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Online Stability Solutions – Recent Advances

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SUMMARY

We are embarking on a revolutionary new paradigm where high-resolution synchrophasor "measurement-based" analytics are being introduced at the control center; these new analytics complement and augment the traditional "model-based" EMS analytics. This paves the path to being able to monitor and analyze grid behavior at a sub-second rate; which in turn makes online grid stability analysis more of a practical reality. Phasor Measurement Units (PMUs) are being increasingly deployed across power grids worldwide. Managing the smart grid of the future will require these real-time, time-tagged, sub-second synchrophasor measurements for monitoring, analysis and mitigation of the spread of grid disturbances.

Operational benefits of adding synchrophasor applications at the control center include:

- Maximizing utilization of existing transmission capacity by confidently operating the grid closer to its actual, 'true' operating limit,
- Providing an early warning system to quickly identify grid disturbances to guard against blackouts,
- Monitoring for un-desirable grid dynamics and oscillations,
- Identifying islanding conditions, and
- Enabling efficient forensic post-disturbance analysis to find out what just happened, where and why?

A major benefit of combining traditional EMS model-based analytics with the new measurement-based analytics is that we can now implement online grid stability analysis in a production environment. This paper describes recent advances in online stability analysis that have been implemented at control centers.

KEYWORDS

PMU, DSA, synchrophasors, EMS, stability analysis

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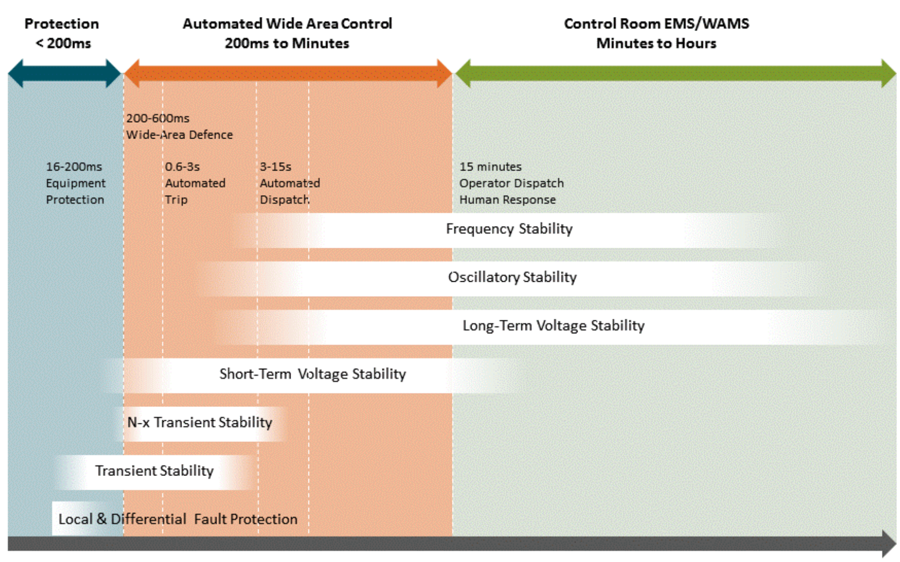
The electric power grid is probably the most complex engineering machine in existence today. A typical large interconnected grid consists of millions of pieces of equipment that need to work together in order to supply electricity 24/7, from the generating source to the end-user customer. Millions of customers need to be served reliably, in order to keep the lights on 24/7.

The grid operates in a ‘load-follow’ mode. This means that generation responds to customer load changes. Since the typical large interconnected grid supplies millions of customers, instantaneous load demand is always changing and the grid is in a constant state of quasi-steady-state flux. Occasionally larger disturbances occur due to outages of transmission and generation equipment. Hence oscillations and disruptions constantly occur in the grid - and as long as they stay within limits and are well damped, the grid stays in balance and the lights stay on. Figure 1 shows the different types of dynamic phenomena that occur in the grid.

Energy Management Systems (EMS) have successfully managed the grid for these quasi-steady-state conditions for decades; this is shown on the right of Figure 1 - the “Minutes to Hours” response time region. Protective relays have been successfully protecting equipment in the field for decades, instantaneously in response to faults & other disruptions; this is shown on the left of Figure 1 - in the “less than 200ms” response time region.

In the middle of Figure 1, are the phenomena that are not being addressed well today and are the source of many grid problems and blackouts. These are dynamics in the “200ms to minutes” response time range. Instabilities in this region are not monitored or managed by the EMS nor by the protective relays, and may quietly become the invisible source of grid dynamic instability, which could result in a local blackout, and may eventually cascade into a blackout of the entire grid. Online stability solutions (OSS) that are being implemented at the EMS address this specific range of grid dynamic problems.

Figure 1:
Dynamic Grid Stability Phenomena



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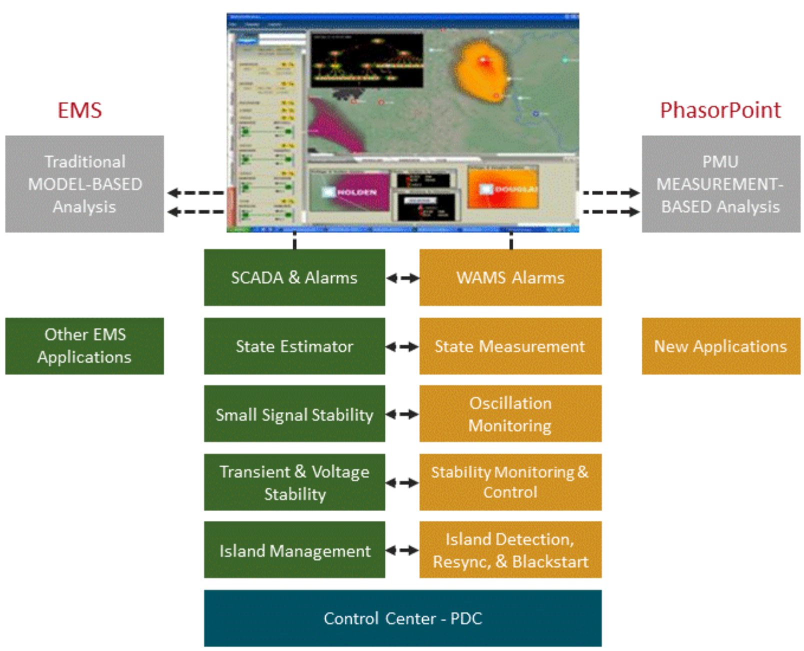
Integration of the new synchrophasor solutions with modern day EMS analytics is our best promise for implementing a practical production-grade OSS at the EMS; this is our vision of the 'next generation EMS' as shown in Figure 2.

"Synchrophasor" is shorthand for synchronized phasor measurements. They provide a representation of voltage and current waveforms that shows a sinusoidal signal simply as a magnitude and phase angle with an associated GPS time stamp. These measurements monitor and track the fast dynamic grid behavior which today's SCADA cannot. Synchrophasors are typically measured 25-60 times a second by phasor measurement units (PMUs) providing typically 12-16 measurements per device – up to 240 times the frequency of traditional SCADA.

In Figure 2, on the left, we have the traditional EMS analytics (SCADA, State Estimator, etc) that have been developed over the past 5 decades. More recently, we have integrated 'model-based' stability analytics which use the network model and the State Estimator solution to run dynamic stability studies. These are called dynamic security assessment (DSA) and include assessments of small signal stability (SSA), voltage stability (VSA), and transient stability (TSA). These have traditionally been offline planning tools since they are computationally very intensive. More recently, with faster computing processors and DSA software performance enhancements, these functions have migrated into the online EMS and can now run in 'close to real-time'.

Figure 2:
The 'Next Generation' EMS



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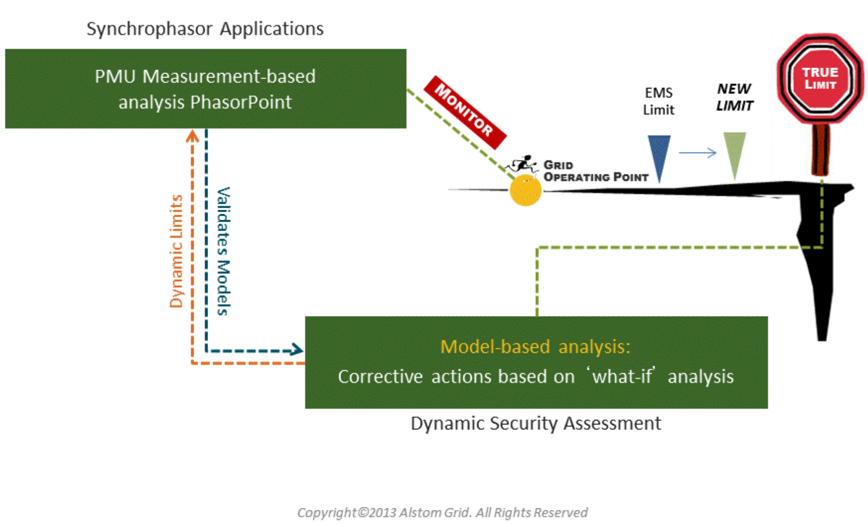
The advent and growth of PMU data at the control center has spawned a new suite of synchrophasor analytics at the EMS as shown on the right side of Figure 2. These applications do not have the overhead burden of the large network model (along with uncertainties in the model data and SCADA data) and use the actual power system as the 'model'. PMU data are measurements from the grid which are used to determine the current operating state (bus voltages, currents, line flows, frequencies, etc) in real-time - and at sub-second rates. These analytics are based on digital signal processing techniques and can identify (in real-time) oscillations, changes in MW flows, voltage problems, location of disturbances, islanding conditions, etc.

So for the very first time, the EMS operator will be able to monitor oscillations and be made aware of problematic oscillations as soon as they occur. Some of these synchrophasor analytics have analogous DSA analytics such as SSA and VSA. This allows us to validate results with parallel analytics and also to help improve the individual analytics themselves, by calibrating their results against field data obtained from actual grid disturbances.

Figure 3 illustrates how the model-based and measurement-based analytics work together. The synchrophasor applications tell you what the current operating state is, and tracks its changing behavior at sub-second rates. The operator wants to know how far the current state is from the edge of the cliff or the limit at which the grid would collapse – this is called the 'true limit.' This 'true limit' is determined by the DSA tools since they are based on a network model and can perform what-if studies to increase loading and stress on the grid till its point of collapse. Once the true limit is determined, the EMS operator then adds a safety margin to establish the 'EMS limit' to which he would operate the grid. The safety margin is required since the State Estimator solution which was used to calculate the limit is based on model data and SCADA data that are not 100% accurate; furthermore the SCADA data may have unknown latencies as well.

Figure 3:
Integrated "measurement-based" &
"model-based" Stability Analysis



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By using synchrophasor recordings of real-life grid disturbances we can fine-tune the dynamic parameters in DSA models to more closely match the actual field recordings. Figure 4 shows how synchrophasor measurements, along with simulated reconstructions of the disturbance, can be utilized in an offline mode to verify and calibrate the dynamic model data. When there's a clear discrepancy in the time-domain, a modal decomposition is used to identify the particular mode contributing to the mismatch and the associated mode shape is used to identify the specific power system element that needs validation. For example, in Figure 4, the discrepancy shown can be attributed to a 1.07Hz local mode where a positive damping (5.59%) has been identified from the measurement recording, while a negative damping (-0.73%) is indicated from the corresponding simulations.

As we improve the accuracy of the model data used in DSA, we increase our confidence and trust in the DSA results. With this improved confidence, we can then relax the safety margin to more confidently operate the grid closer to it 'true' limit as indicated by 'new limit' in Figure 3. This is one example of how integration of OSS analytics with the EMS and DSA benefits grid operations – we can release latent transmission capacity in stability-limited corridors and maximize utilization of existing transmission assets.

Figure 4:
Dynamic Model Data Validation with PMU data

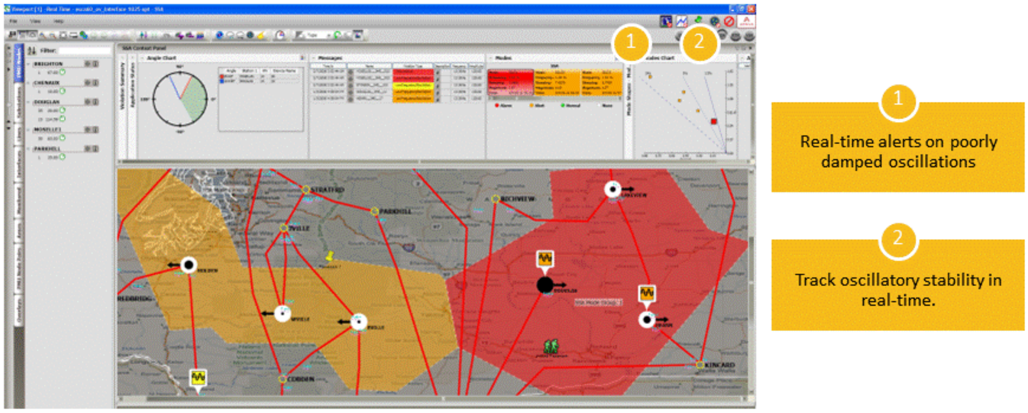
Having synchrophasor data will allow us to operate the system closer to its actual limit by intelligently updating this limit in real time. This results in cost savings to the utility and in environmental benefits, since you don't need to invest in new lines and transmission towers.

Other examples of the benefits of synchrophasor analytics to address grid dynamic instability are shown in Figures 5 and 6.

Figure 5 shows oscillations in the grid – something that is invisible to today's EMS operator. It shows that certain groups of generators oscillate in unison and as a group, and that one group could be oscillating against another group (inter-area oscillations). Oscillation magnitudes, energy, damping and frequencies are monitored; damping is the key indicator being tracked since if an oscillation is poorly damped or negatively damped it could grow over time and create grid problems. The location of the oscillation energy source can also be identified.

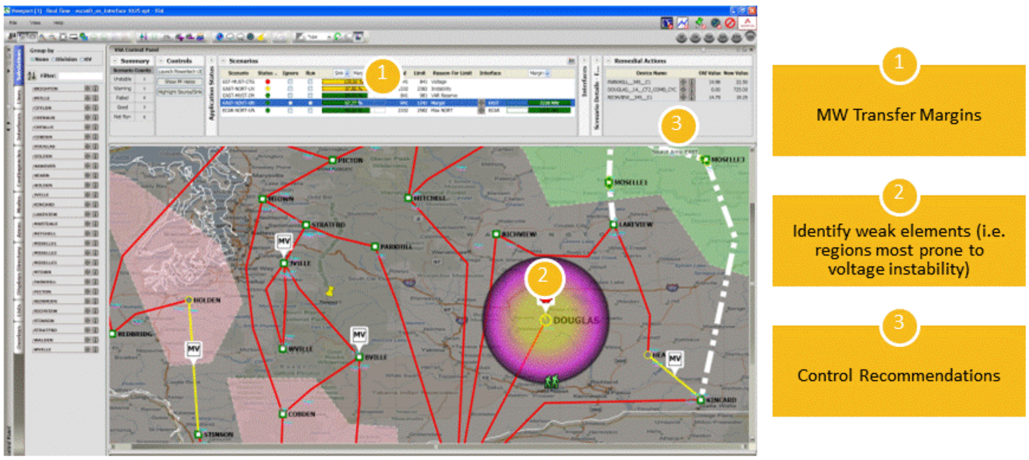
Figure 6 shows low voltage areas - from the fast synchrophasor analytics - and also the recommended controls available (from DSA) to remedy the problem. This is not just situational awareness but 'actionable information'. Operators want to fix problems. They do not just want to be aware of them - without any recourse to remedy them.

Figure 5:
Small Signal Oscillations
Modes shapes, amplitudes, damping, frequency, etc



Identify regions where inter-area oscillations are observable

Figure 6:
Voltage Stability
Voltage Contours, MW Margins, Weak Elements, Remedial Actions



Figures 7 and 8 illustrate how transient stability issues can be monitored and potentially mitigated with the intelligent integration of synchrophasor and DSA tools.

Figure 7 shows synchrophasor analytics monitoring the voltage angle differences across a transient-stability-limited corridor. If these angles exceed a certain limit, the corridor would collapse due to transient instability - this is a very fast phenomena and collapse occurs in less than a second hence controls also need to be fully automated for sub-second invocation.

The question is how do we know what these angle limits are for current grid conditions? This is answered by the DSA TSA function. DSA runs various simulated stress scenarios to determine the transient stability angle limits for current system conditions under the most binding contingency (i.e. “what-if” predictive capability).

Using ‘voltage angle differences’ to express stability margins (as opposed to just MW flows) is a more direct indicator of grid stress, because it monitors not just MW flow problems but also encapsulates impedance changes due to line outages which weaken the transmission paths. Increased MW flows or weakening of transmission paths both result in greater stress on the grid. Additionally, since topology changes are reflected in the monitored angle differences themselves, it is our premise that the corresponding stability limits (when expressed as angles) will remain more static in nature. The traditional approach of pro-rating the MW limits to account of outages on the grid is therefore no longer necessary when moving to an ‘angle difference’ approach; this is a significant benefit to managing and operating the grid more reliably and effectively.

Figure 7:
Real-Time Dynamic Limits

Releases latent capacity across PG&E's stability limited transfer paths.

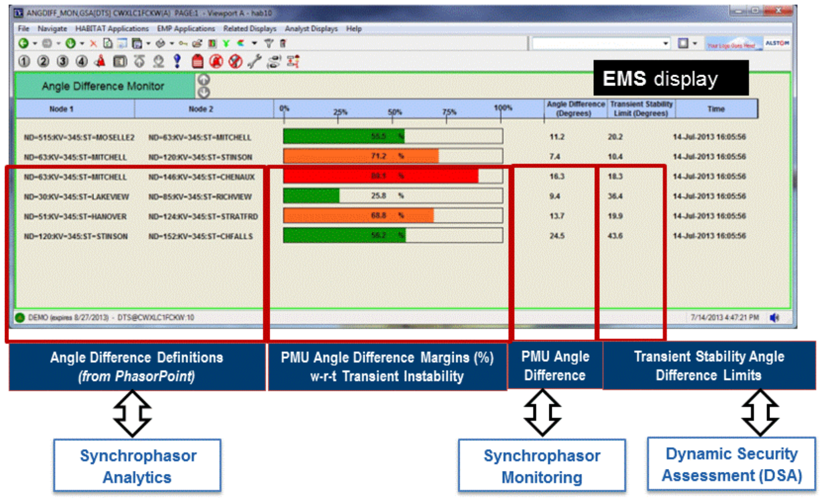
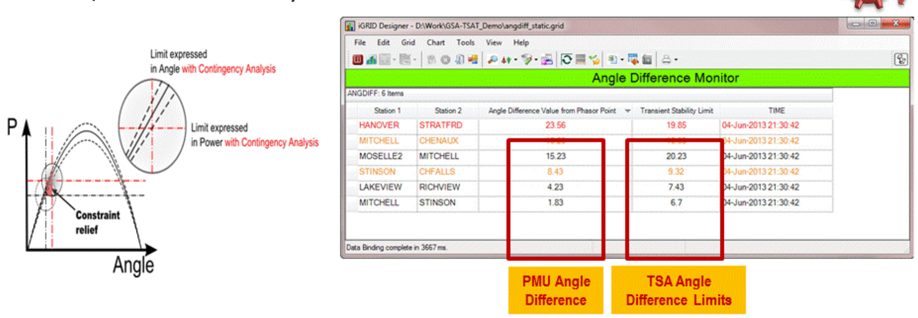


Figure 8 shows how the voltage angle limits from the EMS State Estimator and DSA are then used online, in conjunction with the wide area monitoring system (WAMS) synchrophasor applications to quickly alert and alarm the EMS operator.

Figure 8:
Constraints: WAMS - DSA Transfer Limits

- EMS/DSA defines stability limits



- WAMS based Violations/Alarms in EMS

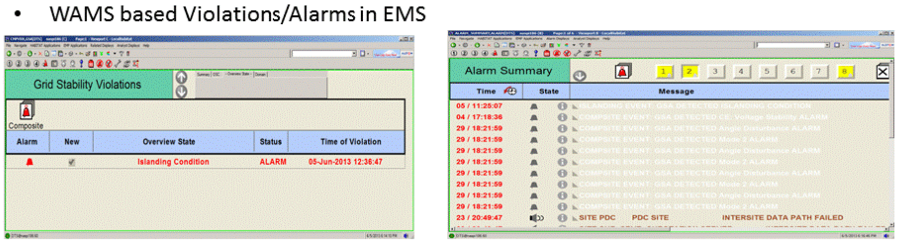
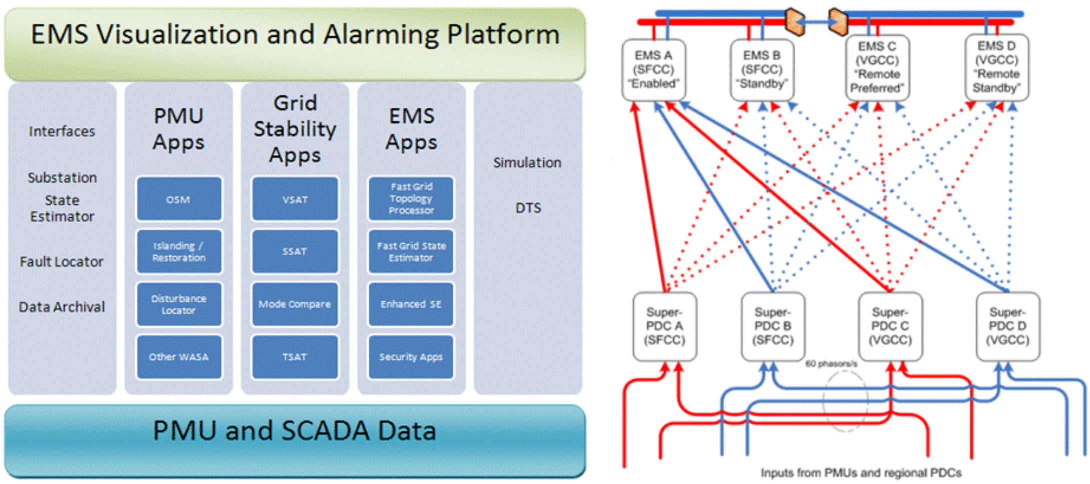


Figure 9 is an overview of an implementation of this technology at Pacific Gas & Electric in San Ramon, CA. This project is partially funded by the US Department of Energy as part of the Smart Grid Invest Grants. This is a test facility that will be fully operational in 2013 and its advanced functionality will subsequently migrate to their production EMS.

Figure 9:
EMS Synchrophasor Test Facility

Pacific Gas & Electric, San Ramon CA



Multi-host Redundancy

To summarize: the rapid growth of PMU synchrophasor measurements at control centers, along with faster computational speeds, enhanced DSA tools, advanced EMS visualization techniques and modern EMS analytics, creates a synergistic nexus of technologies and solutions, that allows us to monitor grid dynamic behavior in real-time - in a manner that has never been done before. This in turn facilitates improved reliability of grid operations.

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