and deenergization within the stated two seconds.

Transmitting TE measurement from one IED to another allows the IED to perform a logical comparison of the two values to measure the difference. The data transmission considerations between these two IEDs make TED-based control considerably easier than phase angle comparison.

We can use protective relays as the IEDs making the comparison, and simplify the control action necessary to trip the unintentionally islanded generation as Standard 1547 stipulates. In this case, we must provide for communication between the relay at the generator and another relay outside any predicted island area. We must also establish the maximum stable phase angle difference between the two locations. For example, consider the system shown in Fig. 7.

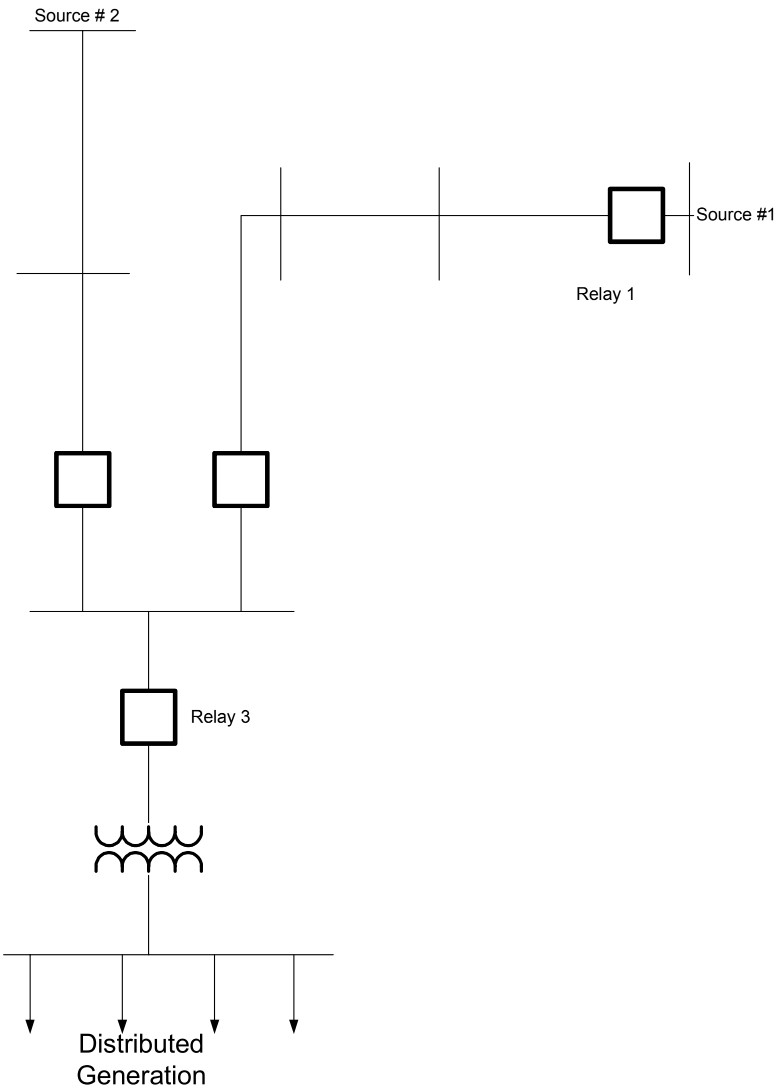


Fig. 7 Distributed generation islanding detection

In this example, for as long as there is no intermediate voltage support, the phase angle between Relay 3 and Relay 1 must always be less than 90 degrees on a steady-state basis for any power flow condition. This corresponds to a TED of about 4.2 milliseconds.

The rapid swings shown in the previous event reports again illustrate the advantage of using TED instead of phase angle difference directly. If phase angle were compared, even at high speed, there is a possibility that a complete swing could cause the instantaneous phase angle to be within an acceptable range. With TED, the difference in frequency between the islanded and grid system will cause a "sealed-in" TED. A frequency difference of only 0.2 Hz, small for a distribution island, would cause a TED of 6.67 ms in 2 seconds.

Another practical consideration for using TED instead of phase angle is communication. To use synchrophasor measurements to compare phase angles between different points on a system, it is necessary to include the timestamp associated with each angle. This information is necessary because any frequency deviation from perfect system nominal will cause a drift in phase angle between a measured wave and the synchrophasor reference wave over time as shown in Fig. 8.

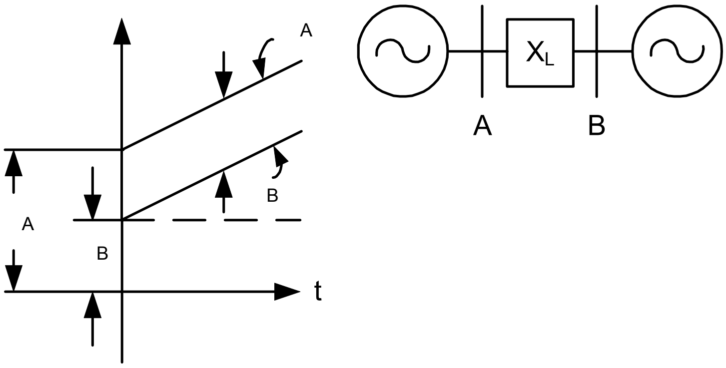


Fig. 8 Phase angle drift with time

In synchrophasor measurements, we account for this drift by ensuring comparison of phase angle measurements only with others taken at exactly the same time. This is why time information must accompany phasor measurements.

While the same problem exists in theory with TED measurement, the nature of an out-of-step or islanding condition minimizes the effect of non-simultaneous error measurement. Any frequency difference, although small, between an islanded system and the main grid depends upon a load-generation mismatch. This difference will not change in a small amount of time.

Relays can send an analog value, such as TE, directly to another relay, either through a direct serial connection or an IEC 61850 message string. In either case, the time of transmission is known within a fairly small range. Relays can use measured rate of change of frequency to correct for received time error prior to calculating TED.

$$\text{TED} = \text{TEL(corrected)} - \text{TER} \qquad (3)$$

$$\text{TE}_{\text{L(corrected)}} = \text{TE}_{\text{L}} - \left[\frac{(\text{LF} + (\text{df}/\text{dt} \bullet \text{TT}) - \text{NF}) \bullet \text{TT}}{\text{NF}} \right]$$

Where:

TED = Differential Time Error
TE_L = Time Error, Local
TE_R = Time Error, Remote
TT = Data Transmission Time (processor to processor)
LF = Local Frequency
NF = Nominal Frequency
df/dt = Instantaneous rate of change of frequency measured at the local relay

Time error does not "wrap around" every 360 degrees, so this correction is more reasonable for control purposes than for correction on phase angle directly.

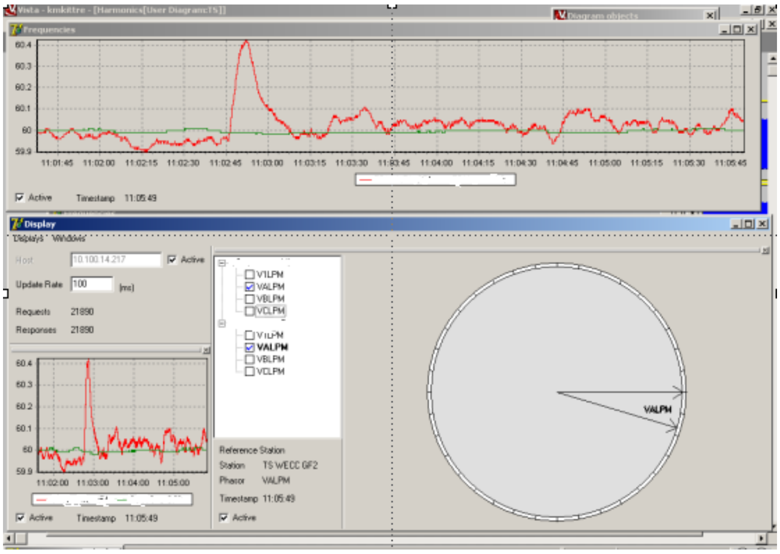
Obviously, communication time is critical to this application. To transmit an analog data point over a serial port takes approximately two cycles, depending on baud rate. By minimizing the amount of data transmission to only what is necessary for control, we increase the accuracy of these data. Use of TED instead of phase angle can help minimize the need for data transmission.

IMPROVEMENTS IN REMOTE SYNCHRONIZING AND CLOSING

Use of synchrophasor data for remote synchronization checks has been well demonstrated [3]. We can improve such synchronization checking through the use of phase angle and other additional measurements.

For example, as this paper discussed previously, rate of change of frequency is available both within relays and for transmission in the synchrophasor message. We can use this availability of rate of change of frequency information to address the concern that time delays in data transmission could cause breaker closing at an unacceptable voltage phase angle.

Consider the display that operators use in closing the breaker (Fig. 9).



☑ Active Timestamp 11:05:49

Host 10.100.14.217 ☑ Active

Update Rate 100 [ms]

Requests 21890

Responses 21890

☐ V1LPM
☑ VALPM
☐ VBLPM
☐ VCLPM

☐ V1LPM
☑ VALPM
☐ VBLPM
☐ VCLPM

Reference Station
Station TS WECC GF2
Phasor VALPM
Timestamp 11:05:49
☑ Active

☑ Active Timestamp 11:05:49

Fig. 9 Operator display for remote closing

While an operator can obtain from this display information about the instantaneous phase angle across the synchronizing breaker and the trend in frequency, there is no display of the rate of change of frequency. If this were added to the display, an operator would know if the system were accelerating out of phase or decelerating into phase. An operator can use such information to minimize shock to the system from closing the breaker.

SUMMARY

Synchrophasors provide data that have never been available to operators. Through the full use of the complete data set, not just magnitude and phase angle, it is possible to improve and simplify system operation. Advanced relay logic can mathematically manipulate data to make improved automatic control both possible and practical.

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