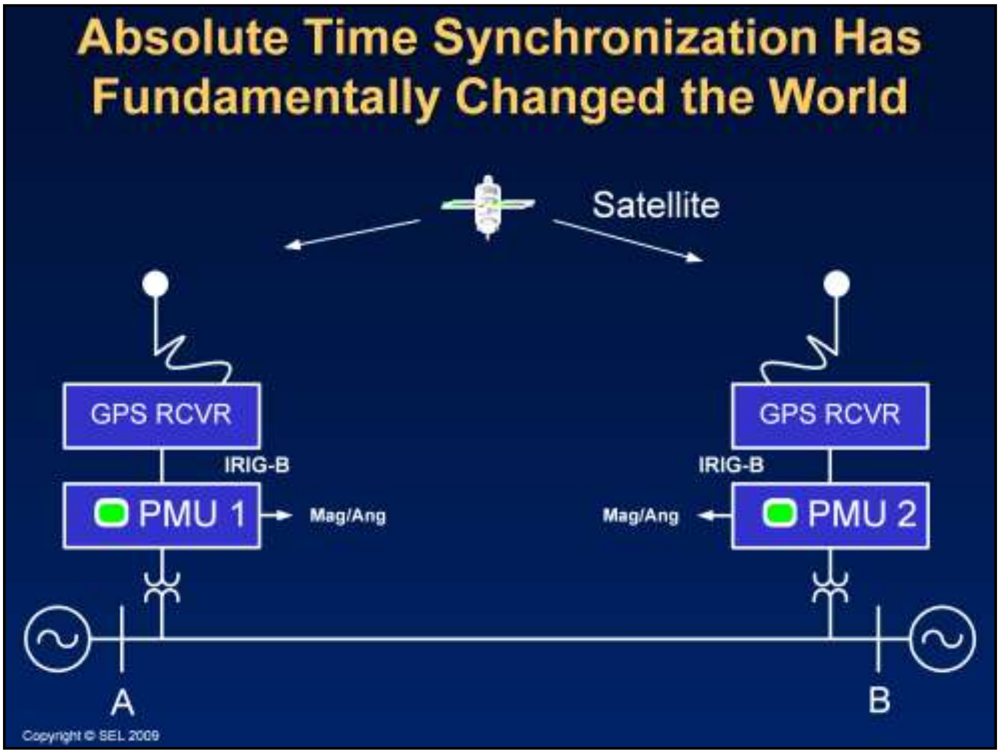
SEL Synchrophasor Solutions

Roy Moxley and Bill Flerchinger

Making Electric Power Safer, More Reliable, and More Economical®

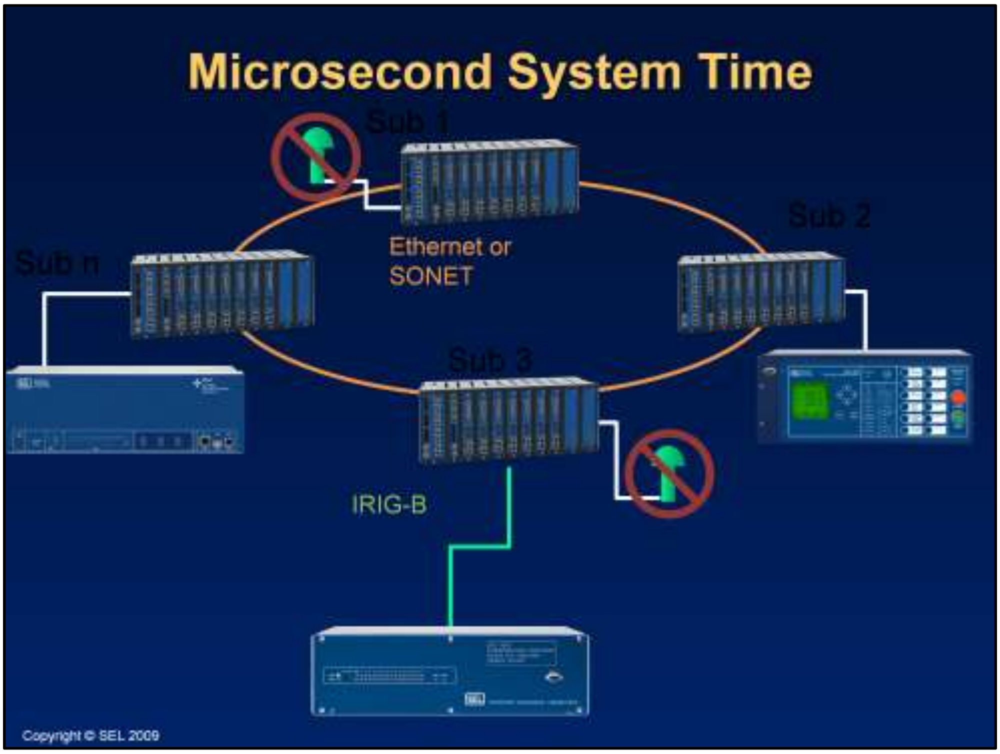


Low-priced satellite clocks have changed the way we look at the power system. Install clocks everywhere to be ready for future applications.

GPS Time – Good, Not Guaranteed!

- Jamming or interference
- Equipment failure
- DoD control
- Solar flares

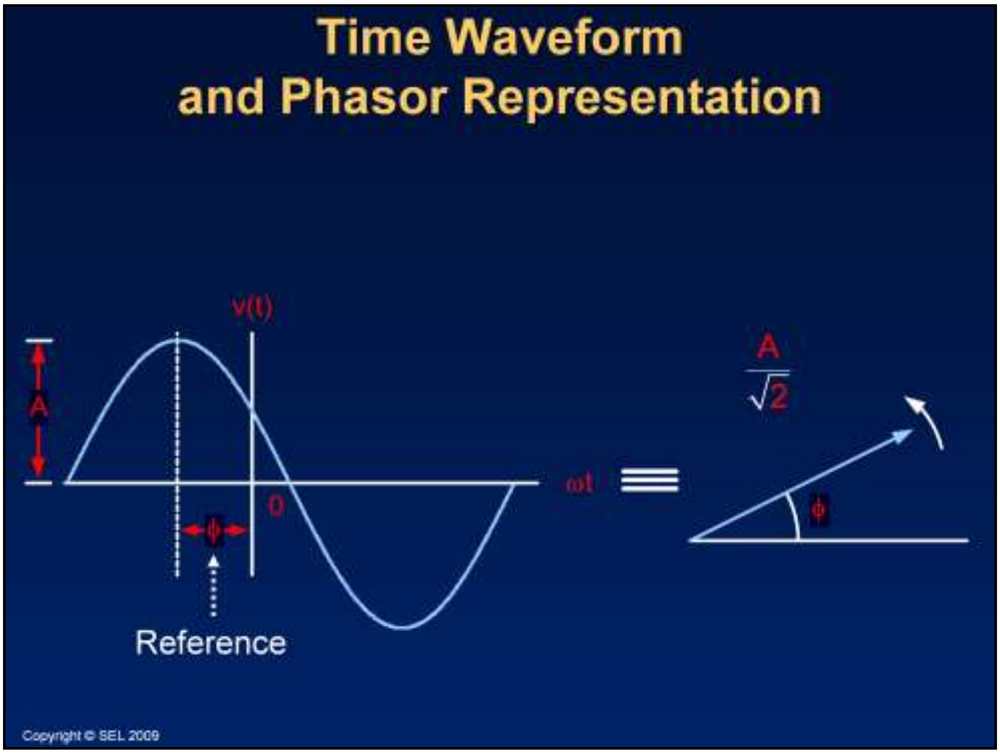
"On December 6, 2006, a solar flare created an unprecedented intense solar radio burst causing large numbers of receivers to stop tracking the GPS signal."



Loss of a single clock source in the system will not affect the accuracy of the time at that station.

Even when all clock sources are lost the time stays within 1 microsecond “relative time” across the system.

Multiplexer systems to distribute time signals are becoming available.



Angle Φ is used to specify the value that *v(t)* has at the reference time *t* = 0. The larger that Φ is, the farther from the *t* = 0 axis the maximum of the cosine wave. In the phasor plane (right side), a larger Φ means phasor *v* is farther from the real axis. Angle Φ is measured in the counterclockwise direction.

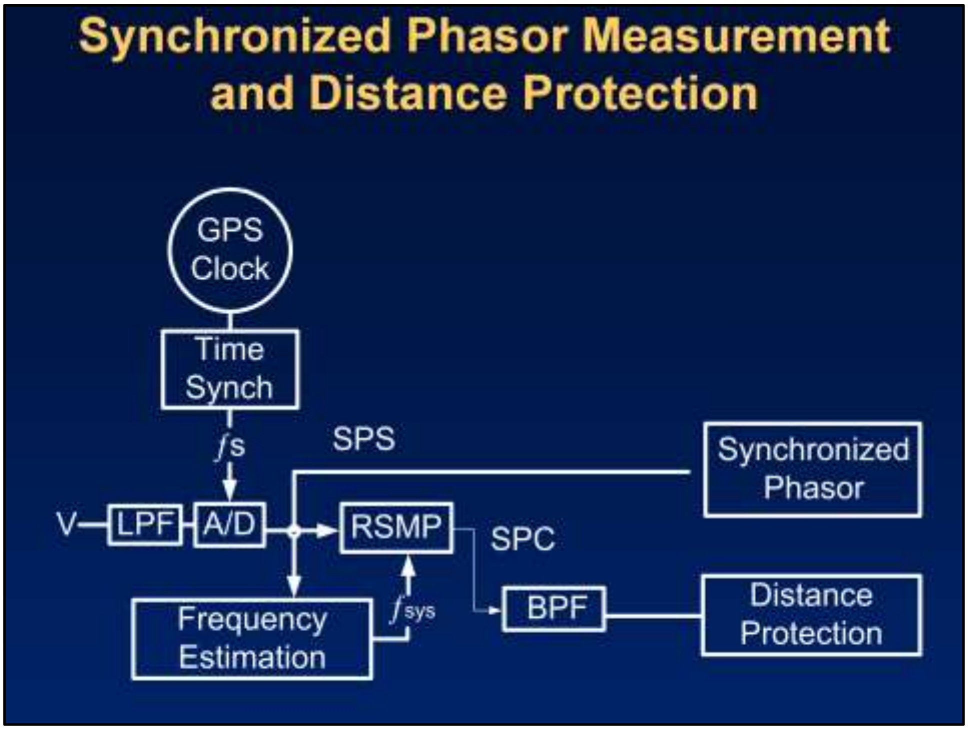
Phasor definition:

- The current and voltage of alternating current electrical systems, in steady state, are normally represented by perfect sinusoidal functions. This figure shows an example of a sinusoidal voltage signal (or function) called *v(t)*. The signal is periodic with a period of *t* seconds. The signal frequency *f*, in hertz, is the reciprocal of the period: f = 1/t

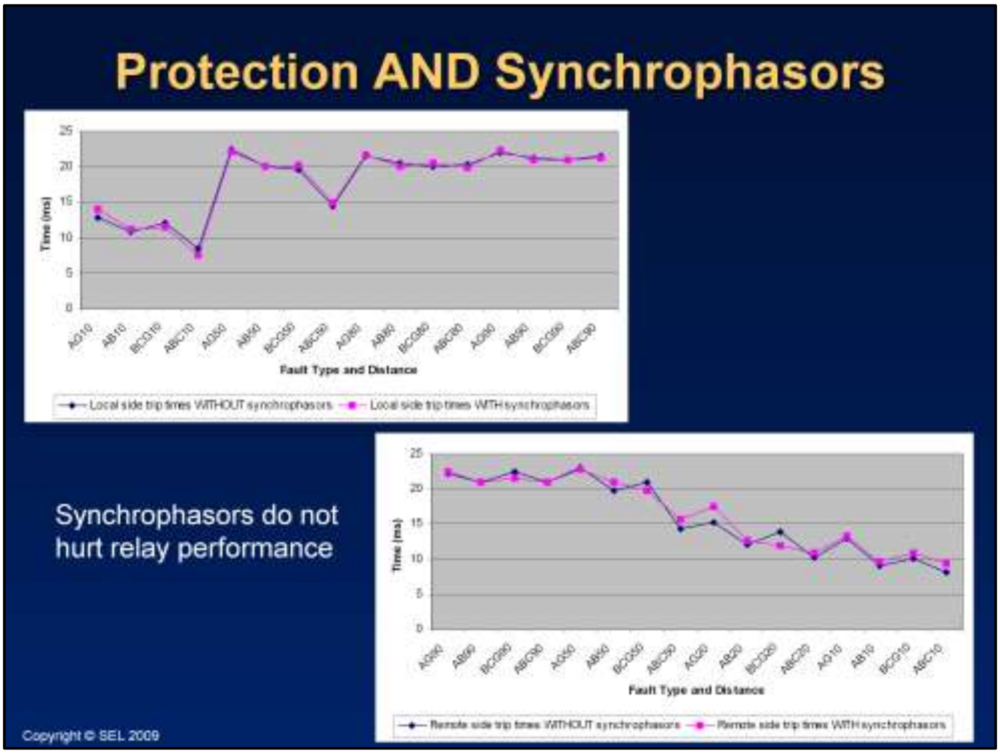
- The analytical expression of a sinusoidal function of period *t* is the following:

  $$v(t) = A \cdot \cos(2 \cdot \pi \cdot f \cdot t + \phi)$$

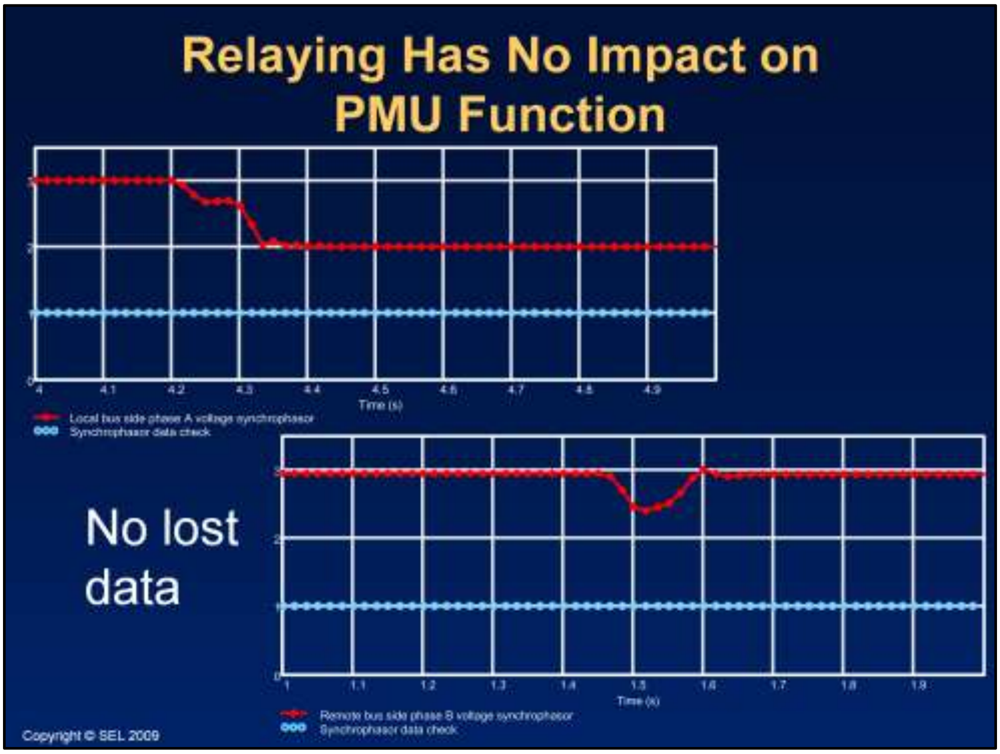
- Notice that the angle ϕ is the angle of the cosine function at *t* = 0, and the signal amplitude is *A*. In this plot, *t* = 0 is taken as the time reference.



The multiple-application device acquires data at fixed time intervals; the sampling frequency (ϕ_S) depends on an external clock signal (from a GPS clock) with absolute time reference. For synchronized phasor measurement applications, the device uses the GPS time reference. The A/D converter acquires data at a constant number of samples per second (SPS). These data are suitable for synchronized phasor phase measurements. The device estimates the system operating frequency, f_{sys}, from the SPS data. The device uses the system operating frequency, f_{sys}, to resample the data to obtain data at a constant number of samples per cycle, SPC. The resampled data pass through a digital band-pass filter, BPF, which extracts the fundamental frequency component of the signal. The device uses the filtered signal to calculate synchrophasor magnitude and fault distance.



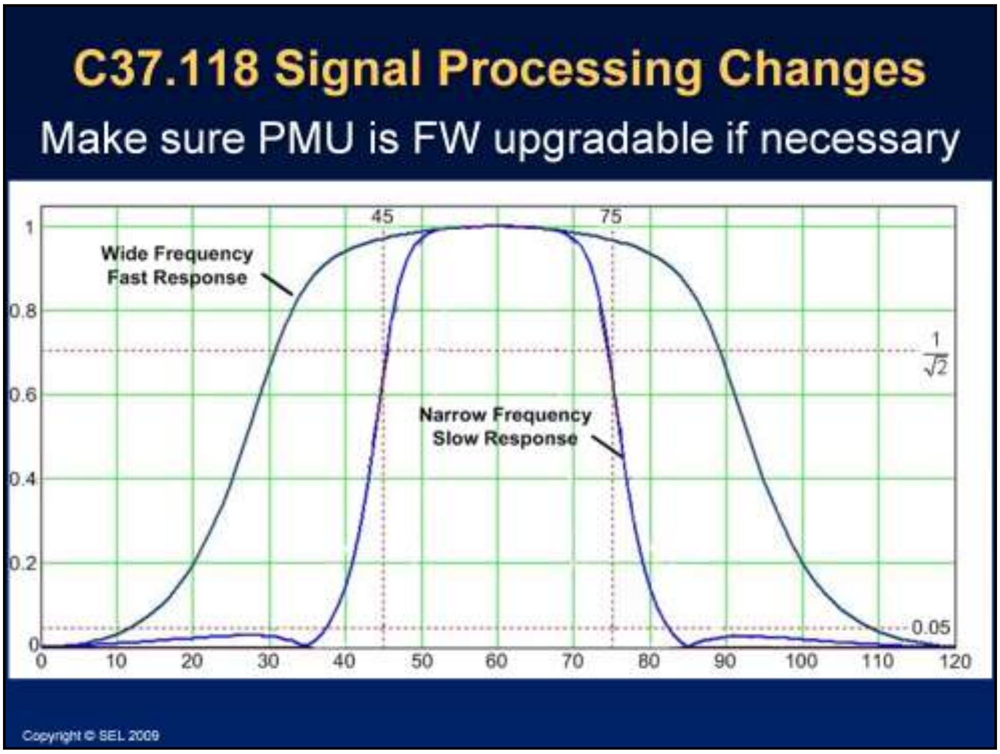
Tests prove that SEL relays with synchrophasor capabilities do not suffer deficient performance when synchrophasors are turned on.



Tests by SEL and a utility (AEP) also show that a relay providing synchrophasor data will continue to send data during a fault.

Potential control applications increase the value of phasor measurements inside a relay. Phasor measurement and control units (PMCUs) are how we refer to relays with PMU capabilities.

Because of these advantages, it is natural that synchrophasors should be in relays.



SEL-421, 451, 487E and 487V relays have a selectable filter response. This provides for either a fast response for control applications, or a slower response for monitoring applications.

SEL has been providing synchrophasor capabilities for 8 years


Continuing Significant
Support and Investment
2010++
Synchrophasors in a Relay (4xx)
Synchrophasors in a Meter
Synchrophasors on the Web
IEEE Protocol in a Relay
SYNCHROWAVE
Synchrophasors in 3xx Relays
Hardware PDC
PMU receives synchrophasors + control
SCADA Synchrophasors
Synchrophasor Vector Processor
Advanced Archiving
RTAC
'02
'03
'05
'06
'07
'08
'09
Our synchrophasor team is
working on products and
customer's solutions now
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SEL-421, 451, 487V

- Full IEEE C37.118 compliance
- Up to 60 messages per second
- Includes Synchrophasor RTC
- 6 I, 3 V (6V in 487V)

The most popular family of distribution relays in North America now comes standard with IEEE C37.118 synchrophasors at no extra charge. This brings low cost, standard synchrophasors to distribution or transmission applications.

For a complete station of synchrophasors, 6 – three phase currents and 2 – three phase voltages, the SEL-487E provides protection and automation capabilities.

Station and Feeder PMU labeling are available for the SEL-487E and SEL-351A relays


Many Additional Relays Include PMU
SEL-787, 751A
1 – 10 messages/s
IEEE C37.118 - 2005 protocol
Existing SEL-351, 311 Relays
One message/s
Fast message protocol
Software upgradeable for older units
SEL-700G Generator Protection
Full IEEE C37.118 compliance
60 messages/s
3I, 3V
10 years
WARRANTY
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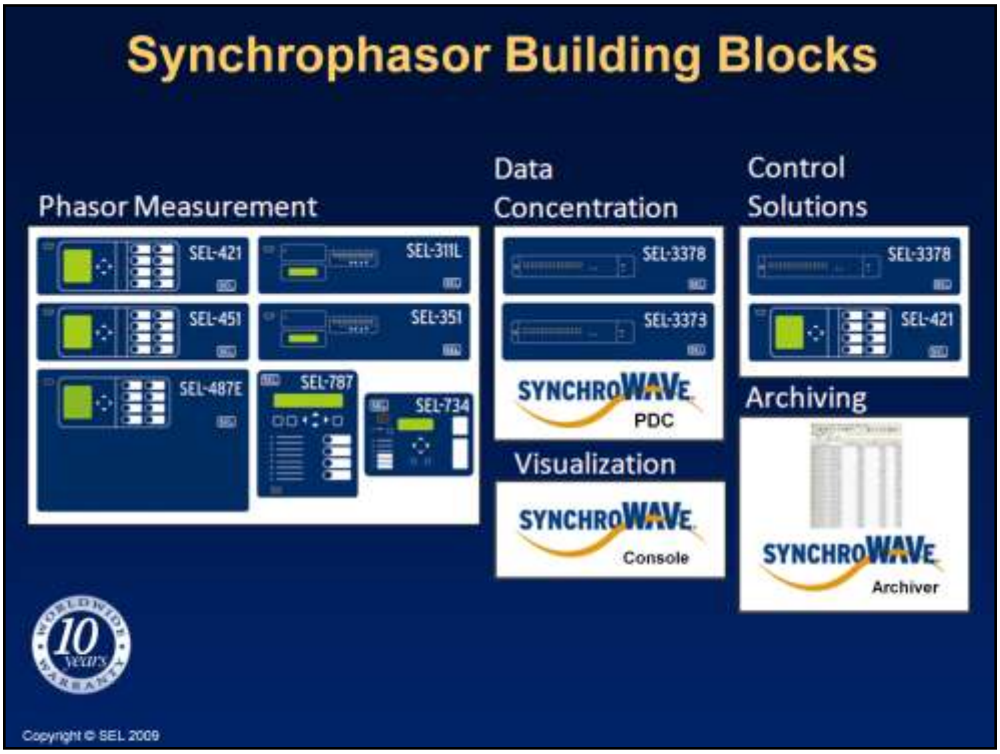
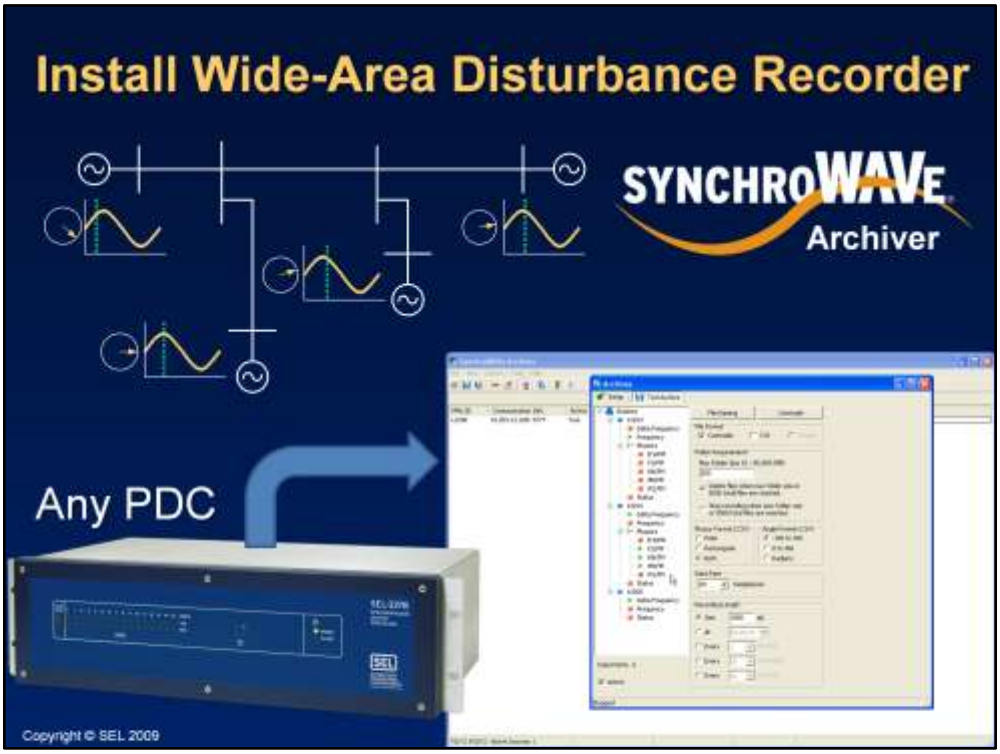
SEL Celebrating 25 Years of Innovation

Synchrophasor System Building Blocks

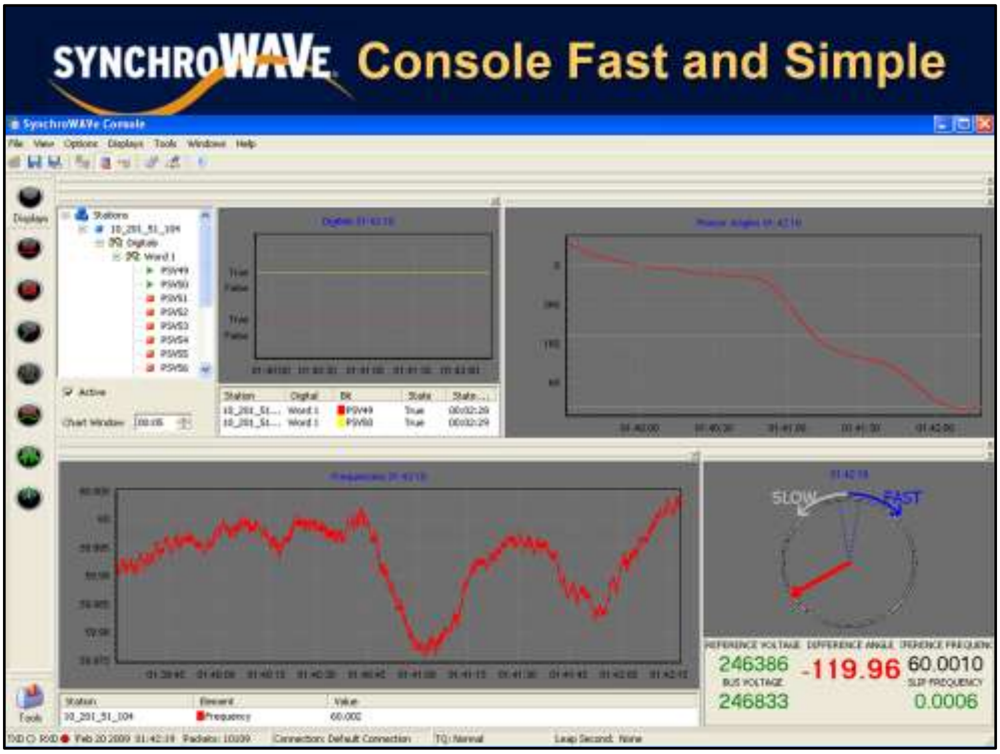
Making Electric Power Safer, More Reliable, and More Economical®



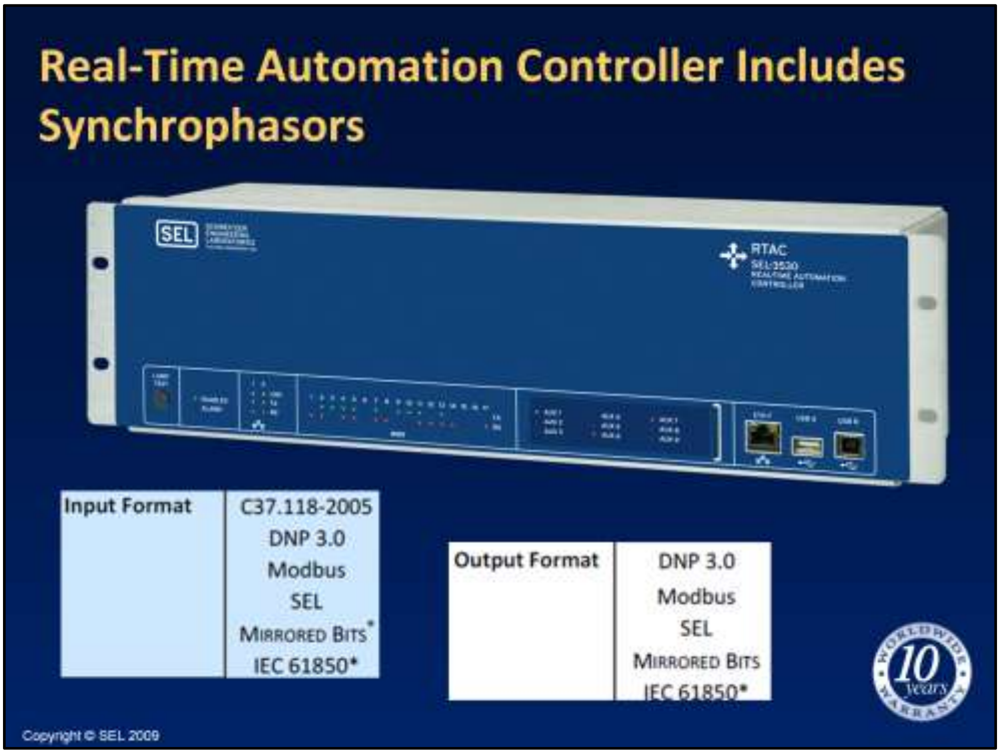
SEL has all the components of a complete synchrophasor system available.



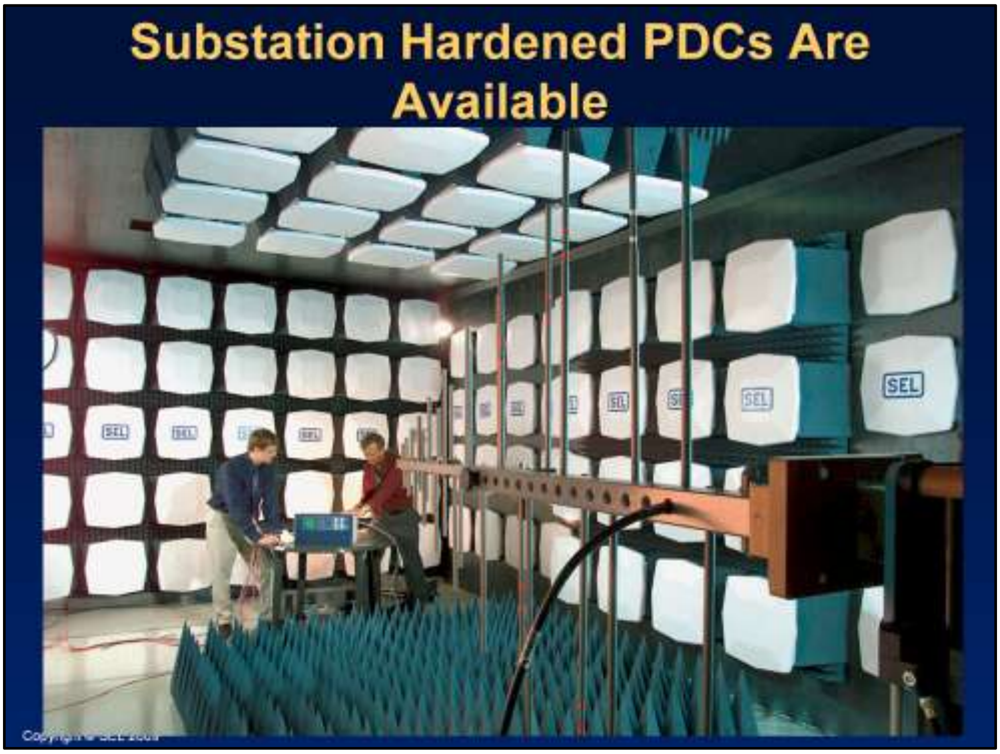
SEL-5076 SynchroWAVe Archiver software provides continuous or triggered recording of synchrophasor quantities.



SEL-5078 SynchroWAVe Console software provides simple and complete synchrophasor viewing.



The RTAC can process synchrophasors at rates up to 5 messages per second

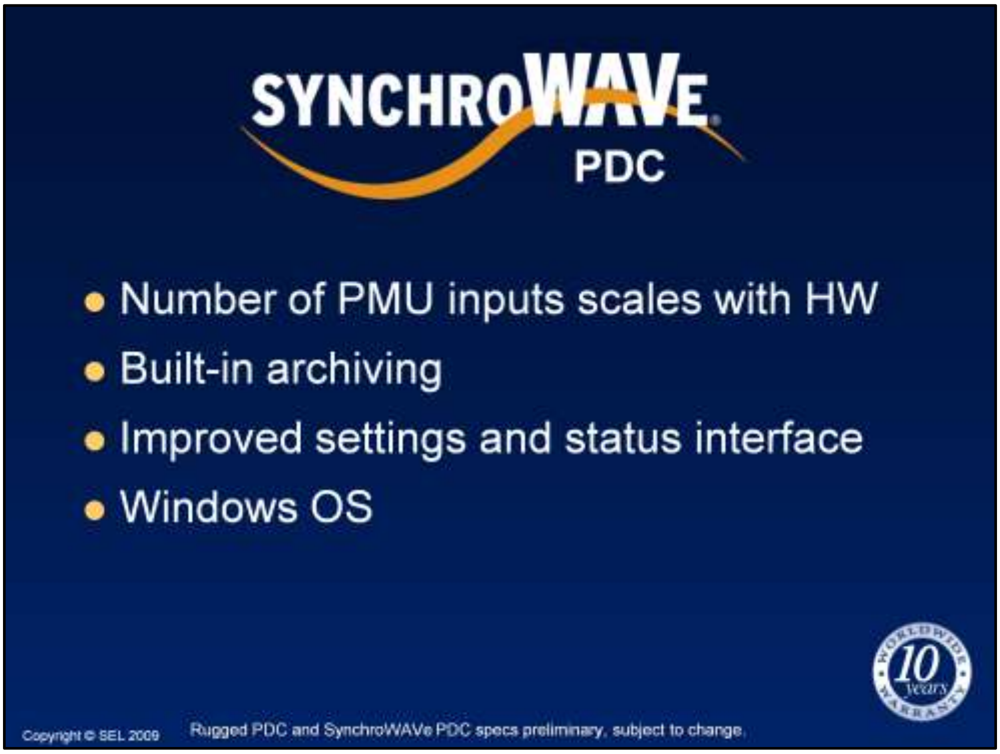


SEL PDCs, either in hardware or in software on an SEL rugged computer, are built to operate in substations.

Station PDC

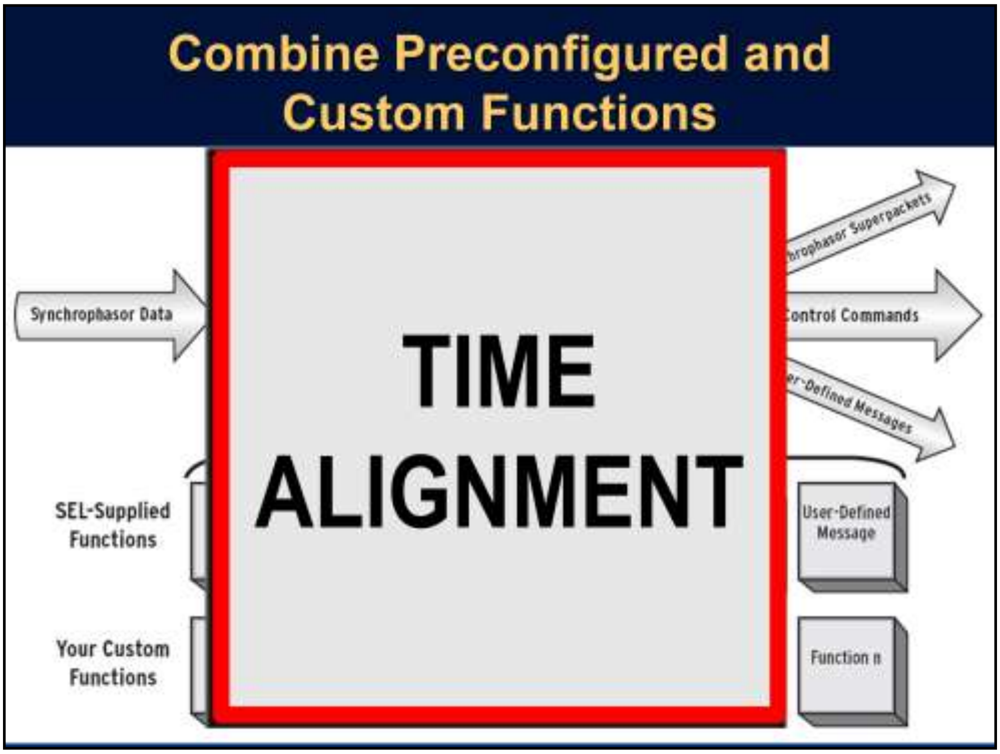
- Built-in archiving
- Improved settings and status interface
- High performance (>>40 PMUs)

Station PDC and SynchroWAVe PDC specs preliminary, subject to change.

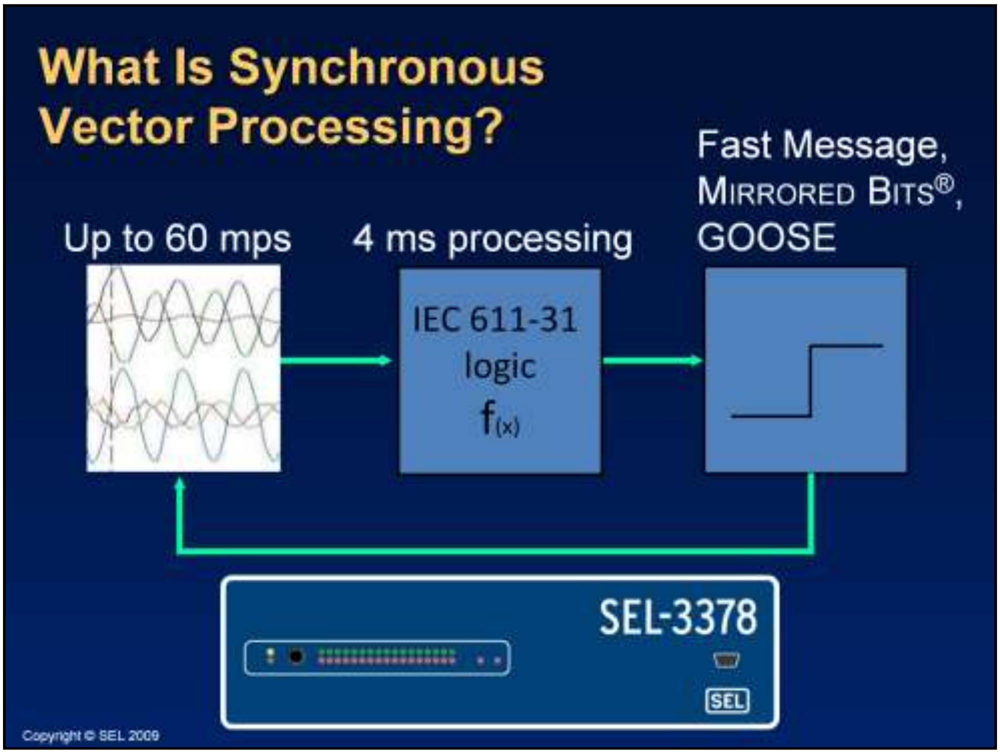


For Windows applications, SEL SynchroWAVe PDC provides a high-function, economical PDC.

The SEL-3378 provides high-speed vector processing for real-time control and analysis.



Applications are built up using a combination of predefined and custom functions.



The SEL-3378 Synchrophasor Vector Processor (SVP) provides closed-loop control using synchrophasor data.

Synchrophasors Are a Flexible Tool

- State measurement
- Disturbance recording
- Modal analysis
- Dynamic response measurement

  and…

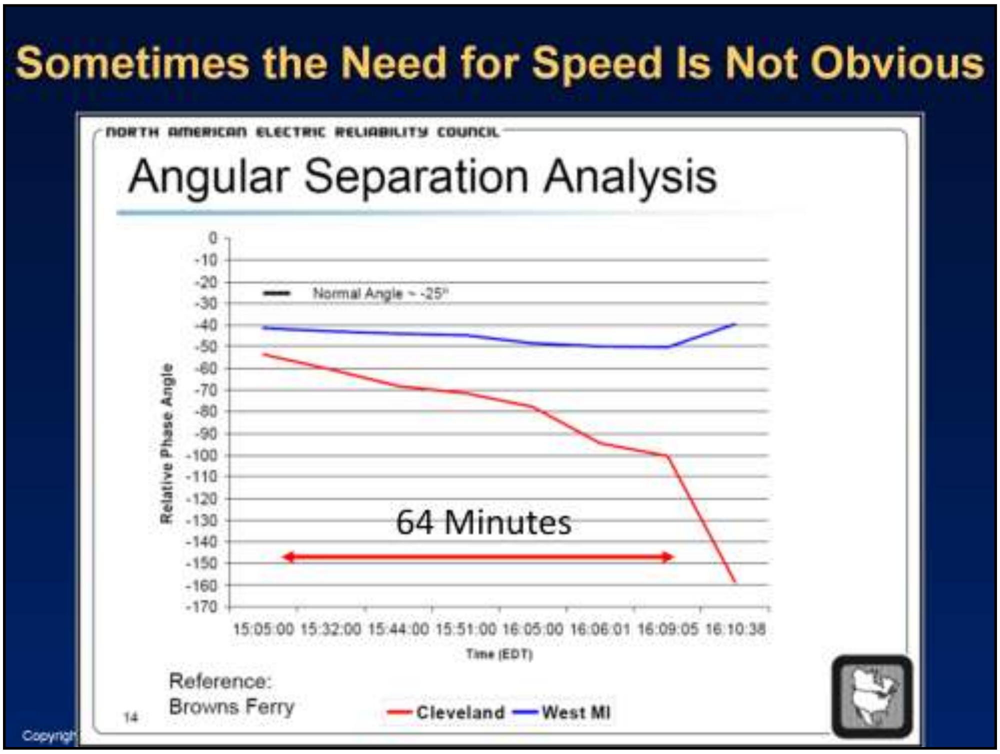
  High-Speed Protection and Control

If a clock is connected to the relay, it is a good idea to turn on synchrophasors. This makes **MET PM** available, along with synchronized event reports and streaming synchrophasors.

One or two messages per second is fast enough for traditional SCADA (supervisory control and data acquisition) applications. Most reliability councils consider 12 to 20 messages per second acceptable for disturbance recording.

For high-speed control, it is good to use the fastest possible rate. This actual rate used is subject to communications capabilities.

Many system "events" take time to build to a crisis. By simply viewing data that can be easily understood, operators can take action to prevent the crisis—starting generation, bringing transmission assets back into service, or shedding minimal load.



The 2003 blackout in the northeastern United States developed over the course of more than one hour.

This is the same event as the previous slide but with a linear time scale.


SEL
Celebrating
25 YEARS OF INNOVATION
A Few Real Application Examples
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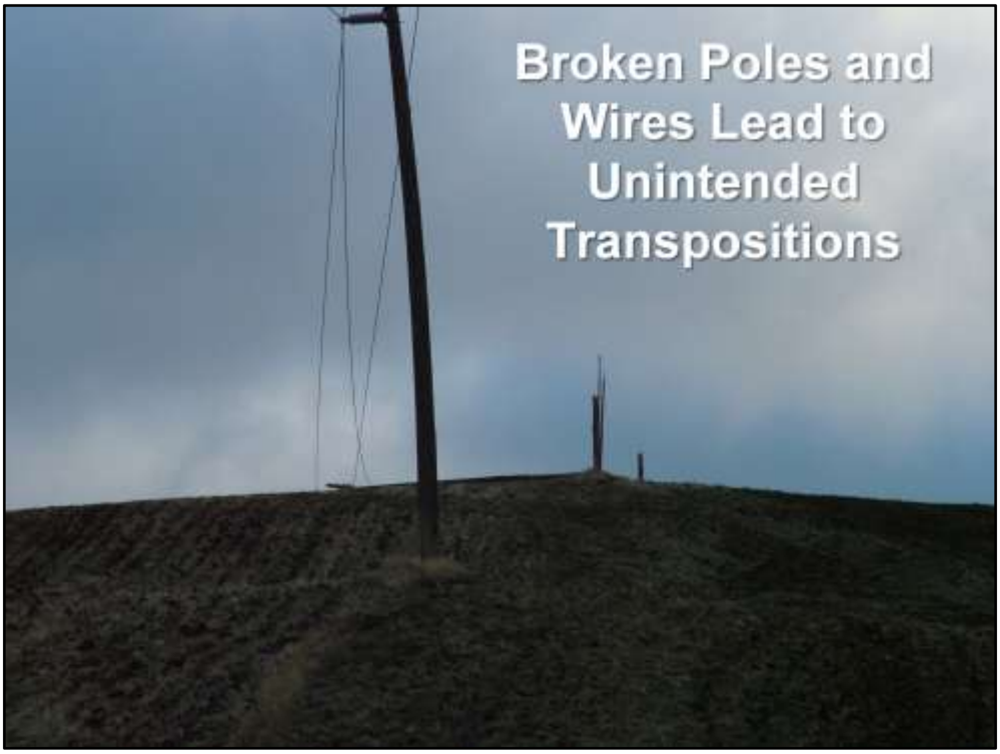
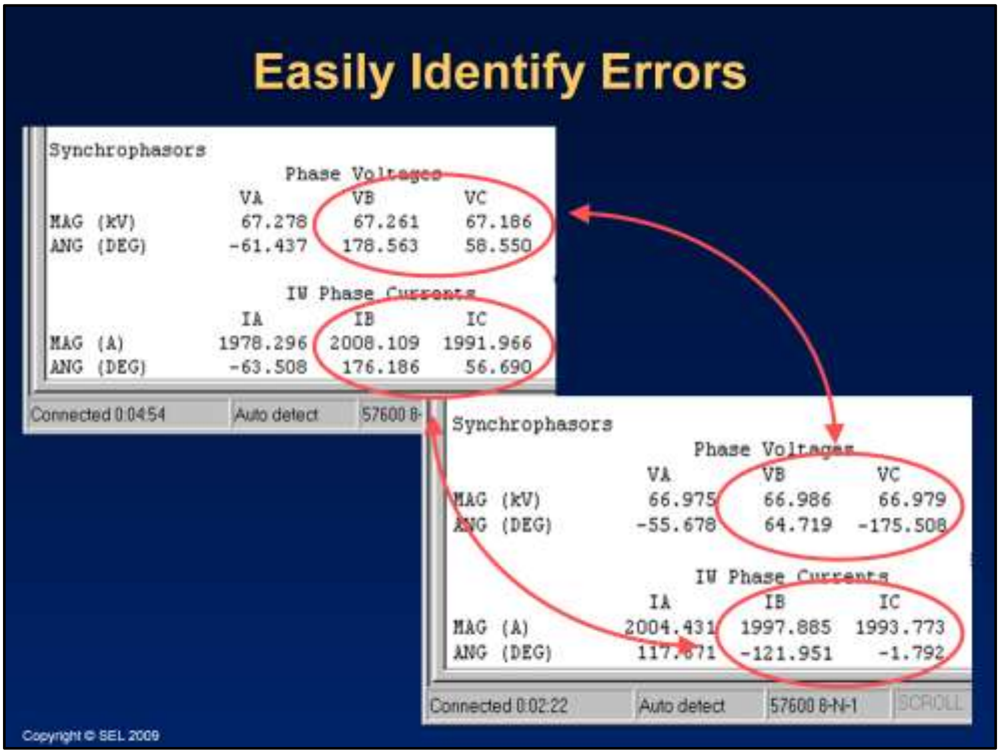
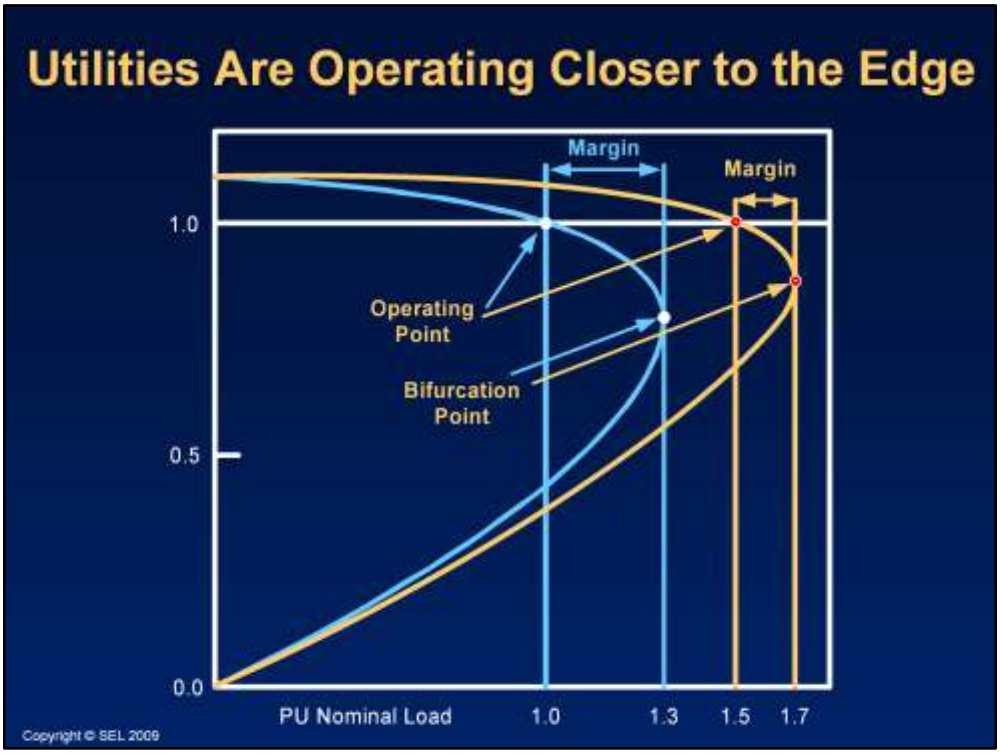


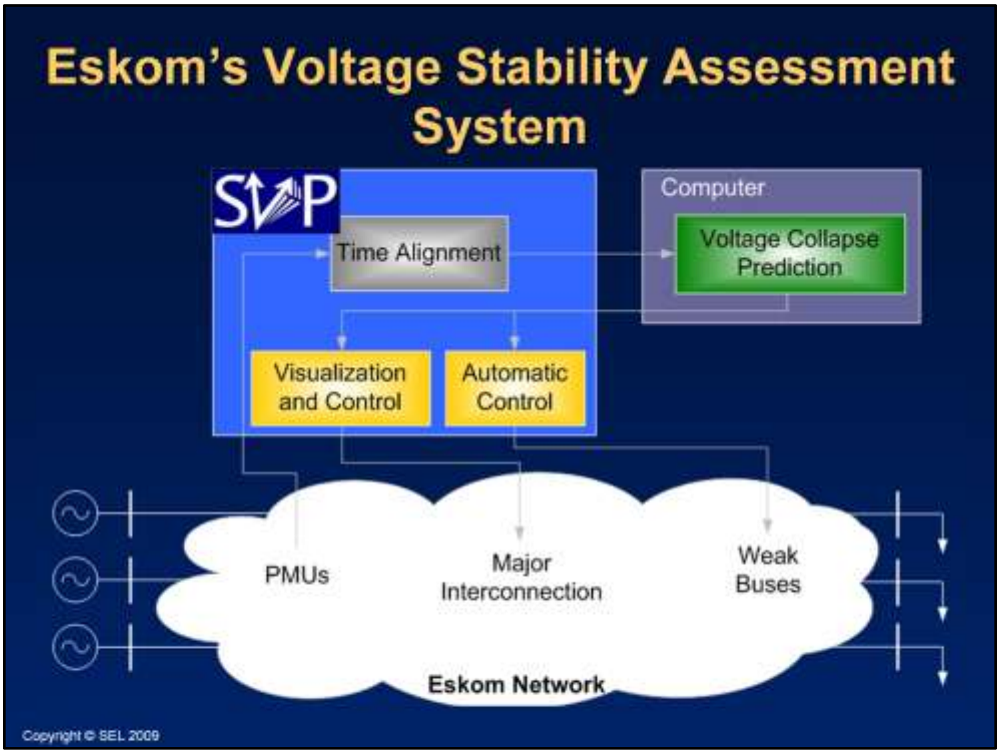
If the poles and wires snap, similar to what is shown here on a line north of Pullman, Washington, it can be difficult to ensure proper phasing. **MET PM** provides a “no cost” solution.



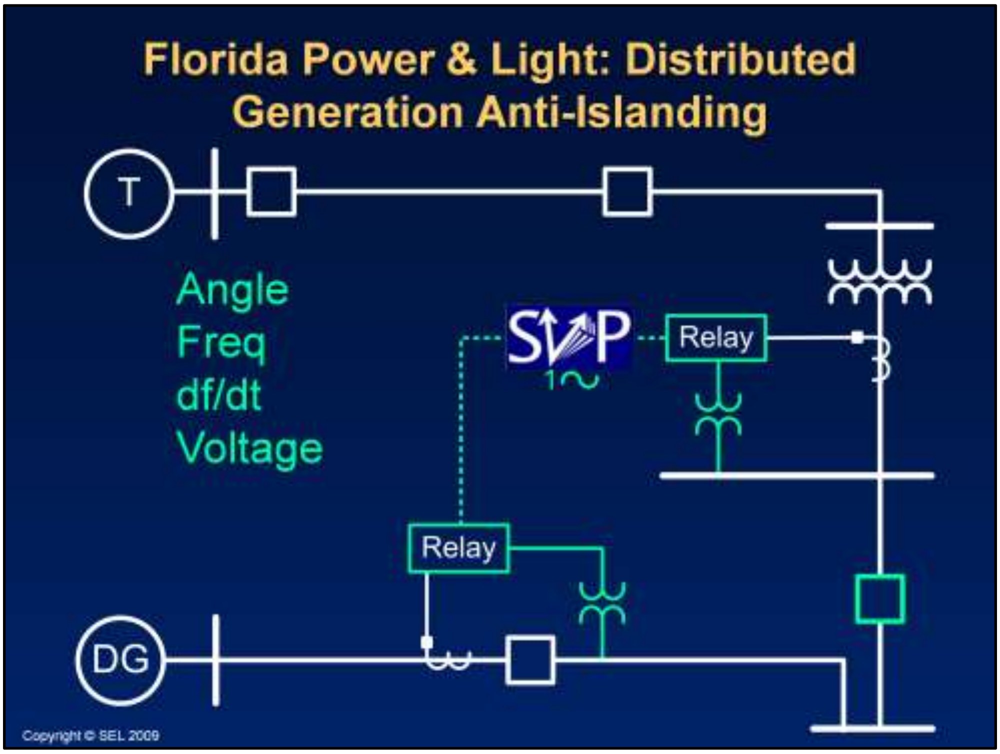
On any transmission line, the voltage angles should be fairly close together, while the currents should be close to 180 degrees out of phase. Errors are simple to identify.



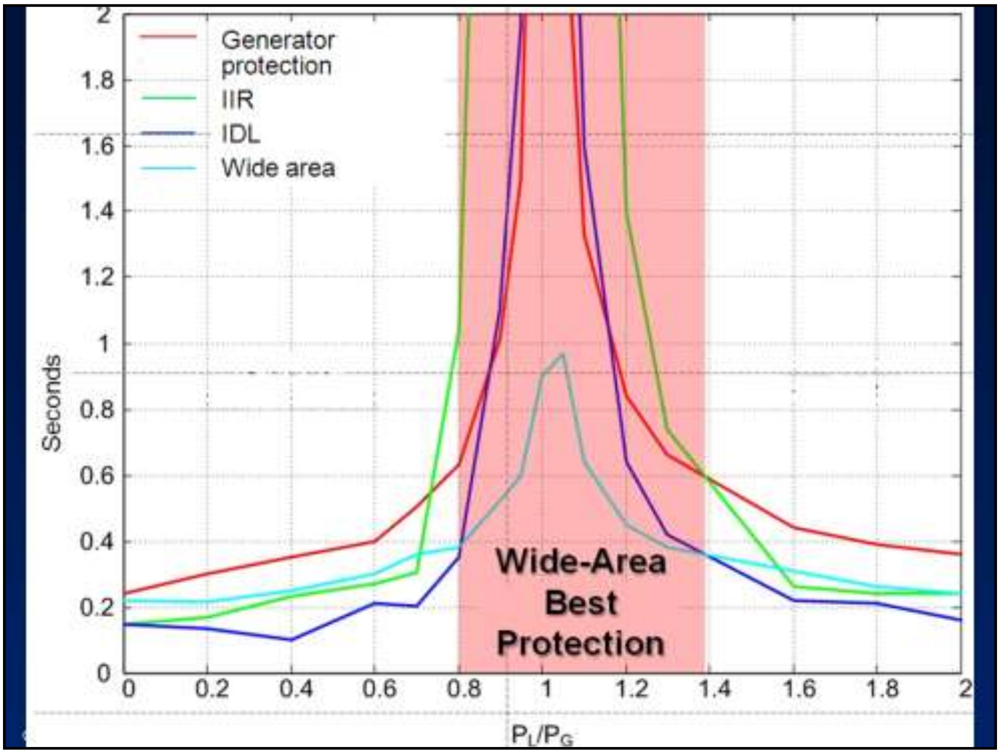
Adding shunt capacitors to a distribution system increases power transfer capability. This makes maximum use of precious transmission and distribution capacity. The problem is that it reduces the stability margin amount.



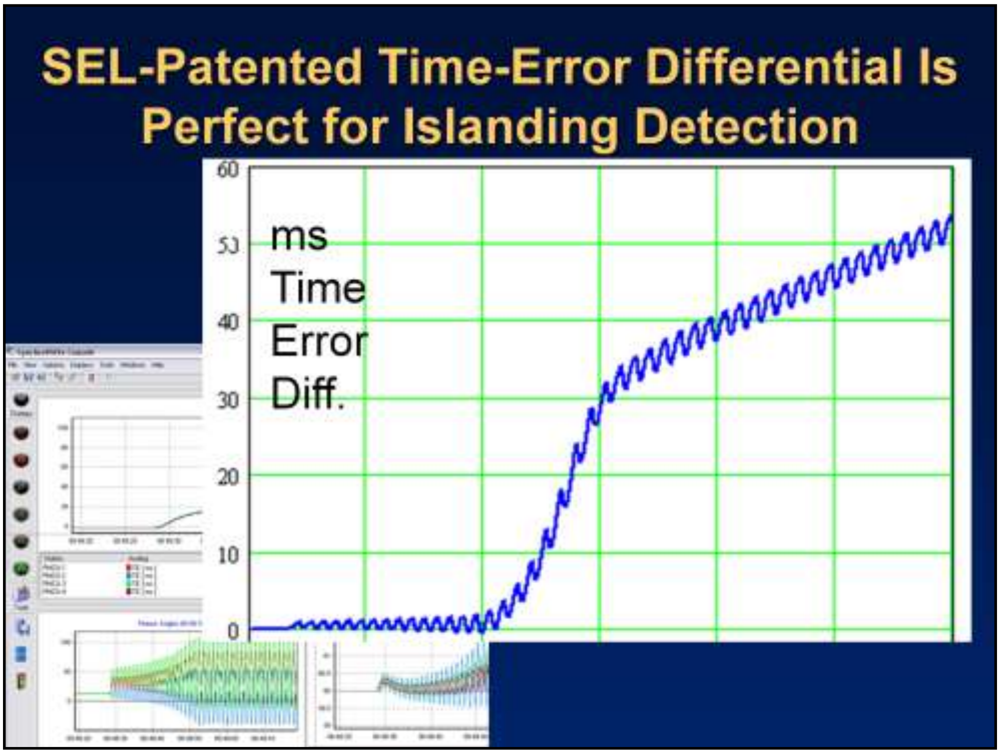
Using synchrophasor measurements Eskom (national transmission utility in South Africa) is applying predictive voltage collapse to improve system operations.



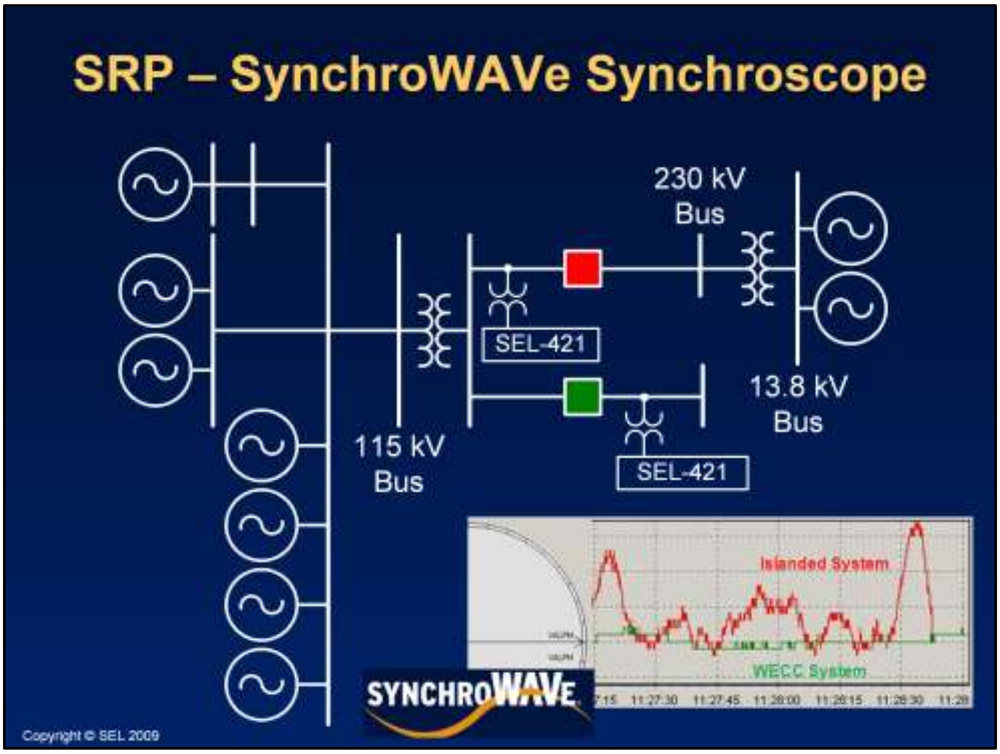
FP&L has tested a system applying multiple wide-area inputs to trip distributed generation in case of islanding. Future applications can involve multiple generators and eventually islanding control instead of tripping.



Tests of the system shown on the previous slide indicate that wide-area islanding detection is the best system when the load-to-generation ratio is close to unity.

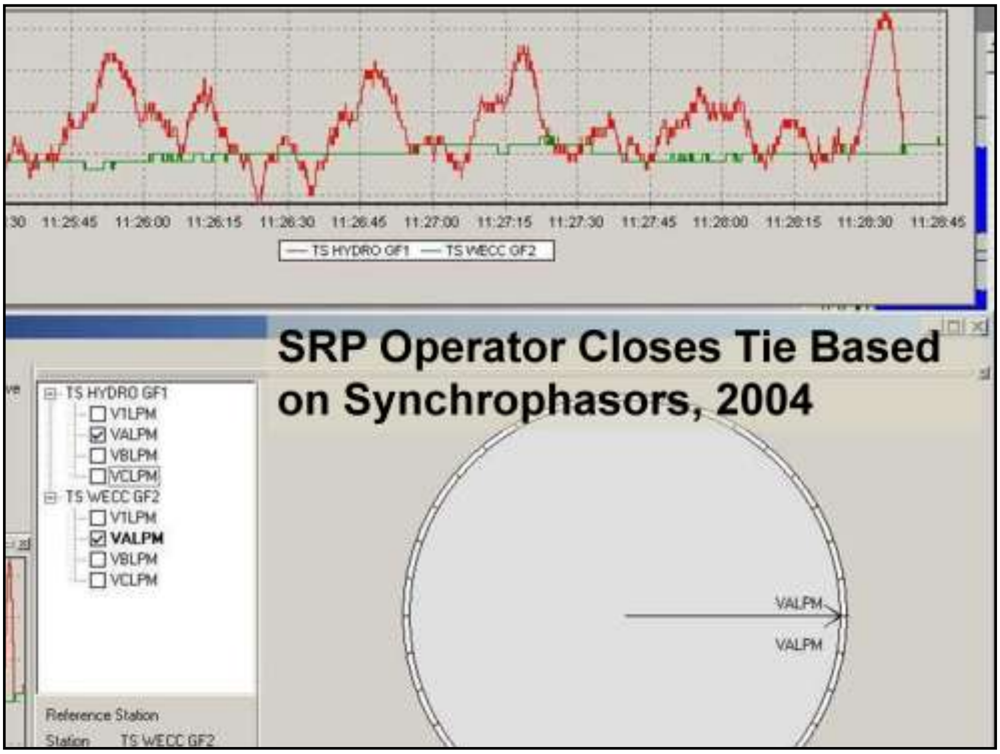


Time Error is available in SEL-421 relays. This element has microsecond accuracy and as such is suitable to use for measurement of system conditions by comparing the time error between different points on the system.

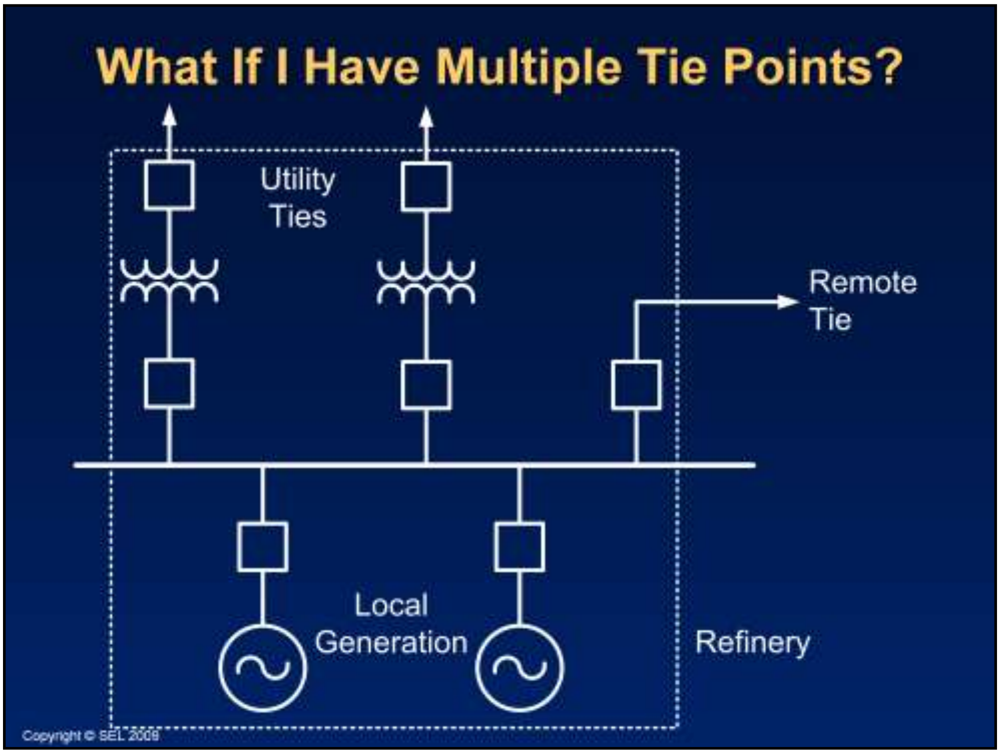


Salt River Project used synchrophasors to control reconnection of a portion of their system following a black start test. Remote control, based on synchrophasor measurements, was successfully demonstrated.

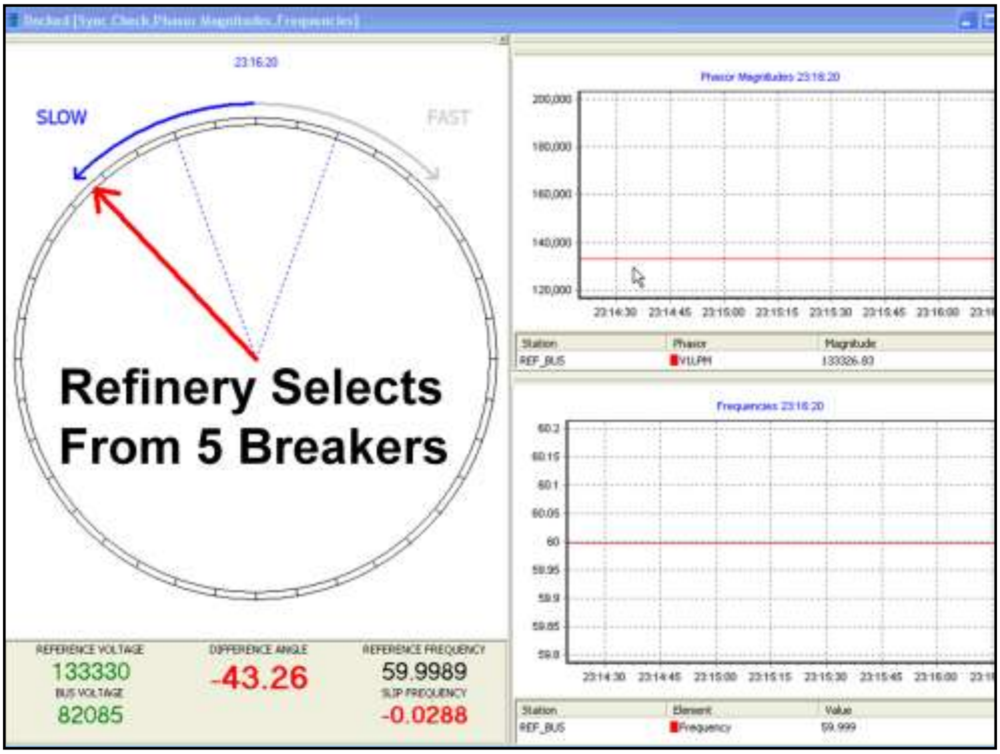
43



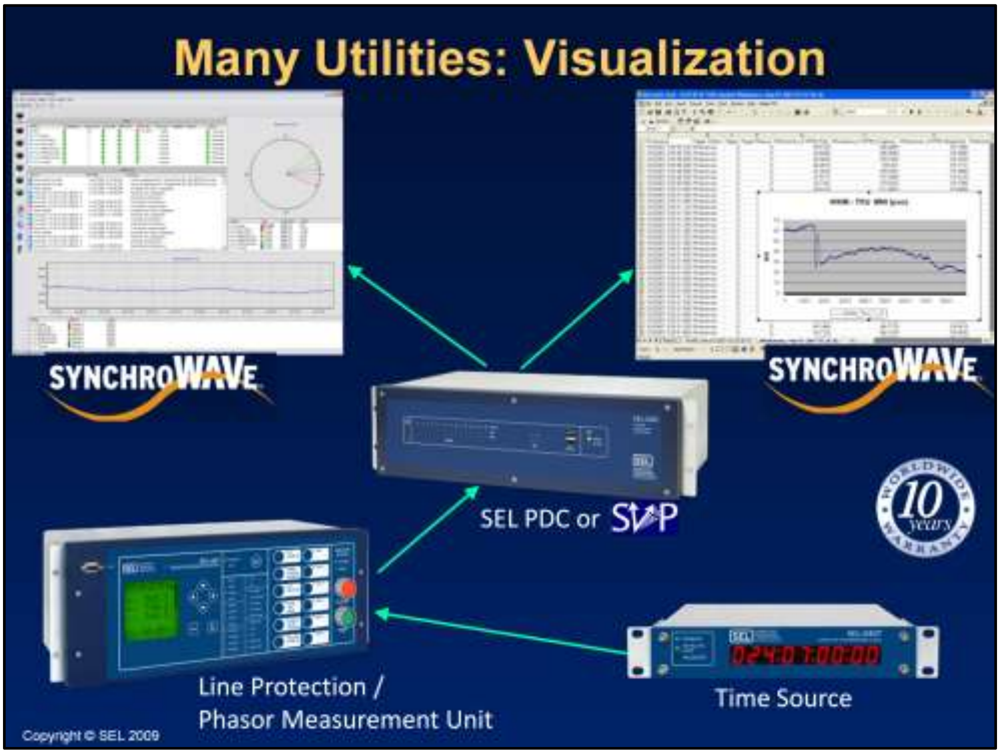
In an application of synchrophasors for remote synchronizing, operators could see the system frequency and phase angle difference as if they were inside the synchronizing station. Previously, someone in the substation would perform this operation.

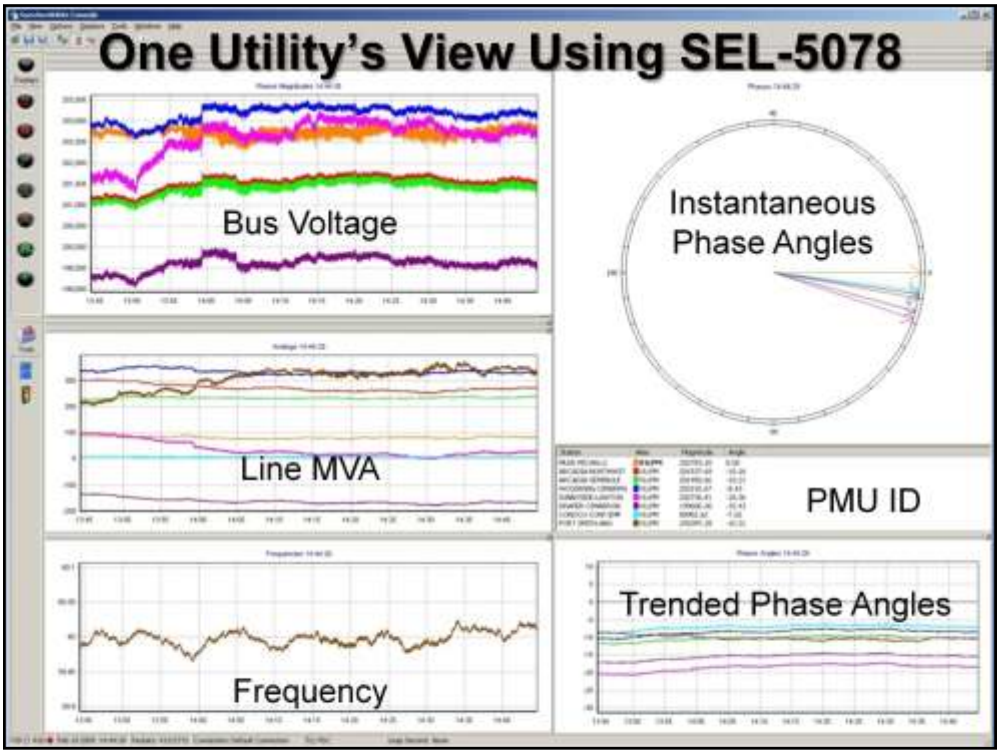


A refinery in the southern United States, as illustrated in this slide, wants to perform synchronizing for multiple tie points.

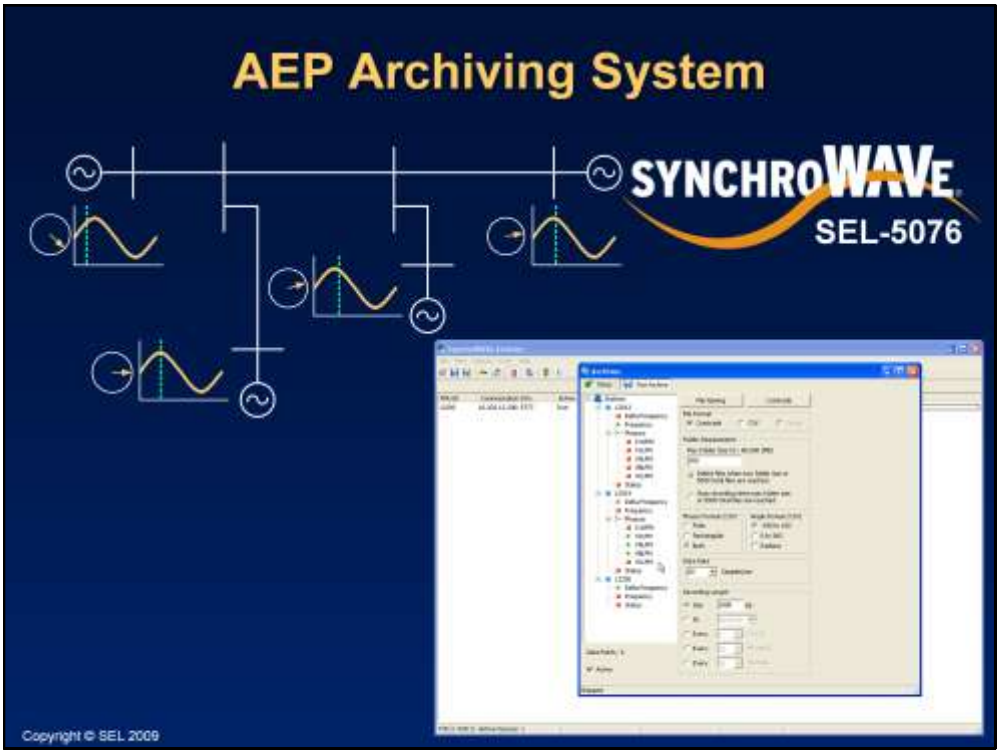


Selecting from any of the PMUs connected at all ties of the system, operators can close any breakers necessary to restore service.


Many Utilities: Visualization
SYNCHROWAVE
SYNCHROWAVE
SEL PDC or SVP
Line Protection /
Phasor Measurement Unit
Time Source
WORLDWIDE 10 years WARRANTY
Copyright © SEL 2009



This screen illustrates how one electric utility is viewing real-time synchrophasors using SEL-5078 SYNCHROWAVE® Console Software to provide operators with "situational awareness" of system conditions.



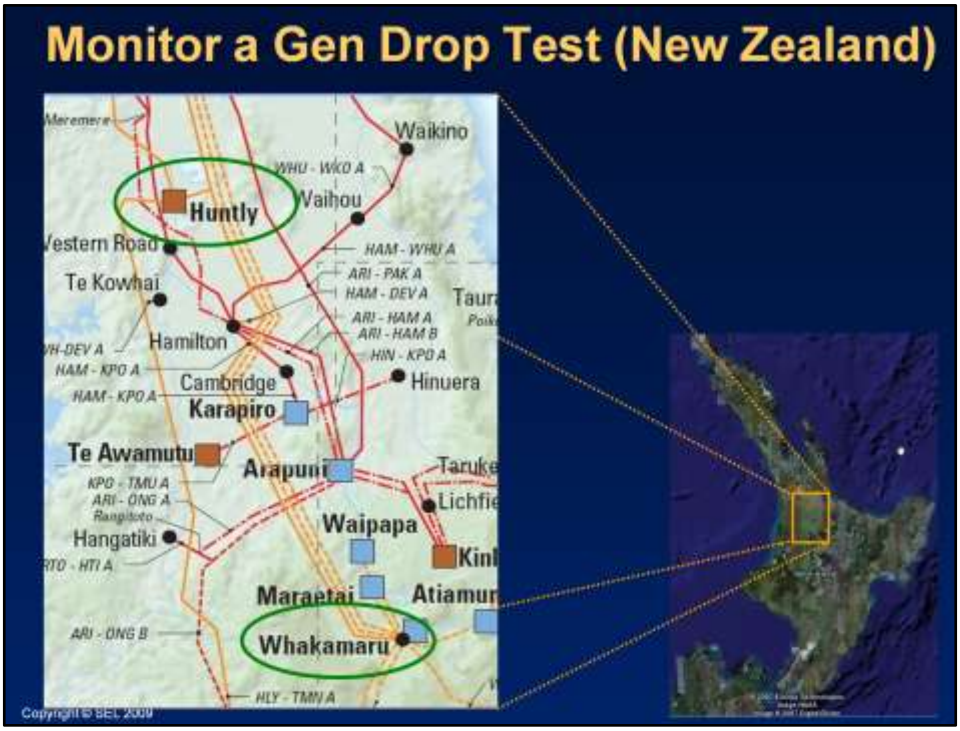
Wide-area disturbance recording is economically provided using SEL software storing data from all over the power system.

SYNCHROWAVE provides two ways of initiating the data storing process, viz. manually or via trigger conditions.

Before manually archiving data, create a new folder in the Archives Folder by double clicking on the New Recorder button , or by dragging and dropping the icon into the Recorders Window. New folder names default to 'Recorder xx', where xx automatically increments to one digit greater than the highest existing folder. Manually archive data by checking the 'Recording' box. Stop archiving by manually unchecking the 'Recording' box.

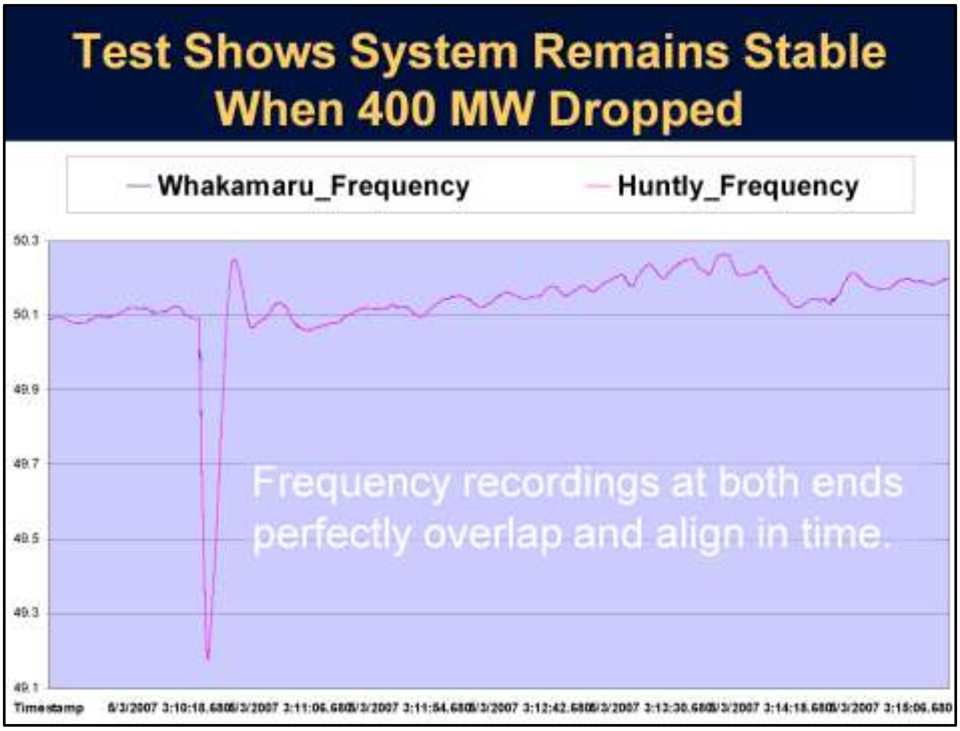
Before archiving by trigger, create a new trigger folder in the Archives Folder by double clicking on the New Trigger button , or by dragging and dropping the icon into the Recorders Window. New folder names default to 'Trigger xx', where xx automatically increments to one digit greater than the highest existing folder. Trigger archiving requires two conditions, 1) that the 'Recording' box is checked, and 2) that a PMU trigger is detected in a data packet. All subsequent triggers from the same station are ignored while the recording from a previous trigger is still in progress.

All folders names appear in the Recorders Window together with information about how many data points are selected for archiving and the active status of each folder.



Huntly is the location of the generator load drop testing. Huntly is a thermal generation site, with approximately 400 MW capacity. Whakamaru is a substation near a small hydro generation station. The two stations are connected via a 220 kV double-circuit line. The purpose of the test is to confirm proper operation of the generator protection systems in the event that the generator is islanded. However, due to the size of the generator, removing it from the system can have a significant impact on system stability. By monitoring the main network near the generator site and further down, the engineers can attain a better understanding of the effect on the network when a generator of this size is tripped off.

51

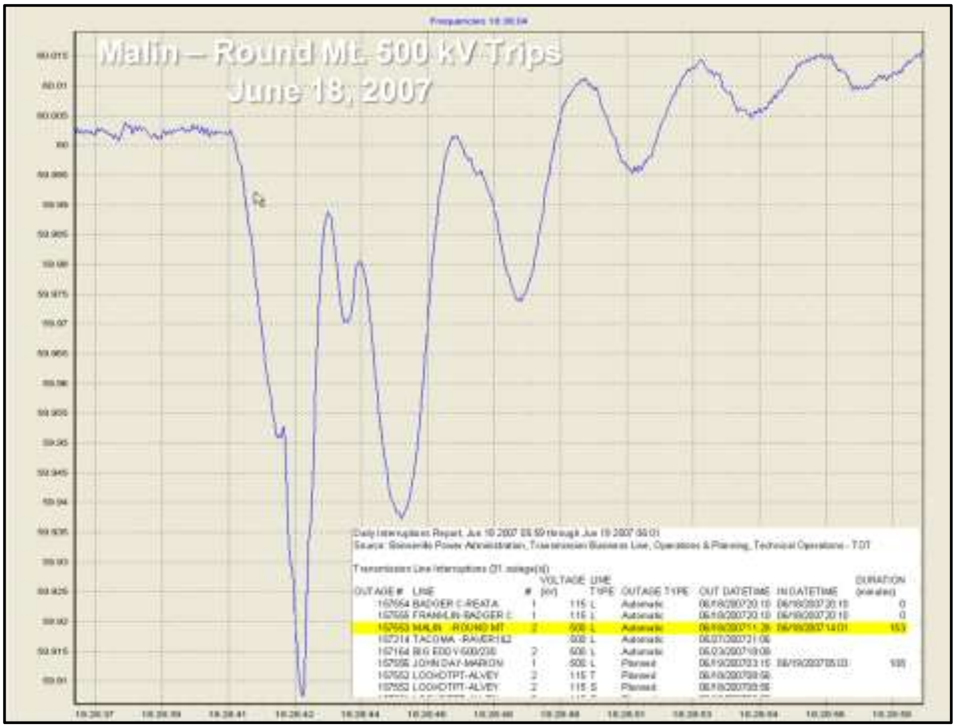


The units functioned extremely well for them and they were very happy with the data they received. Senior management in both the operations and planning areas became aware of the success of the testing and the data captured using the synchrophasor principle. They have decided that this type of information is a must for the future operations and development of the network and have instructed that permanent synchrophasor data capture functionality be installed in the network.

The first stage of this project is to install PMU units (SEL-421) in 10 major substations in the network and bring the data back to a central location. This is due to be completed by the end of October. They want to archive the data at this stage and are currently working on a plan to do this.

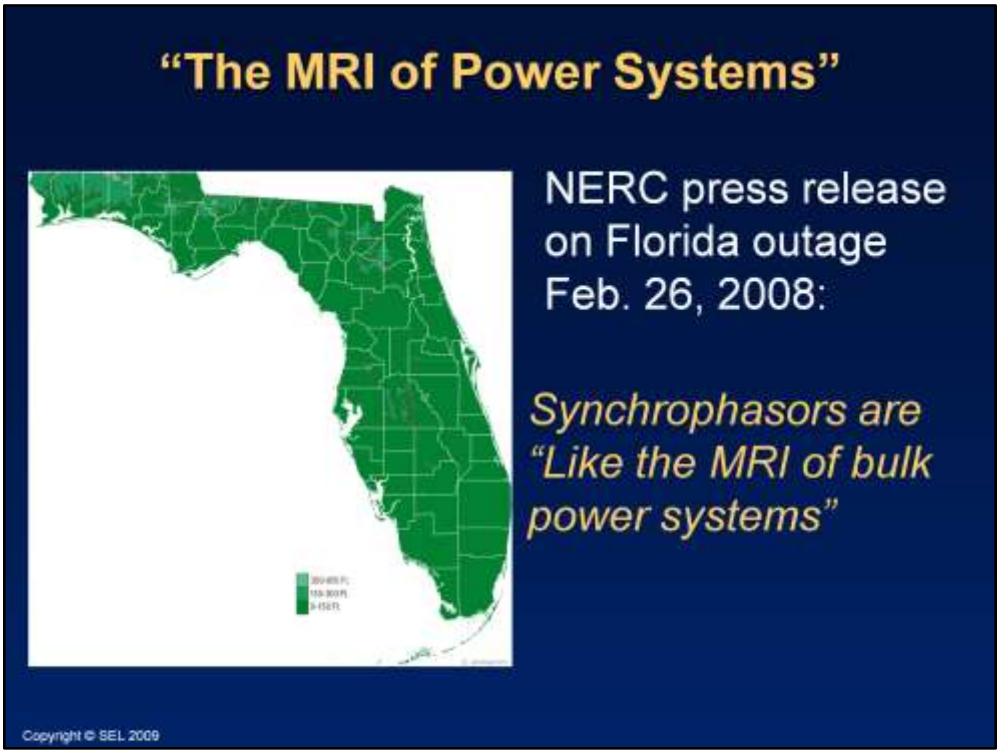
Transpower has also accepted the SEL421 as one of the approved distance relays for their network. So once the first stage of the PMU project is completed Transpower expects to coordinate the installation of further SEL-421s depending on the existing need for relay replacements as well as the need for synchrophasor data from the rest of the substations.

52



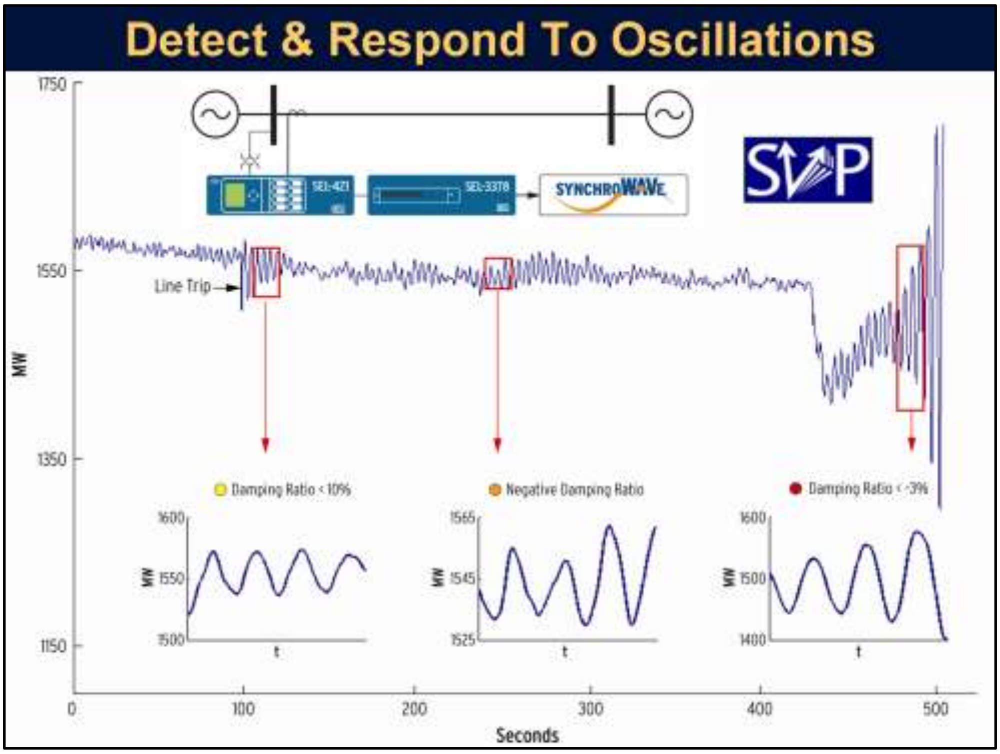
System oscillations can be recorded and analyzed in real-time using synchrophasors.

53

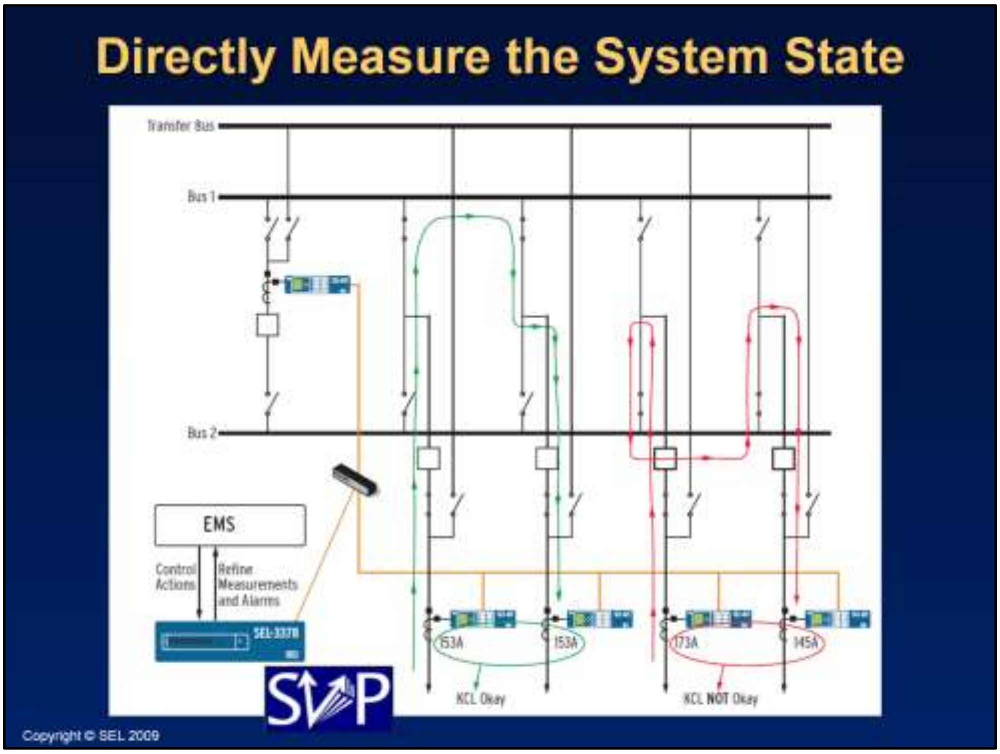


- EIPP participants using SEL Synchrophasors
- ATC
- ITC
- Florida Power and Light
- Consolidated Edison
- AEP

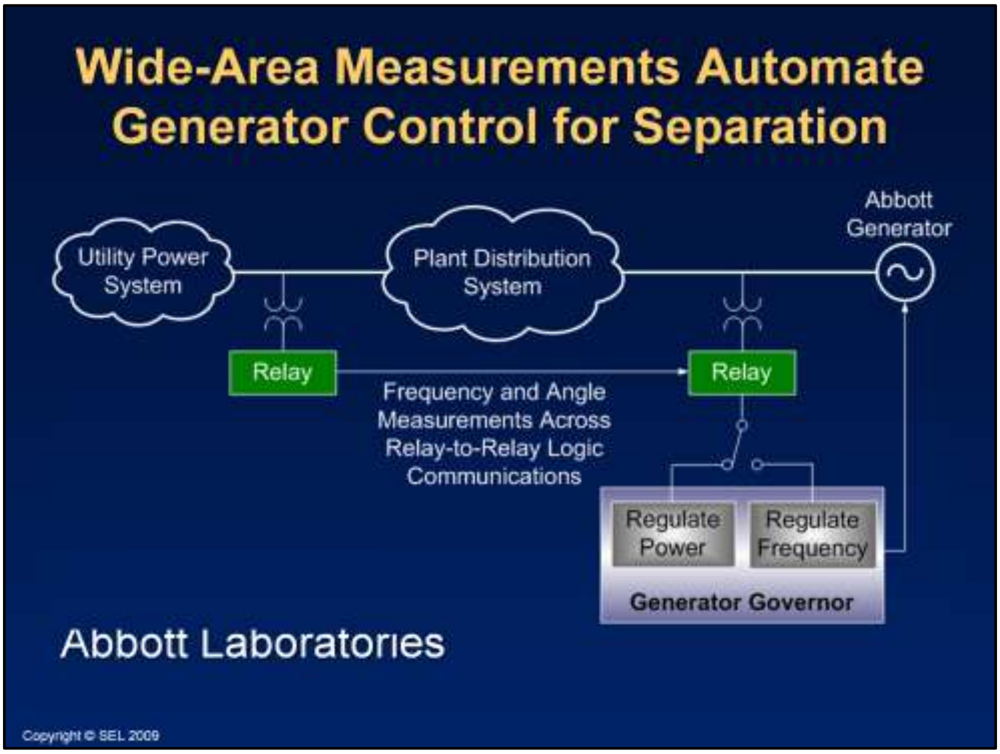
54



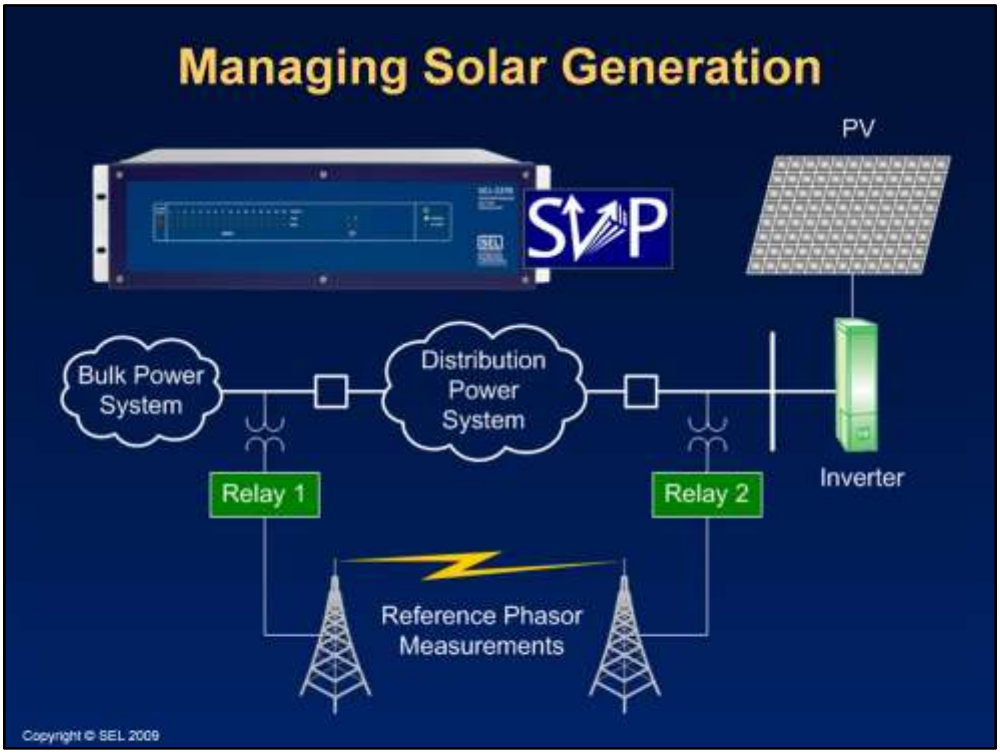
The SVP can provide a real-time measurement of power oscillations that are faster than SCADA can detect. Alarms to inform operators are easy to set up.



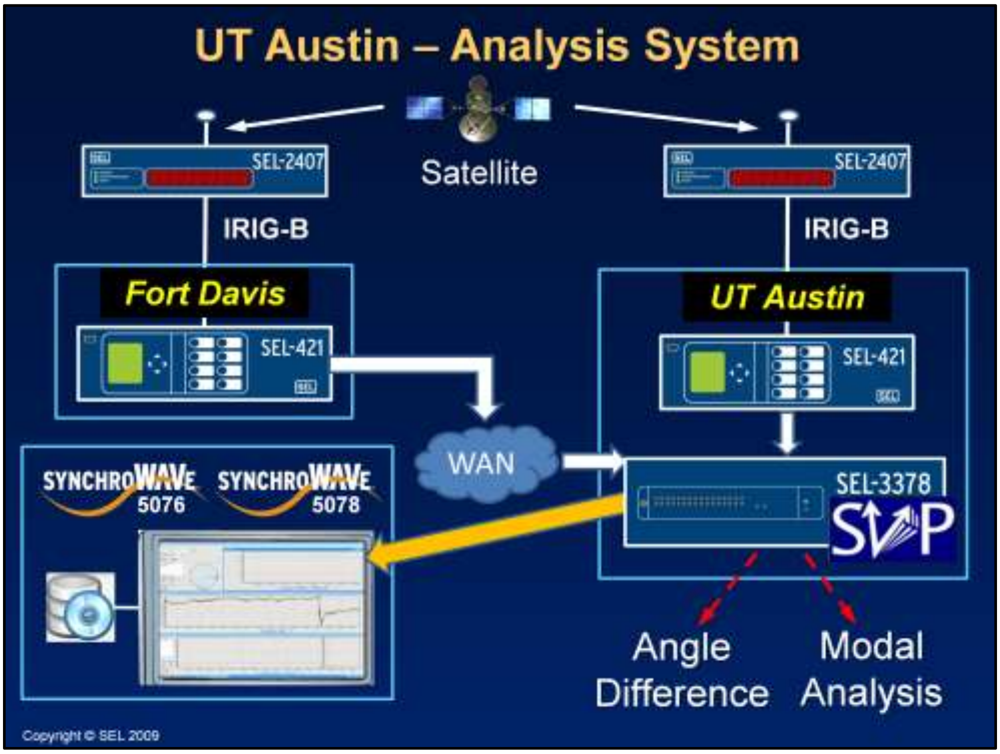
Determining station conditions, and checking for measurement accuracy is a pre-programmed function in the SVP.



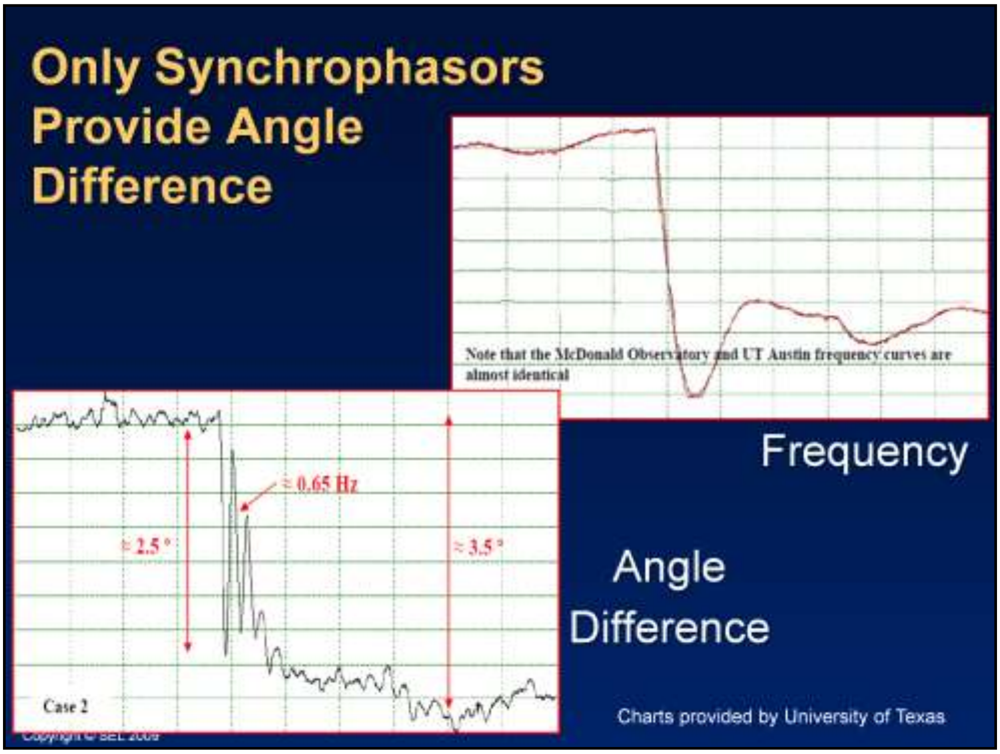
To improve operation of local generation, Abbott uses wide area measurements to control separation.



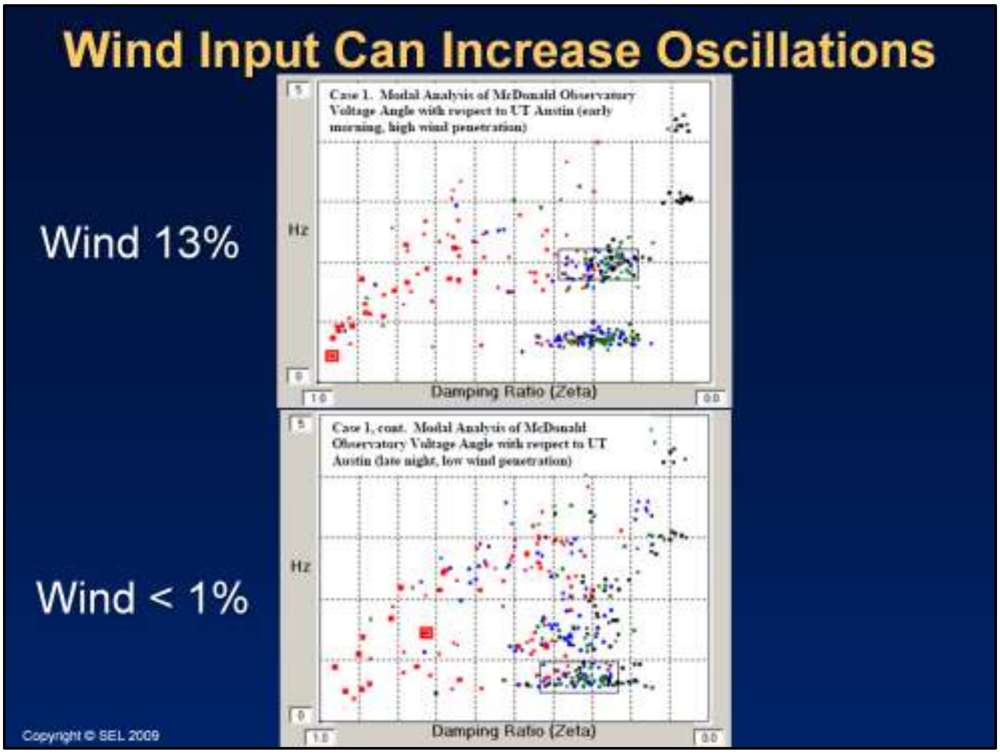
The SVP is used to test algorithms applied in discreet devices for solar generation control.



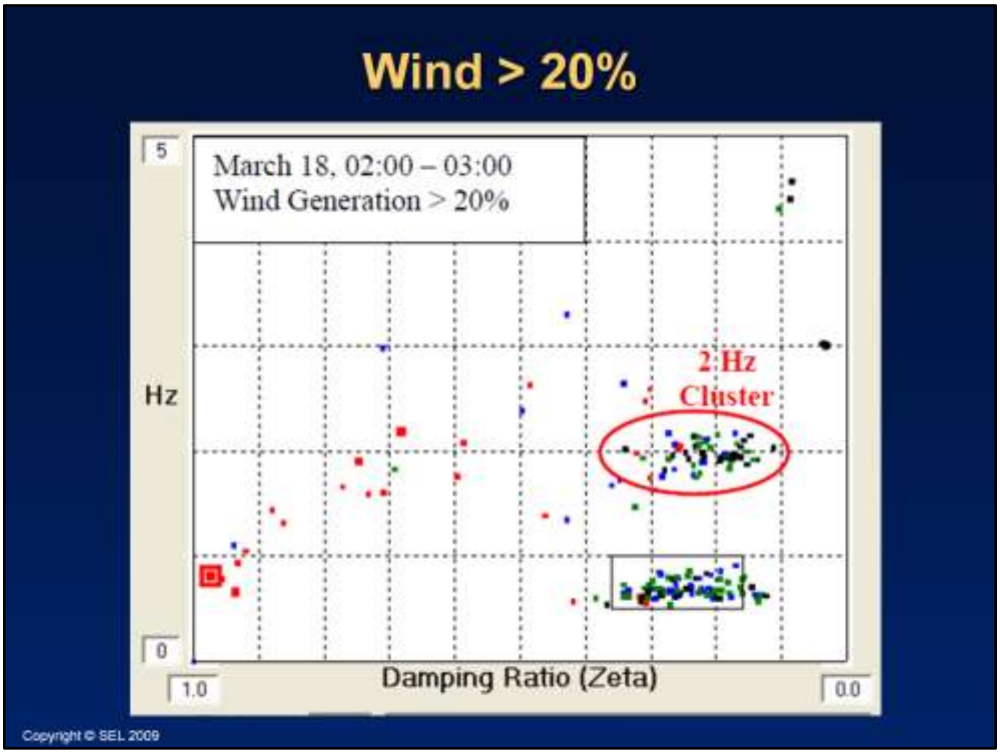
The University of Texas at Austin is running a wide area synchrophasor system to examine the impact of wind generation in Texas.



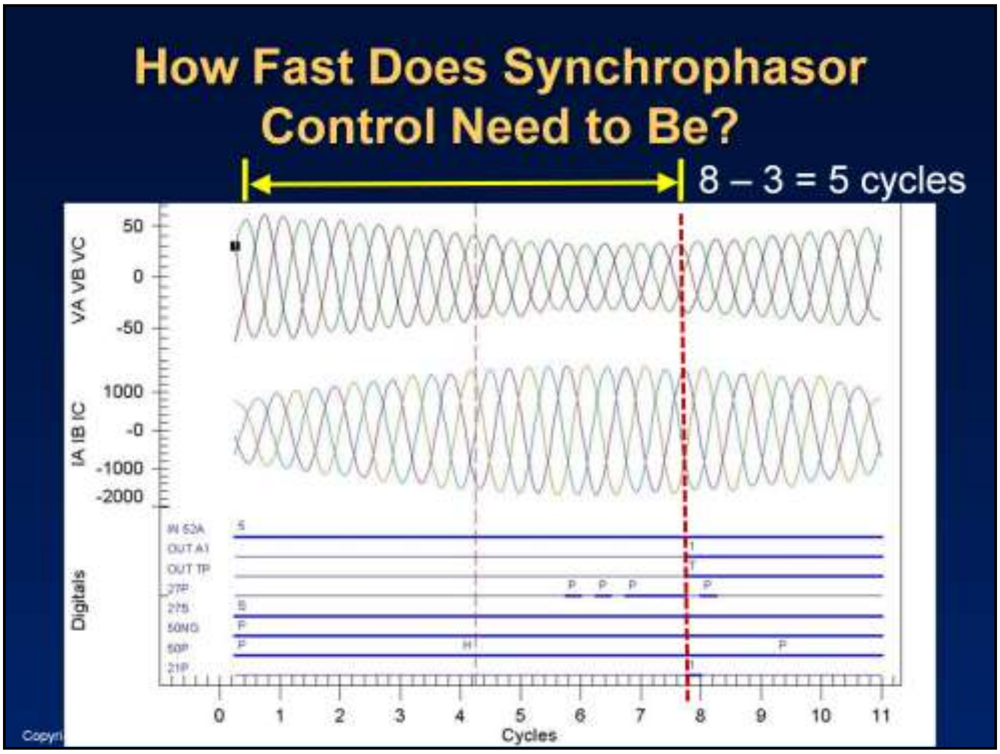
A loss of generation event in Texas shows how frequency plotting, while useful, provides less detail on system dynamics than phase angle.



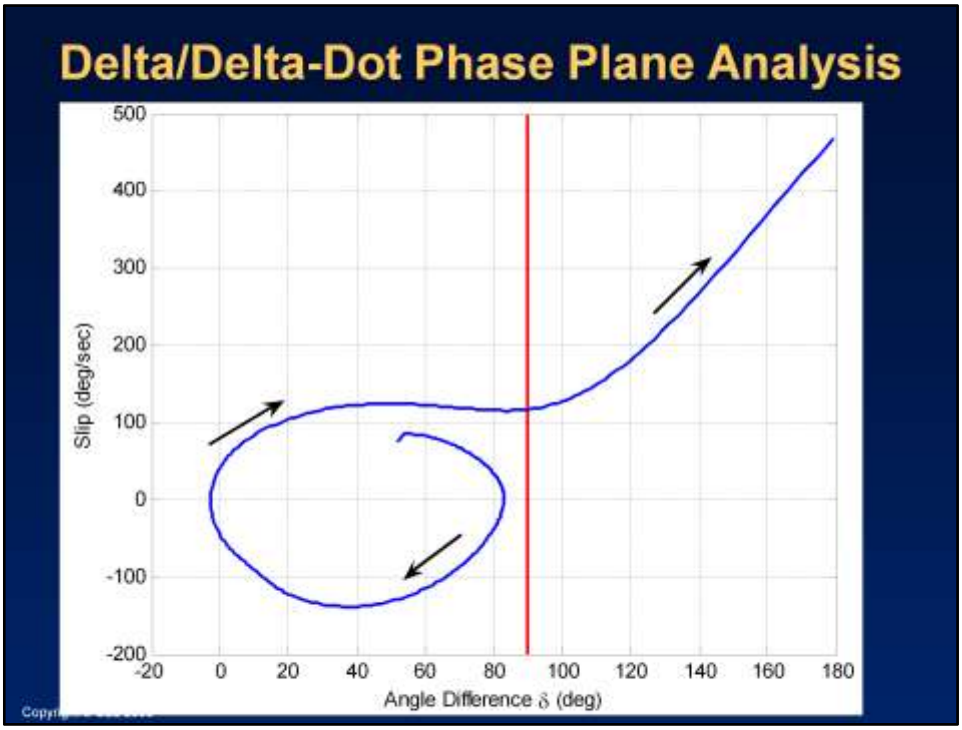
As wind generation becomes a greater part of the overall generation mix, measurement of 2 Hz oscillations increase, as detected by the SVP.



With wind over 20% of total generation 2Hz oscillations are becoming more critical.

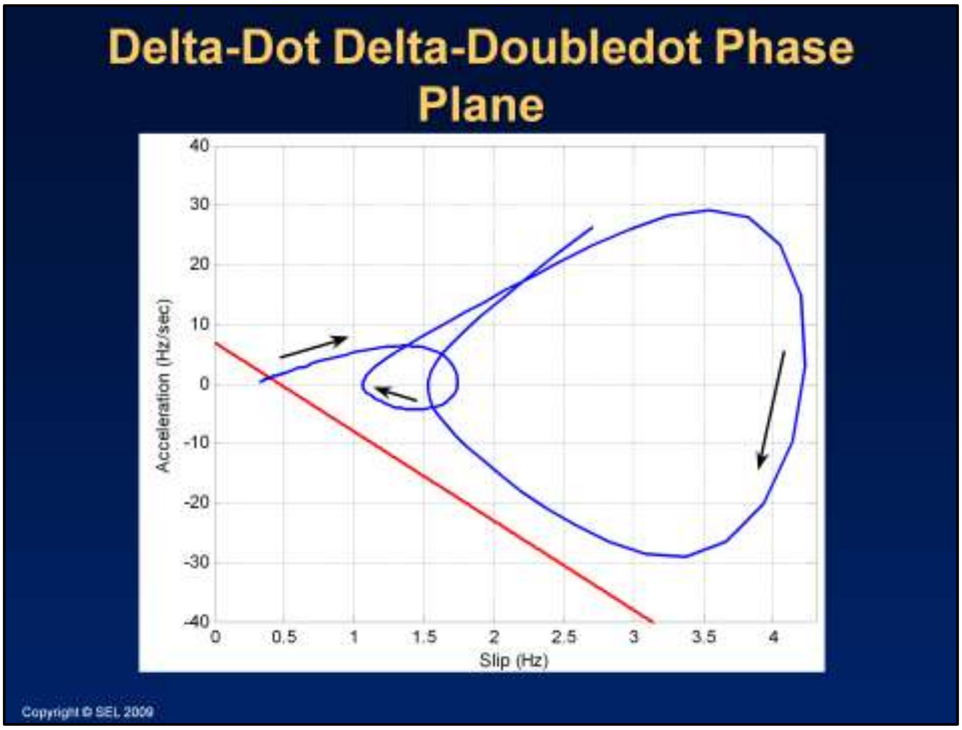


This slide shows a power swing from the 2003 blackout in the northeastern portion of North America. To prevent an out-of-step (OOS) trip at an undesired location, the controls must operate to mitigate the power swing at least before the OOS trip initiate minus breaker clearing time, which in this case is 5 cycles.

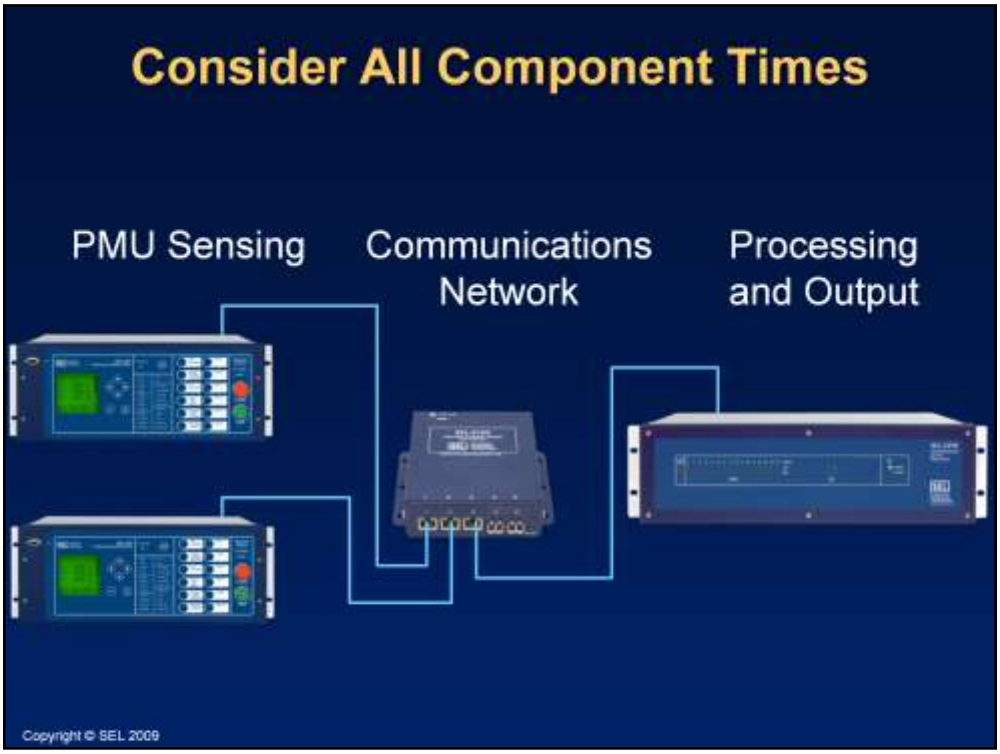


The delta-slip plot shows the angle difference and slip calculations from 0.81 to 3.87 seconds. Three seconds after fault inception, delta is greater than 90 degrees, and the swing becomes unstable.

64

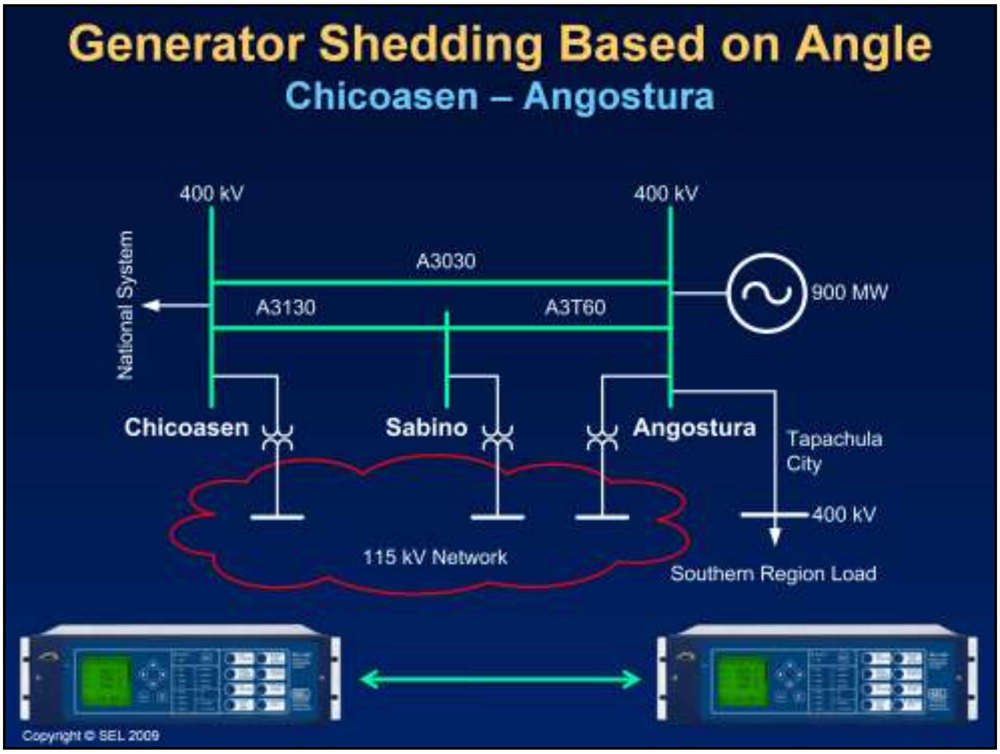


The slip-acceleration plot shows the slip and acceleration calculations from 3.39 to 4.79 seconds together with the OOST element characteristic. In this example, we set 78_Slope = –15 and A_{Offset}= 7.



The end-to-end processing time includes PMU input and filter delays, network delays, and output processing.

An application installed in 2007 uses direct relay-to-relay synchronized phasor measurements.

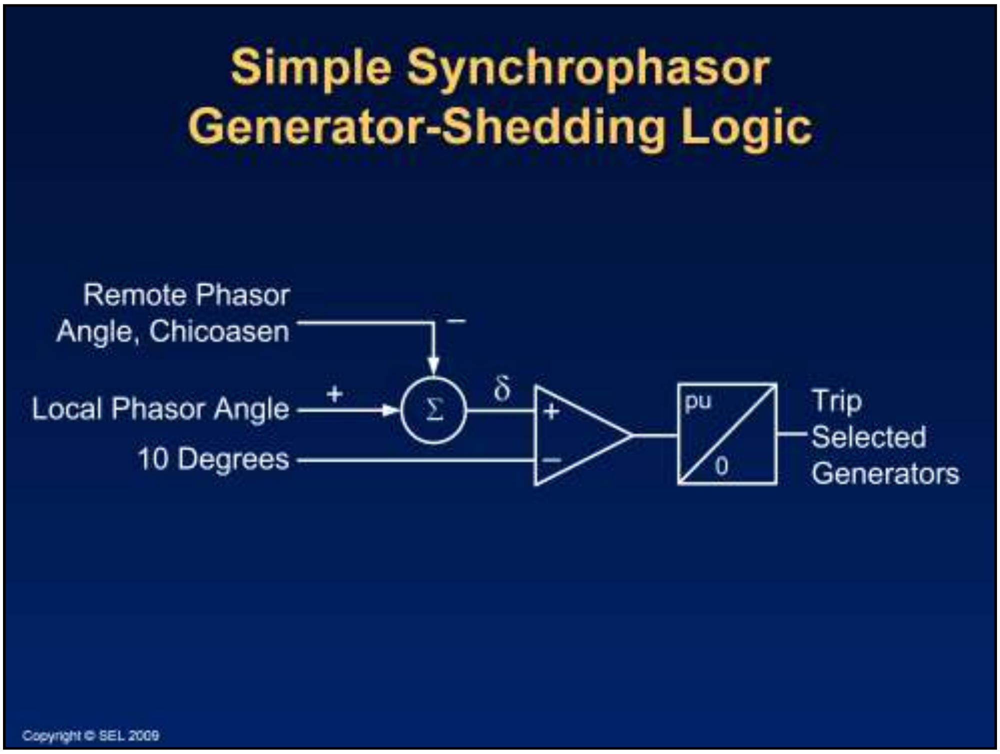


One of the AGSSs (automatic generation-shedding schemes) in service at the Angostura Hydroelectric Power Plant monitors the loss of the transmission link between Chicoasen and Angostura. During normal conditions, Angostura can generate as much as 5 • 180 = 900 MW, while the total load of the Tapachula and South Chiapas region does not exceed 100 MW. The excess power in the region flows from Angostura to Chicoasen and from there to the rest of the system. If two 400 kV parallel lines are lost between Angostura and Chicoasen, both areas remain connected through the 115 kV network with the following consequences:

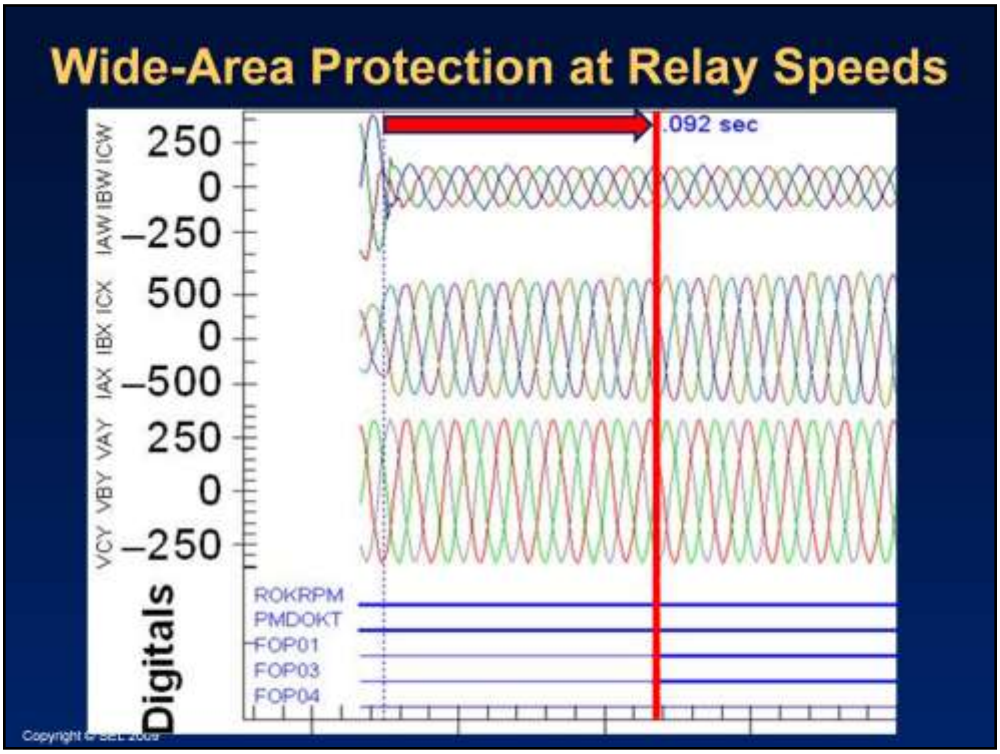
- The transfer impedance between the Angostura and Chicoasen power plants increases, causing the Angostura machines to accelerate. This machine acceleration may lead to angular instability.

- The 115 kV network is overloaded until the line or transformer overload protection operates. When this happens, the Angostura and Tapachula area forms a network isolated from the rest of the system.

For some operating and fault conditions, this double contingency could lead to a blackout at Tapachula City and south of the State of Chiapas.

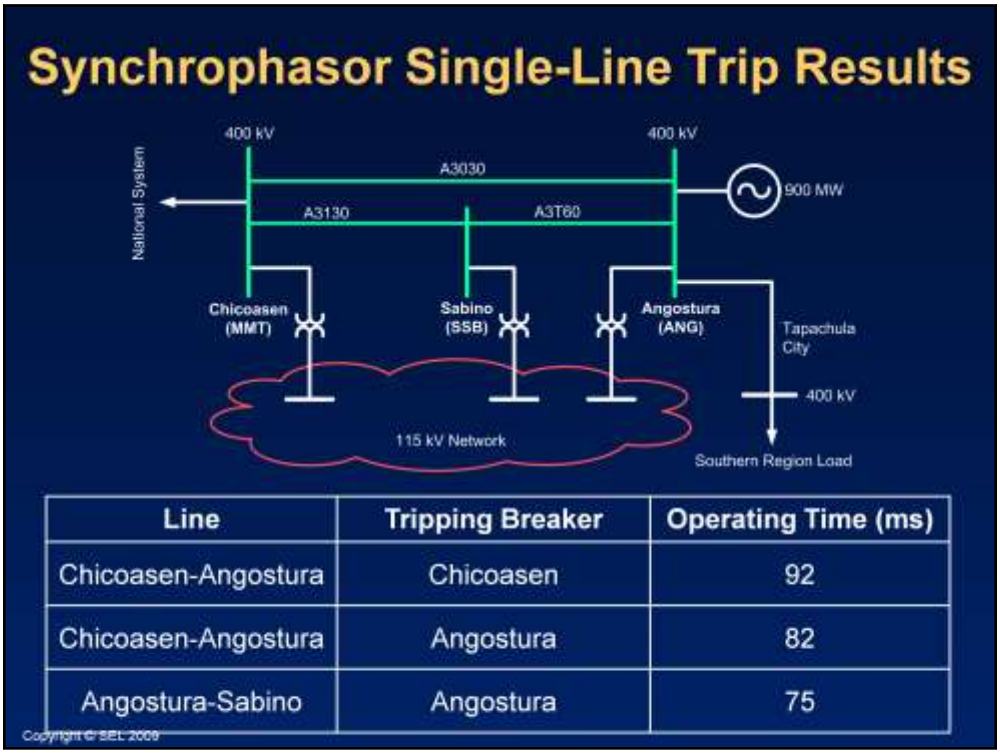


Simple logic is applied in the relay using a local phasor that has been time-delayed to exactly match the time from the received phasor data.



The event report on this slide shows how wide-area measurements are used in a protection system. The internal relay points captured in the report are as follows:

IW	Angostura-Chicoasen currents
IX	Angostura-Sabino currents
ROKRPM	Received remote data successfully
PMDOKT	Total data successful
FOP01	Angle difference element set to 3 degrees
FOP03	Angle difference element set to 4 degrees
FOP04	Angle difference element set to 5 degrees



Line	Tripping Breaker	Operating Time (ms)
Chicoasen-Angostura	Chicoasen	92
Chicoasen-Angostura	Angostura	82
Angostura-Sabino	Angostura	75

The angle difference element operating time includes the PMU measurement delay, communications channel delay, and latency because of the message rate. In this case, 20 messages per second introduce a delay of as much as 50 milliseconds. Simulation results show that a trip time of 150 milliseconds is good enough to avoid stability problems in this area.

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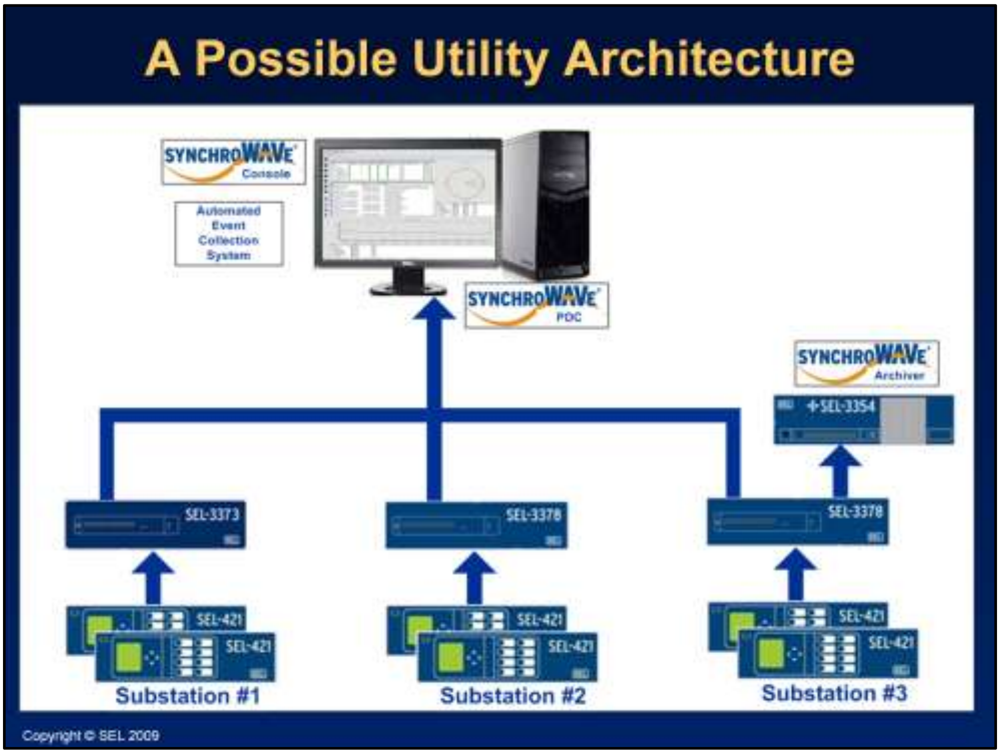
A Possible Utility Architecture
SYNCHROWAVE Console
Automated Event Collection System
SYNCHROWAVE PDC
SYNCHROWAVE Archiver
SEL-3354
SEL-3373
SEL-3378
SEL-3378
SEL-421
SEL-421
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SEL-421
Substation #1
Substation #2
Substation #3
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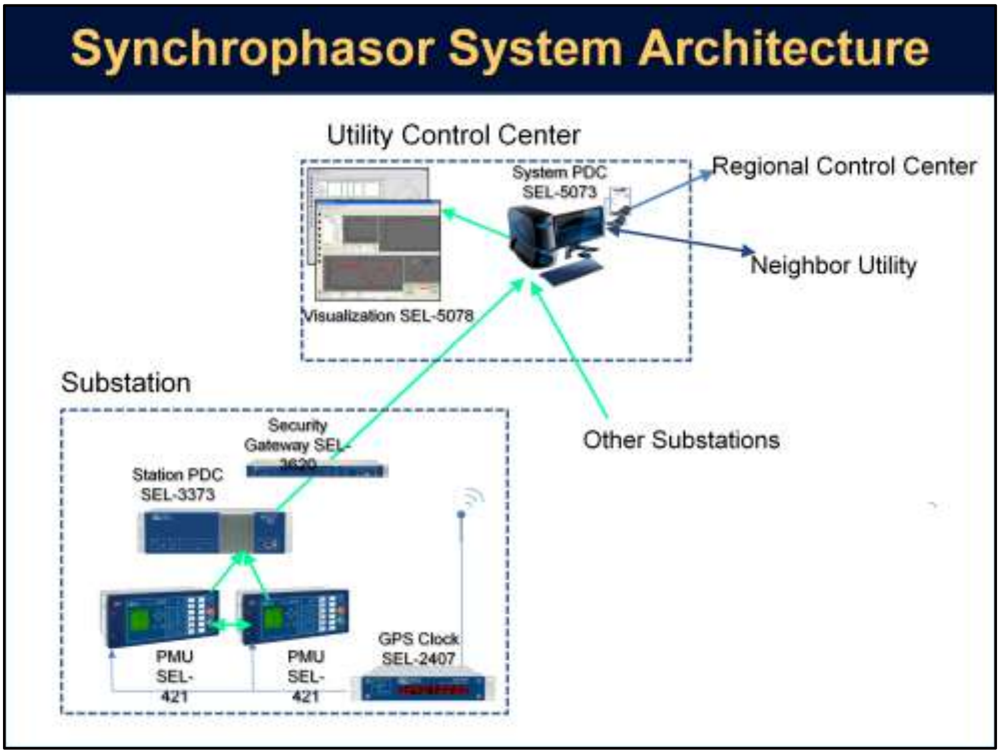
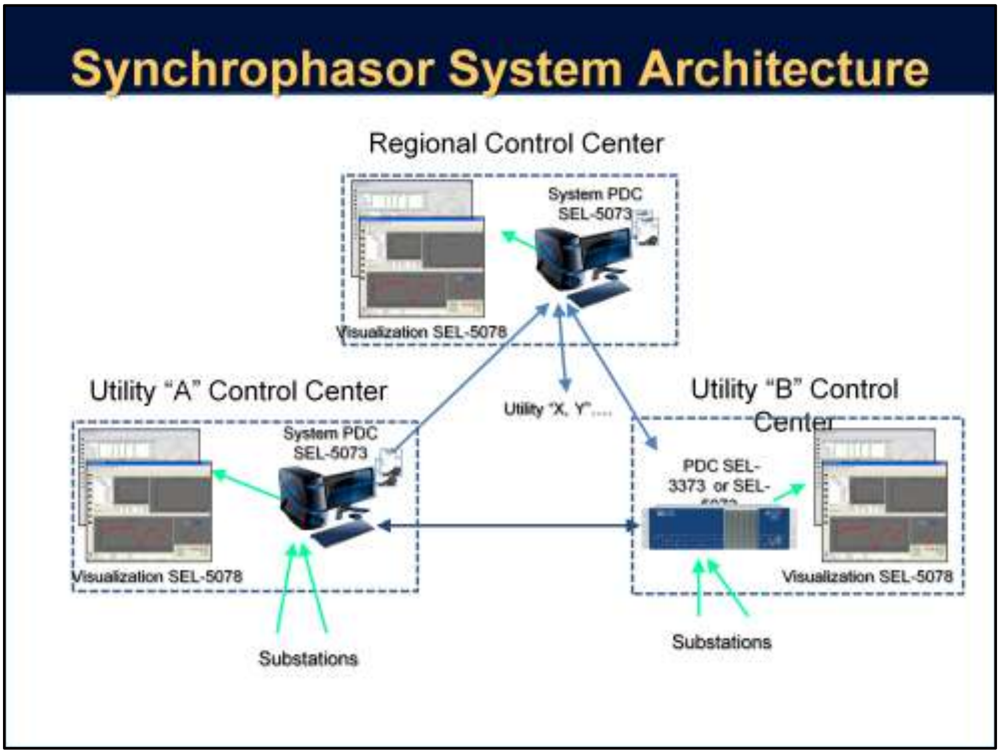
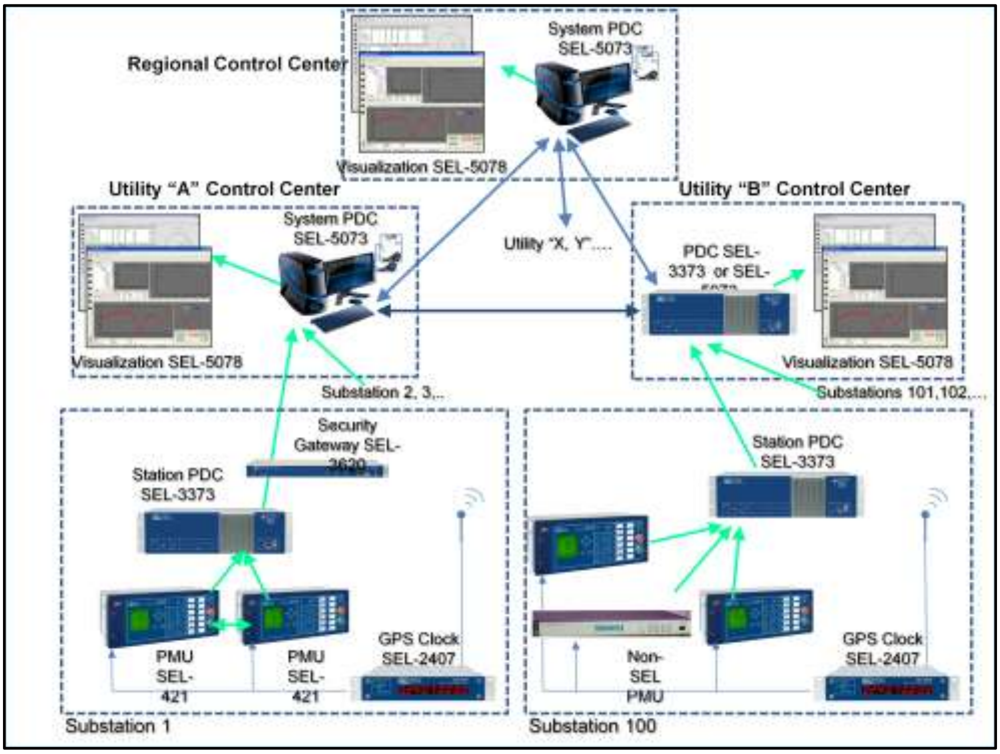

Synchrophasor System Architecture
Utility Control Center
System PDC
SEL-5073
Regional Control Center
Neighbor Utility
Visualization SEL-5078
Substation
Other Substations
Security
Gateway SEL-
3620
Station PDC
SEL-3373
PMU
SEL-
421
PMU
SEL-
421
GPS Clock
SEL-2407


Synchrophasor System Architecture
Regional Control Center
System PDC
SEL-5073
Visualization SEL-5078
Utility "A" Control Center
Utility "X, Y"....
Utility "B" Control Center
System PDC
SEL-5073
PDC SEL-
3373 or SEL-
Visualization SEL-5078
Visualization SEL-5078
Substations
Substations


Regional Control Center
System PDC
SEL-5073
Visualization SEL-5078
Utility "A" Control Center
Utility "B" Control Center
System PDC
SEL-5073
Utility "X, Y"....
PDC SEL-
3373 or SEL-
Visualization SEL-5078
Visualization SEL-5078
Substation 2, 3,..
Substations 101,102,...
Security
Gateway SEL-
Station PDC
SEL-3373
Station PDC
SEL-3373
GPS Clock
SEL-2407
PMU
SEL-
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PMU
SEL-
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Non-
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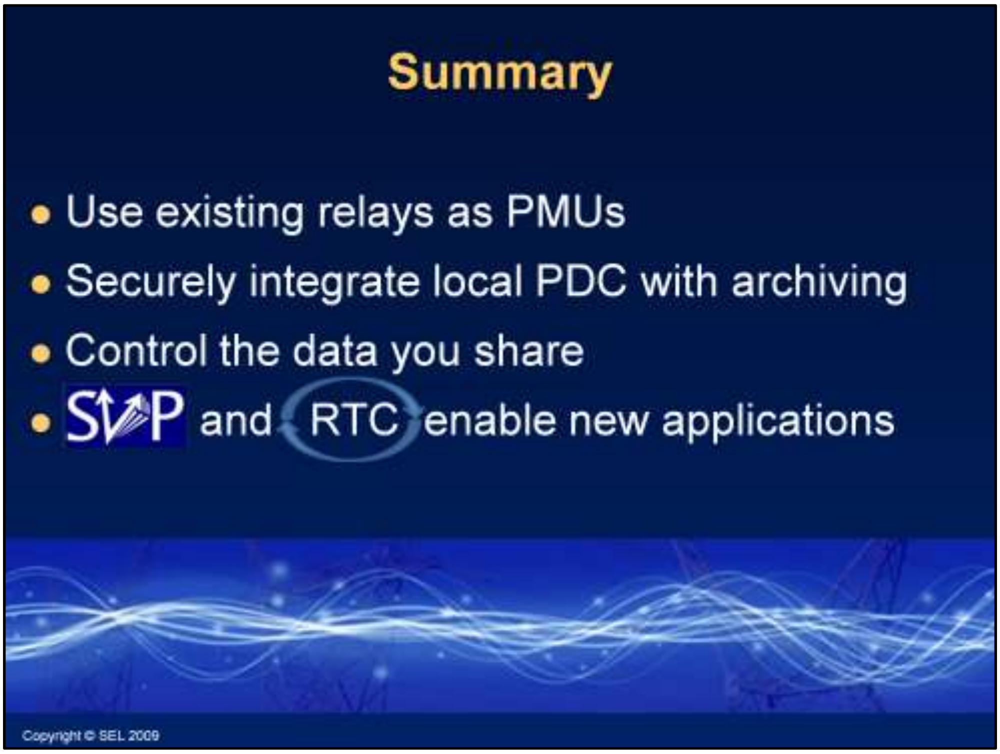
PMU
GPS Clock
SEL-2407
Substation 1
Substation 100



Summary
Use existing relays as PMUs
Securely integrate local PDC with archiving
Control the data you share
SVP and RTC enable new applications
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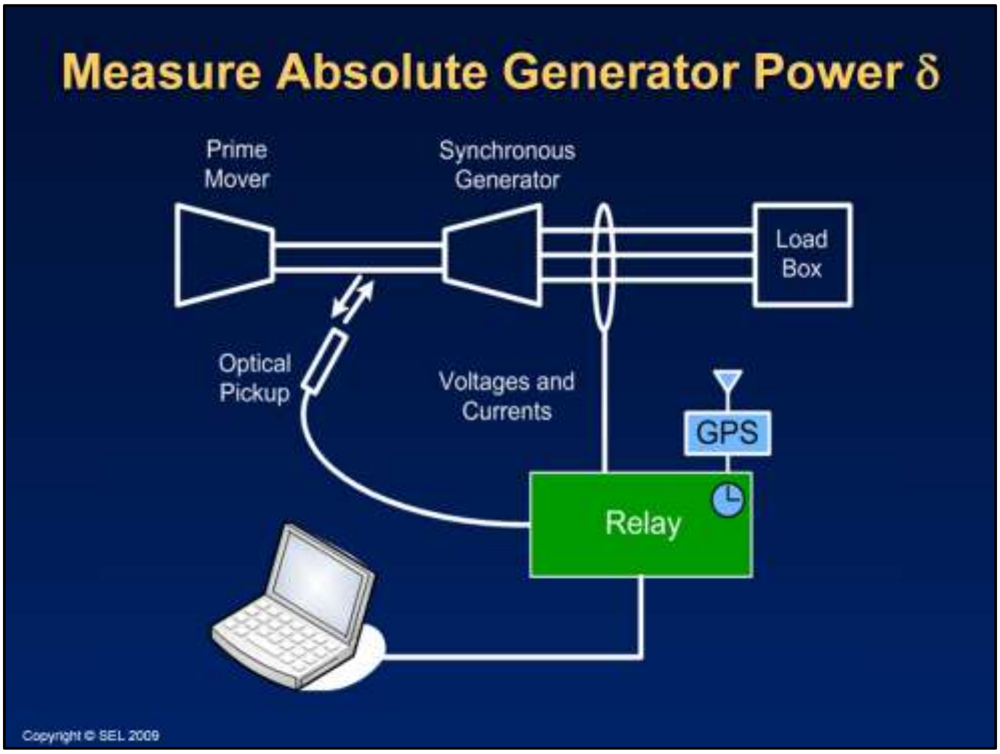
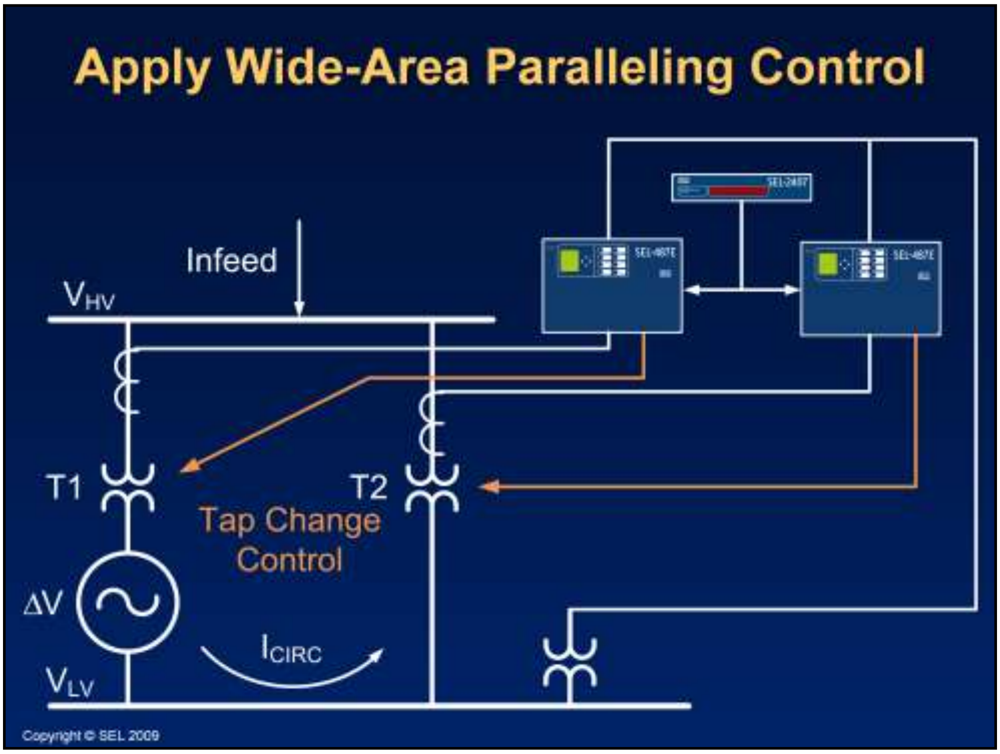
Synchrophasors
Are Made for
Wide-Area
Applications

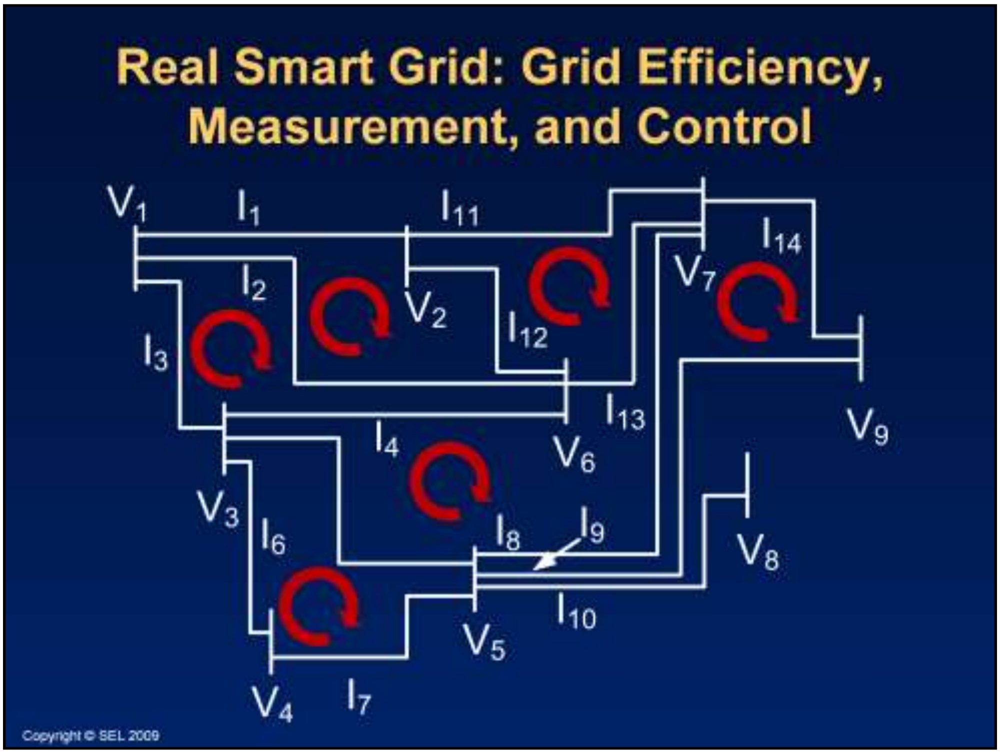

From The Research Lab!



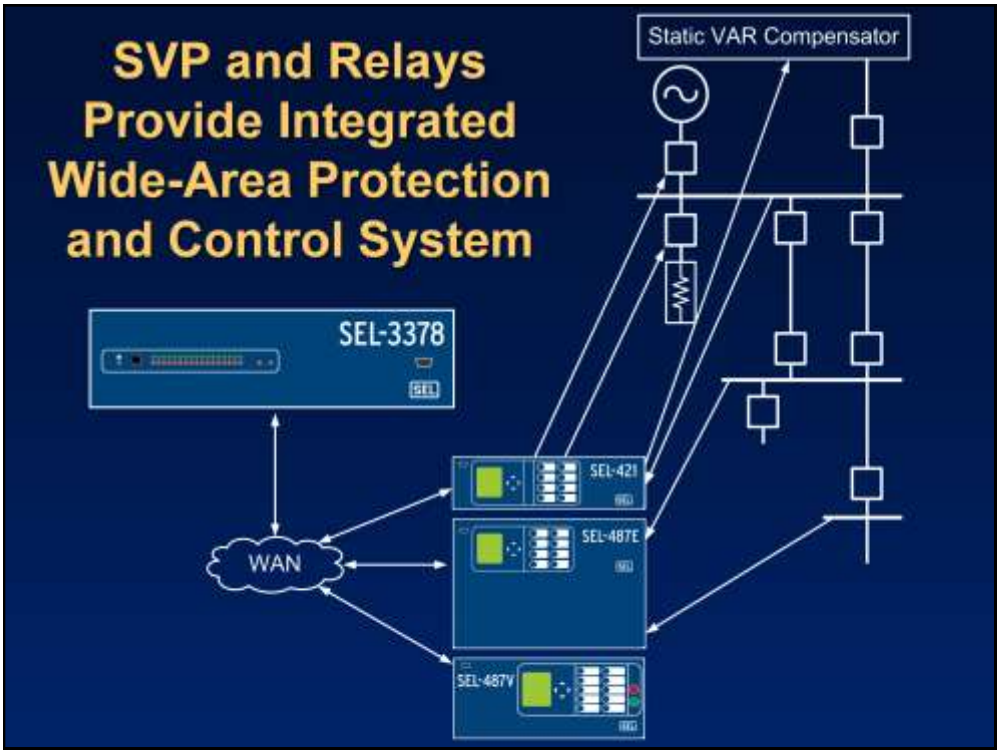
Add an optical measurement of shaft angle to the electrical measurement in a PMU for direct generator response measurement.



Loop flow inside a station with LTC (load tap changer) transformers is well known and controlled with "paralleling" control of the LTCs. However, what if the stations are remote from each other? The SVP uses system-wide measurements to minimize loop flow.



Loop flows can occur throughout a system. Put PMUs everywhere that it is economically possible, and use the information to make a smart grid.



Implement wide-area protection and control schemes using the SVP.

Apply Synchrophasors Now

- Disturbance recording
- Relay-to-relay control
- Modal analysis
- Special protection schemes
- System control


Don’t Imagine It – Engineer It
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