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Model Validation Using Synchrophasor Data
-- A Synchrophasor Success Story

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SUMMARY

Mathematical models – from models of individual transmission elements and power plant components to production cost models and system models -- are used for every aspect of power system planning and operations. When a generator or system does not act in the way that its models predict, the mismatch between reality and the model-based expectations can lead to severe disturbances and costly equipment damage. Inaccurate models of generators, transmission assets and the system as a whole have contributed to a number of North American power outages. With wider deployment of phasor measurement units across North America, it is now possible to use the high-speed, time-synchronized data about grid conditions (voltage, current, frequency, and phase angles) from PMUs to validate and calibrate operational models of various grid assets -- and soon, of the grid's dynamic behavior. Model validation is now recognized as a highly successful use for synchrophasor data, because model testing and improvement using actual grid performance information is more accurate and often economical than traditional off-line asset testing. This paper explains the benefits of using synchrophasor data to validate operational models and reviews numerous cases in which synchrophasor data have been used to validate and improve key models across the North American grid.

KEYWORDS

Model - validation - synchrophasors - synchrophasor success story

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1. BACKGROUND

The power system is designed and operated based on mathematical models that characterize the expected behavior of power plants, grid elements, and the grid as a whole. When a generator or the system does not act in the way that its model predicts, the mismatch between reality and model-based expectations can cause severe disturbances and costly equipment damage. Inaccurate models have contributed to a number of recent North American power outages, including the 1996 Western States outage.

With wider deployment of phasor measurement units across North America, it is now possible to use the high-speed, time-synchronized data about grid conditions (voltage, current, frequency, and phase angles) from PMUs to validate operational models of various grid assets -- and soon, of the grid's dynamic behavior. Model validation and calibration is now recognized as a highly successful use for synchrophasor data, because model testing and improvement using actual grid performance information is more accurate and often economical than traditional off-line asset testing.

This paper explains what models are and why they matter for the electric power system, explains the benefits of using synchrophasor data to validate operational models, and reviews several cases in which synchrophasor data have been used to validate and improve key models across the North American grid.

2. POWER SYSTEM MODELS

A mathematical model of a power plant or other piece of electrical equipment is a set of mathematical equations and variable values that together describe or explain the device and how it behaves under different circumstances and inputs. Models of individual generators and types of transmission equipment are combined into system models that predict the grid's operational behavior. A static model describes how something behaves at a single point in time; a dynamic model predicts how it behaves over time. In the case of the power grid, transient models describe how the grid behaves over time in response to disruptive events such as an electrical fault on the system.

The modern electric power system uses a variety of models for every facet of system management, from long-term resource planning to minute-by-minute operational decisions. Figure 1 shows the major model and data types and their many uses.

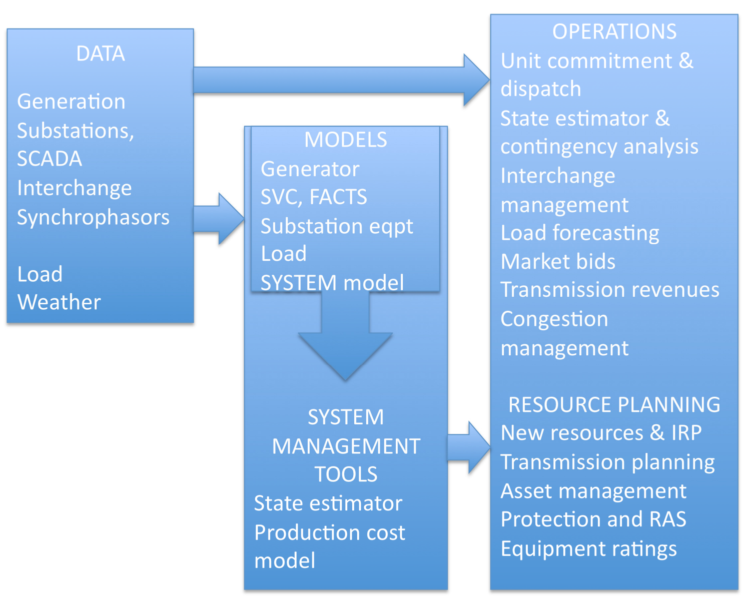

Figure 1 -- Uses for Power System Models

Given the many ways that utilities, generators and grid operators use models, the accuracy and speed of those models can have multi-million or billion-dollar consequences. If a power plant model is wrong, that plant cause grid voltage problems or have higher fuel costs than predicted; if a system model is wrong, a fault could lead to a major grid collapse or a Remedial Action Scheme operation could hasten a major customer outage; if a market model is wrong, it could cost millions in lost profits or excess costs.

Poor models don't accurately represent how specific assets -- individually, or in combination with other grid elements -- will behave under a range of grid conditions. Grid planners design and build the grid using the best operational models available, with expectations that the grid's performance under stressed conditions will track the simulated performance. But sometimes the models are wrong, and events that the models predicted would recover turn out very differently. In the case of the Western States August 1996 outage, a set of grid conditions that engineers predicted would damp out and return to stable conditions (Figure 2, bottom graph showing simulated power flows for the pre-blackout conditions) in reality became an un-damped oscillation (Figure 2, top graph) that led to a multi-state blackout affecting over seven million people.

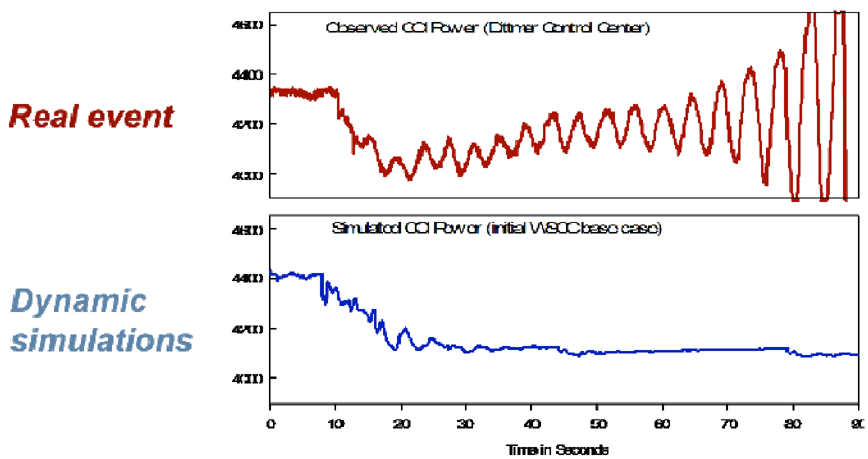

Figure 2 -- WSCC August 1996 Outage -- actual event (top) and the simulation that showed what planners expected would happen (Source: BPA)

The Western States 1996 blackout led the Bonneville Power Administration (BPA) to discover that its models couldn't predict the voltage changes that led to the blackout -- in other words, "the models were unable to predict the reliability impacts of grid disturbances." [1] Based on this discovery, the Western Electricity Coordinating Council (WECC) instituted baseline performance testing requirements for western power plants, including mandatory five-year updates, feeding the performance test results directly into model validation. In 1999, BPA began monitoring several generators using phasor measurement units (PMUs) to collect high-speed data on how the plants responded to real grid disruptions, and in 1999 BPA began using the collected data for generator model validation in lieu of taking the plant off-line for performance testing. WECC adopted the Generating Unit Model Validation Policy, officially allowing the use of disturbance recordings for power plant model validation, in 2006.

Model validation and calibration uses synchrophasor data records of voltage and frequency deviations and oscillations, collecting data on the voltage, frequency and unit control signals at multiple locations across the grid -- particularly at a generator's point of interconnection with the grid. A good model is one that predicts real power and reactive power and frequency responses accurately relative to actual grid events. [2] A bad model misses on one or more of these three performance variables, as shown in Figure 3.

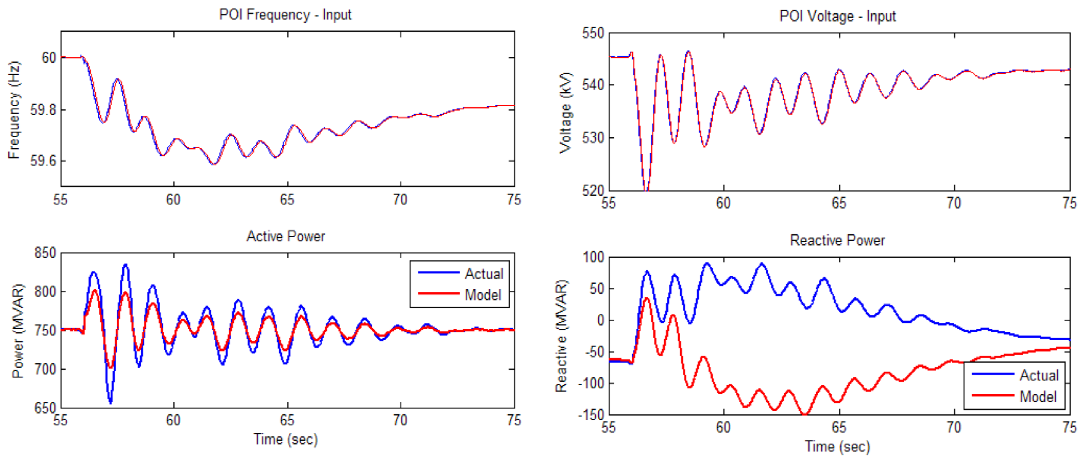

Figure 3 -- What a bad model looks like (800 MW steam-turbine generator) (Source: BPA)

3. BENEFITS OF PMU DATA-BASED MODEL VALIDATION AND CALIBRATION

The time granularity and geographic specificity of synchrophasor data make it perfect for validating operational asset models, allowing the analyst to benchmark and improve generator and other models against actual system performance rather than hypothesized behavior. There are several benefits from using synchrophasor data for generator and system model validation and calibration:

- Better models of grid assets and their interactions improve grid reliability and asset safety because synchrophasor data capture real operating ranges and operational relationships more accurately than testing of individual physical assets.
- Models validated using synchrophasor data improve asset and system efficiency by setting more accurate operating limits for grid assets, which may enhance asset utilization.
- Models validated using synchrophasor data allow engineers to detect acute generator control failures or equipment mis-operations in real-time, which may prevent potential equipment damage.
- Synchrophasor-based model validation is more economical and accurate than validation methods that take the model off-line for performance testing, because they allow the asset owner to continue operating the plant and realizing revenues.
- Synchrophasor-based model validation is an accepted and cost-effective way to satisfy the requirements of NERC reliability standards MOD-26, MOD-27, MOD-32 and MOD-33, to verify generator real and reactive power capability and control systems and assure their appropriate responses during system disturbances. [3]
- At the resource planning time-scale, accurate models help transmission owners and system planners identify and invest in the correct amounts and types of grid and generation equipment.

Generator model validation using off-line "staged testing" requires a significant investment of time and planning to design the test procedures, instrument the plant for test monitoring, take the plant off-line (during which it is not producing revenues but is consuming fuel), conduct the test, and safely return the plant to service. That testing can be constrained by operational requirements such as maintenance schedules or air emissions limitations, and may not identify and test all the extreme operational conditions that could challenge the plant in real life. Additionally, test results can differ -- two different testing firms and protocols could produce materially different test results with different plant model calibration outcomes. [4] Furthermore, baseline testing of a power plant does not always yield a model that accurately describes the plant's behavior under a broad span of grid conditions, such as unplanned system disturbances. BPA (the entity with the longest history in model validation) has found that within many power plant models, the models for the power system stabilizers and turbine governors have been "deficient," or found a mismatch between actual Automatic Generation Control settings and the settings assumed in the model. BPA's experience testing models developed by Generation Owners suggests that 60 to 70 percent of the power plant models did not accurately predict actual plant performance recorded with PMUs under actual system disturbances. [4]

In contrast, once PMUs are connected to the plant, they provide continuous high-speed monitoring that records the plant's response to actual transmission-level grid disturbances such as generator loss, faults or line trips. This yields a wider range of plant responses than would be examined in a formal off-line test, with exact responses that reflect both in-plant and external grid influences. And while an off-line test is costly and may only be conducted every five years, the availability of synchrophasor data enables the asset owner to review asset performance and recalibrate its model -- or spot mis-operations or erroneous settings -- much more frequently. Thus PMU disturbance recordings can complement baseline test-based model development. [4]

4. HOW TO PERFORM MODEL VALIDATION USING SYNCHROPHASOR DATA

Whether working with physical test data or synchrophasor data, the broad process of generator model validation first requires verification that the basic structure and assumptions of the model is correct, and then that its essential parameters are accurately calibrated. Comparison of a power plant's recorded performance using PMU disturbance data against the model's prediction for the event's characteristics should reveal whether the model's predictive capability is so far off that it should be fully refuted, restructured, or recalibrated, as shown in Figure 4. [5] In Figure 4, the plant's actual performance (black lines) during two disturbances was not predicted accurately by the initial plant model (red lines); the model was then recalibrated with better data and parameters to produce significantly better predictions (blue lines matching black lines).

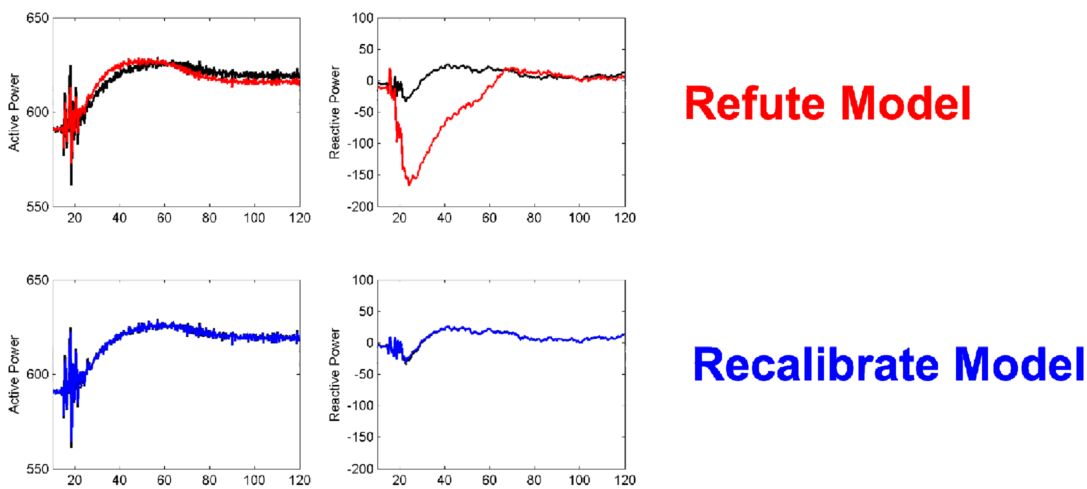

Figure 4 -- Comparing Model Simulated Results Against Actual Plant Performance
(Source: Lesieutre, University of Wisconsin)

Model calibration entails adjusting the parameter values for a model. With PMU data on generator performance during multiple grid events, an engineer can conduct sensitivity analyses to tune and adjust the parameters of a generator model to fit actual observations. It may also be necessary to adjust the structure of the model (e.g., with respect to the nature of its Power System Stabilizer operation).

5. AUTOMATED MODEL VALIDATION AND CALIBRATION TOOLS

Multiple entities have developed automated tools to conduct power plant model validation and calibration using synchrophasor data. The Electric Power Research Institute developed the Power Plant Parameter Derivation (PPPD) tool, first released in 2009. PPPD is a software system that contains all of the IEEE standard models for excitation systems as well as many of the commonly used turbine-governor models. The user first unitizes and then inputs the PMU data for a specific grid disturbance and plant into PPPD, selects the appropriate plant type and model, specifies an initial set of upper and lower bounds for the plant parameters, and starts the PPPD analysis. PPPD then runs an iterative process of running simulations against the data to derive and optimize the model parameters. [6] The tuned or recalibrated model resulting from this process has been shown to be an effective predictor of the plant's performance under later grid disturbances.

PPPD is now being used or studied by over 20 generation owners and transmission system operators, including the Midcontinent Independent System Operator, New York Independent System Operator, and PJM Interconnection. Duke Energy has used PPPD to validate the models for its entire North Carolina generation fleet.

BPA worked with Pacific Northwest National Laboratory staff to develop Power Plant Model Validation, using the General Electric PSLF Play-in Function. The PPMV tool contains a collection of power plant models and model validation studies, as well as disturbance recordings from a number of historic grid events. The user can import data from a new disturbance into the database, which converts PMU and SCADA data into PSLF format, and then run the tool to validate (or invalidate) the model for a specific power plant against its actual performance. [7]

In support of the WECC model validation initiatives and BPA's obligations as a transmission service provider, to date BPA has installed PMUs at 15 power plants, which account for approximately 70 generators and over 20,000 MW of generating capacity across the Pacific Northwest.

EPG's Phasor Data Graphics Analyzer and MathWorks® Matlab Simulink® can also be used for generator model validation and calibration.

6. EXAMPLES OF PMU-BASED MODEL VALIDATION

With the proliferation of PMU deployment facilitated by the Department of Energy's Smart Grid Investment Grants and Smart Grid Demonstration Projects (awarded in 2009 and completed in 2014), a number of generation owners and transmission owners have used synchrophasor data to improve various grid models. This section summarizes a variety of recent model validation examples including hydrogenerators, nuclear generators, FACTS devices, and system and state estimation models.

6.1 Hydroelectric generators

BPA was the first generation owner to install PMUs at the points of interconnection between generators and transmission. BPA collected disturbance recordings of how the plant responded to actual grid events and compared those recordings to plant simulations, working with General Electric to modify Power System Load Flow simulation software to play actual disturbance data directly into the load flow model. If the simulation was inaccurate relative to the actual plant performance, they used the PMU data to adjust the model to better predict future responses.

BPA's The Dalles hydrogenerator was the first power plant model modified using synchrophasor data, in 2001. Subsequently, BPA staff used PMU data to develop verified baseline models of most of their major generators. Such models enable identification of control abnormalities and plant mis-operations. For instance, in 2009 BPA engineers noticed that the Grand Coulee hydropower generators responded differently to a system oscillation than the power plant model would have predicted (see Figure 4).

Investigation using the plant model hypothesized that the plant's Power System Stabilizer was not functioning; this failure was verified by the plant operator. [1]

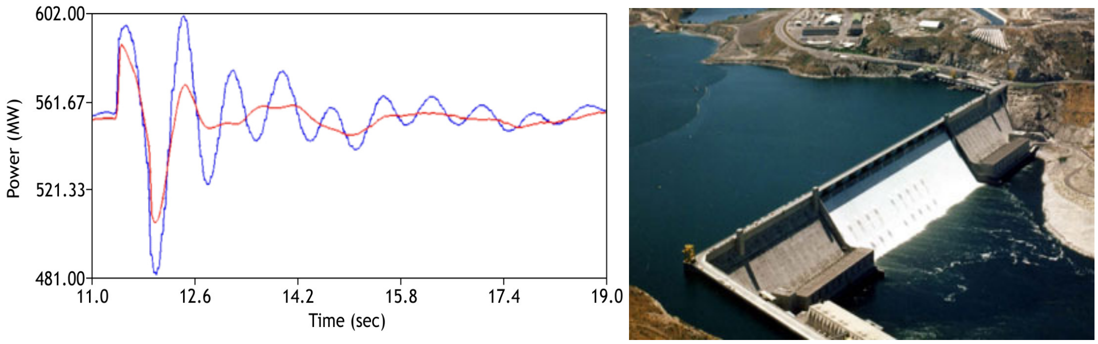

Figure 4 -- Grand Coulee Hydropower Generator response to oscillation (blue) differed from the expected baseline response (red) (Source: BPA)

6.2 Nuclear generators

BPA used PMU data to validate and calibrate the models for the 1,100 MW Columbia Nuclear Generating Station. The model validation effort began with collection of data on the plant's actual behavior in response to four disturbance events to develop the new model. That model was later verified and recalibrated with data from ten subsequent disturbances. BPA estimates that because the plant's owner did not have to take it off-line for model validation testing, the plant yielded from $100,000 to $700,000 worth of revenues that might have otherwise been lost during the test period. [8]

ISO-New England used PMU data for a ground fault that occurred 16 miles away from the Millstone Nuclear Power Plant to validate the model for that plant. ISO-NE has also automated its dynamic model validation process and is moving on to validate other models for generators, loads, HVDCs and SVCs. [9]

6.3 Coal-fired generators

PMU data have been used to validate the models for at least two coal-fired generators, including TransAlta's 750 MW Centralia Coal Plant in 2003, and the Colstrip power plant.

6.4 FACTS devices

EPRI has developed the Static VAr System Validation Model for use validating FACTS device models. NYPA used this tool to improve the dynamic models for NYPA's Marcy STATCOM and its refurbished SVC. Beginning with the generic SVC models developed in 2010 and 2011, and PMU data from disturbance events, they calculated the injected reactive current and reactive power for the devices and played measured voltage back into the models to fit simulated values to the measured values, using least squares estimation fits to optimize the models. [10]

6.5 Wind generators

There are several efforts under way to use PMU data to improve models of wind and solar generators. The Utility Variable Generation Integration Group is doing extensive work on renewable power plant model validation, working in collaboration with EPRI, EnerNex, Hydro Quebec, BPA, the National Renewable Energy Laboratory, and Oklahoma Gas & Electric. Researchers caution that there are as yet few wind and solar plants that are fully monitored by PMUs (making it difficult to build a solid database to validate individual plants), that there are many varieties of wind and solar plants to be validated, and that actual grid events may be asymmetrical (PSS/E and PSLF models are positive sequence only, but three-phase faults and unbalanced events are rare). [11]

ERCOT has used voltage oscillations observed at wind plant PMUs to tune wind plant models, recreating the oscillations using simulation tools such as MATLAB (see Figure 5). With a model that accurately reflects oscillations and their causes, the grid operator can then diagnose the causes of operating events such as wind-driven oscillations and identify appropriate corrective measures. ERCOT observes that reducing generator models to a time-series data component greatly simplifies the model validation process, because it reduces model complexity while reducing analytical time and effort. [12]

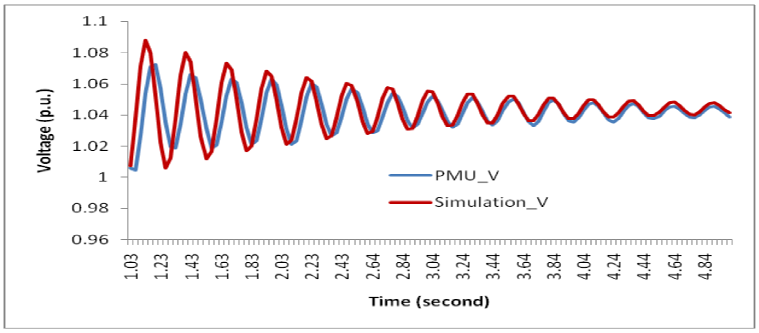

Figure 5 -- ERCOT Benchmarking of a Wind Plant Model Using PMU Data (Source: ERCOT)

6.6 System models

WECC's Modeling and Validation Work Group now conducts a formal model validation study of every major grid disturbance, to identify any gaps between the event as it actually occurred (per PMU and other data) and the simulated event using the system model. [13] WECC treats such events and simulation weaknesses as opportunities to identify flaws and improve the system model. WECC added a governor model recommendation in the early 2000's after system model validation could not reproduce system frequency [14]. Load model improvements were initiated after model validation studies failed to reproduce delayed voltage recovery phenomenon caused by stalled air-conditioners [15].

The July 4, 2012 loss of 1,700 MW of generation in Arizona is an example of one recent model validation study. Figure 6A shows that the Western system models (run using the condition data for the July 4 event) could not closely predict system frequency and power pick-up on a major transmission path. Figure 6B shows that the model's performance improved once the synchrophasor data were used to re-calibrate generator governor data to achieve better correspondence between models and reality. WECC's Western Interconnection Synchrophasor Program (WISP) provides the synchrophasor-based wide-area measurements necessary for model validation and reconstruction of sequence of events.

Continual system model validation is essential to ensure that the overall system model is accurate and up-to-date, [16] and will be required by upcoming NERC MOD-033 Reliability Standards in all three interconnections.

6.7 State estimator models

State estimator models are used in real-time contingency analysis, security-constrained economic dispatch, near-term operational planning, and post-event analysis. Therefore, accurate state estimation is essential for power system reliability and markets. Synchrophasors provide bus voltage angle information that is not available from SCADA measurements. Initially, phase angles from PMUs are being used to benchmark state estimation solutions and improve the underlying system models. New

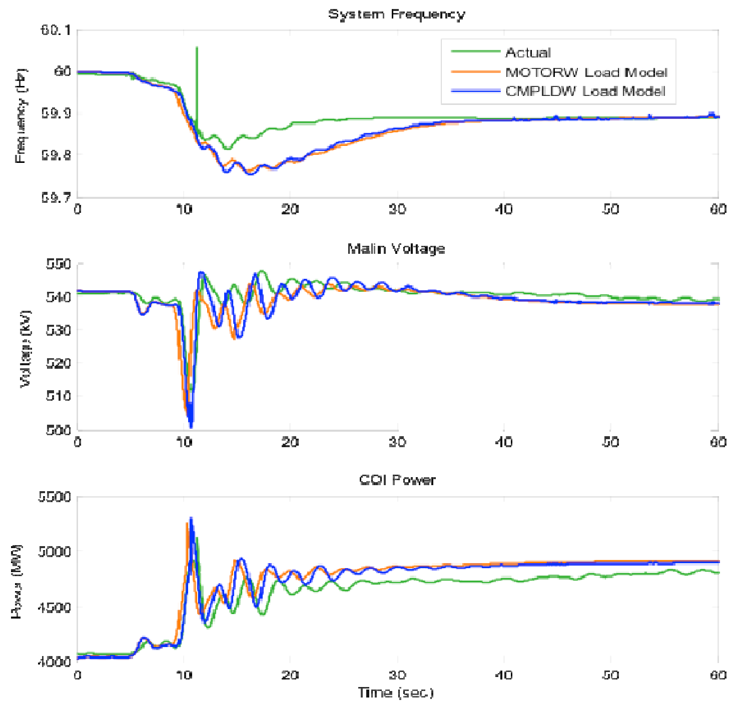

Figure 6A -- Comparison of actual versus simulated July 4, 2012 WECC event using the pre-event system model (Source: WECC)

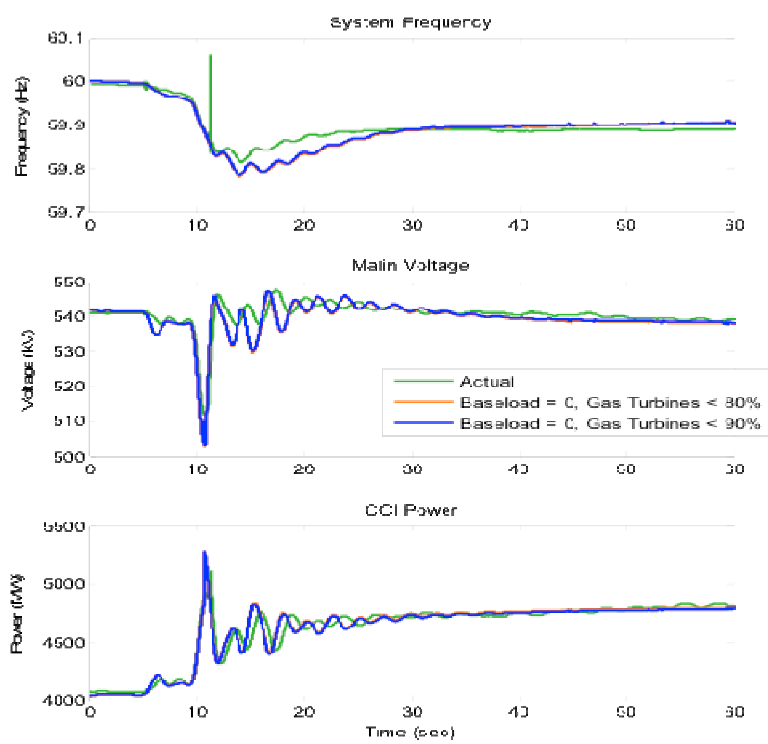

Figure 6B -- Comparison of actual versus simulated July 4, 2012 WECC event using the post-event, synchrophasor data-calibrated system model (Source: WECC)

advanced state estimators are now capable of taking phase angle information as inputs, thereby improving solution accuracy.

7.0 CONCLUSION

Accurate models of electric systems and their components are critical for reliable, economic grid operations. The growing deployment of PMUs collecting accurate, high-speed synchrophasor data is transforming the practice of power plant model validation and is enabling drastic improvements in the accuracy of power plant and bulk power system models. Model validation has become a great success story demonstrating the value of synchrophasor technology.

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