Pacific Gas and Electric Company

EPIC Final Report

Program	***Electric Program Investment Charge (EPIC)***
Project	***EPIC 2.15 – Synchrophasor Applications for Generator Dynamic Model Validation***
Department	*Electric Grid Operations*
Project Sponsor	Tom French
Project Business Lead	Sherman Chen
Contact Info	EPIC_Info@pge.com
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Table of Acronyms

AGC	Automatic Generation Control
CPUC	California Public Utilities Commission
CT	Current Transformer
EPIC	Electric Program Investment Charge
NERC	North American Electric Reliability Corporation
PDCI	Pacific DC Intertie
PG&E	Pacific Gas & Electric
PMU	Phasor Measurement Unit
PQ	Active Power and Reactive Power
PQVF	Active Power, Reactive Power, Voltage and Frequency
PSLF	Positive Sequence Load Flow Software
PSS	Power System Stabilizer
PT	Power Transformer
RAS	Remedial Action Scheme
SCADA	Supervisory Control and Data Acquisition
TD&D	Technology Demonstration and Deployment
VF	Voltage and Frequency
WECC	Western Electricity Coordinating Council

1 Executive Summary

This report summarizes the project objectives, technical results, lessons learned and recommendations from EPIC *Project 2-15, Synchrophasor Applications for Generator Dynamic Model Validation* as listed in the EPIC Annual Report.

Background

In the aftermath of two major grid outages in 1996, the Western Electricity Coordinating Council (WECC) mandated testing and validation of large generator dynamic models and model parameters every ten years or whenever a change is made to the generator, excitation system, or governor. After the 1996 disturbances, evidence indicated that simulation results from dynamic models were inconsistent with measured results. The purpose of the mandated testing is to validate how generator models respond to disturbance recordings to improve accuracy of existing models. The General Electric (GE) Positive Sequence Load Flow Software[1] (PSLF) tool is widely used in WECC for these transient stability studies.

Currently data gathering for generator model validation involves injecting signals into the generator control system to measure the responses of the generator. This offline testing involves engineers installing test instrumentation on the generator equipment and coordinating the test procedure with the plant operator. During the test, the generator may not be available to operate throughout its normal operating range. Once the testing is completed, the model validation is performed by engineers back at the office, which entails a combination of manual and automatic processes.

Key Objectives and Major Tasks

The purpose of this project was to demonstrate a new synchrophasor application that could potentially perform generator model validation without requiring time to conduct onsite tests. If realized, the benefits could reduce the cost of model validation testing and improve generator model accuracy through more frequent assessments using actual disturbance data.

This project installed Phasor Measurement Units (PMU) on the three generators at Pacific Gas and Electric Company's (PG&E) Colusa Generation Station, developed station generator models, and used actual disturbance data collected online (in lieu of offline test data) to test new synchrophasor applications for generator model validation. To develop the station generator models, new model algorithms had to be developed for the generator, governor, excitation system, and power system stabilizer (PSS) models.

The EPIC 2-15 – Synchrophasor Applications for Generator Dynamic Model Validation project had the following objectives:

- Install PMUs on up to four generating stations.
- Test new synchrophasor data analysis software applications to validate the dynamic models. In this report this software will be referred to as the new model validation tool.
- Evaluate the practicality and accuracy of performing generator dynamic model validation using PMU data collected from actual disturbance events.
- Recommend applications for future use as appropriate.

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[1] PSLF by GE is one of the common tools used by PG&E for transient stability analysis of the transmission systems to comply with the NERC reliability standards.

Results

Overall, the project (1) developed criteria to identify a short list of candidates and selected a power generating facility to install PMUs at; (2) designed, procured, and installed fully functional PMUs at Colusa Generating Station; (3) developed station generator models with existing parameters; and (4) applied PMU disturbance data to evaluate the practicality and accuracy of the tool.

Selection Criteria

The project developed criteria to identify a short list of candidates and selected a power generating facility to install PMUs at. The PG&E generating stations were evaluated for four criteria; (1) generator size; (2) adequate existing Information Technology (IT) infrastructure; and (3) scheduled maintenance outage that aligned with the timeframe for this project. Colusa Generating Station was selected as it was the only facility that satisfied these four criteria.

Observations

- The number of generating stations with existing IT infrastructure adequate for collection of PMU data is limited. The older stations such as many hydro plants, have not been updated to digital control systems and therefore do not have adequate IT capability for transmitting collected PMU data.

- When upgrading IT infrastructure at generating stations, future PMU IT requirements should be considered. This includes adequate LAN within the plant as well as adequate WAN bandwidth to transmit PMU data back to a data center. These are the two most important IT requirements for executing PMUs at a generating facility cost effectively.

- Applications of PMU data in generating stations are just developing. Plant operating personnel are often unfamiliar with the technology and are cautious about their installation in generation facilities, thus utilities planning to pursue this approach should plan for extensive change management as part of integrating the technology.

Installation of PMUs

A fully functional PMU system was designed, approved, procured, and installed on the three generators at the Colusa Power Generating Station. PMU installation required a generation shutdown and was scheduled to be done concurrently with a scheduled plant outage. Prior to the shutdown, design drawings were prepared and approved by the plant.

Observations

- PMUs can be successfully installed at power generating stations during scheduled outages with minimal impact on the outage activities.

- Significant advanced planning is required to install the PMU units during a scheduled outage. Each system is different depending on the generating plant design and the architectural network design drawings, and an installation plan needs to be developed, approved and integrated into the scheduled outage timeline.

Development and Testing of the New Model Validation Tool

The project developed generator models to match existing PSLF generator models using the new commercial software and tested the dynamic models using actual disturbance data captured by PMUs for two Remedial Action Scheme (RAS) events on 4/6/17 and 6/23/17. The two disturbances were input into the new models and their simulated responses were compared to the actual generator responses as recorded by the PMUs. The tool utilized a sensitivity algorithm to determine the five generator parameters which had the most impact on moving the simulated responses closer to the actual generator responses. These optimization algorithms developed were found to be inadequate because significant engineering judgement is required to determine which generator parameters should be modified in the curve fitting process.

Observations

- The cost of PMU installation at generators was not found to be cost effective for model validation purposes alone.
- It took more time than expected to model the generation system in the new validation software, because the existing PSLF model algorithms for the generators were proprietary and could not be leveraged in the new tool. Identifying a tool which uses PSLF as the output will eliminate this sort of inefficiency moving forward.
- Some models such as the gentpj generator model can be used for many different power plants, but there are not enough exciter and governor models in the vendor's library to cover most of PG&E's power plants.
- Technical enhancements needed for the tool to be more useful include more stable simulation initialization, a bigger library of generator models used in the WECC, and simplified data input/output including the ability to run multiple disturbances to better calibrate the model parameters.
- Models need to be tested against various grid events to ensure that the models are robust. A robust model is valid with all types of grid events and ultimately delivers better predictions of the plant's response over a wide range of grid events.
- The tool's automated sensitivity analysis which identifies the top correlated parameters must be used with good engineering judgement because not all model parameters should be changed from their baseline values.
- In time, other use cases for generator PMUs could be developed. The collection of disturbance events through PMU data is a valuable resource. PMU Colusa Power Generating Station should be investigated for other reliability purposes such as identifying sub-synchronous resonance, generator asset condition monitoring, PSS tuning, etc., and generator synchronization with the grid.

Conclusions

The integration of PMUs on generators for dynamic model validation is a new technology and the installation at Colusa was the first in PG&E territory for this application. The new model validation software developed in EPIC 2.15 did not result in a tool that is production ready and that could be used in current form for model validation purposes. In addition, the cost of PMU installation at generators was not found to be cost effective for model validation purposes alone. These are the primary reasons PG&E is not currently pursuing the installation of PMUs for model validation at other plants.[2]

However, PG&E recommends that installation of PMUs at generating stations continue to be evaluated as applications evolve which could enhance generator testing or provide other reliability benefits. PG&E Transmission Operations Engineering will continue to utilize and refine the new model validation tool to perform model validation updates at Colusa, Diablo Canyon, and possible future installations using PMU data.

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[2] PG&E's 2020 GRC (Exhibit 5, Chapter 4) mentioned potentially installing the PMUs pending the conclusion of EPIC 2.15; which differ from the close out report's findings. Due to the complexity, magnitude and long-lead time needed to compile the GRC, the GRC description was based on an earlier and thus more open-ended outlook for the project.

2 Introduction

This report documents the *EPIC 2-15 Synchrophasor Applications for Generator Dynamic Model Validation* project achievements, highlights key learnings from the project that have industry-wide value, and identifies future opportunities for PG&E to leverage this project.

The California Public Utilities Commission (CPUC) passed two decisions that established the basis for this pilot program. The CPUC initially issued D. 11-12-035, *Decision Establishing Interim Research, Development and Demonstrations and Renewables Program Funding Level,*[3] which established the EPIC on December 15, 2011. Subsequently, on May 24, 2012, the CPUC issued D. 12-05-037, *Phase 2 Decision Establishing Purposes and Governance for Electric Program Investment Charge and Establishing Funding Collections for 2013-2020,*[4] which authorized funding in the areas of applied research and development, technology demonstration and deployment (TD&D), and market facilitation. In this latter decision, CPUC defined TD&D as "the installation and operation of pre-commercial technologies or strategies at a scale sufficiently large and in conditions sufficiently reflective of anticipated actual operating environments to enable appraisal of the operational and performance characteristics and the financial risks associated with a given technology."[5]

The decision also required the EPIC Program Administrators[6] to submit Triennial Investment Plans to cover three-year funding cycles for 2012-2014, 2015-2017, and 2018-2020. On November 1, 2012, in A.12-11-003, PG&E filed its first triennial EPIC Application at the CPUC, requesting $49,328,000 including funding for 26 TD&D Projects. On November 14, 2013, in D.13-11-025, the CPUC approved PG&E's EPIC plan, including $49,328,000 for this program category. Pursuant to PG&E's approved EPIC triennial plan, PG&E initiated, planned and implemented the following project: 2-15 Synchrophasor Applications for Generator Dynamic Model Validation. Through the annual reporting process, PG&E kept CPUC staff and stakeholders informed on the progress of the project. The following is PG&E's final report on this project.

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[3] http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/156050.PDF.

[4] http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/167664.PDF.

[5] Decision 12-05-037 p. 37.

[6] PG&E, San Diego Gas & Electric Company, Southern California Edison Company, and the California Energy Commission (CEC).

3 Project Summary

3.1 Issue Addressed

In the aftermath of two major grid outages in 1996, the WECC mandated testing and validation of large[7] generator dynamic models and model parameters every ten years or whenever a change was made to the generator, excitation system, or governor. The purpose of the testing is to collect data used to validate how the various generator component models respond to simulated system disturbances on the transmission grid, caused by other large generator and transmission line outages. The standard common tool used in the West to perform this type of simulation analysis is GE PSLF. This validation process is enforced by North American Electric Reliability Corporation (NERC)[8] MODs 026 and 027.

Today, the data required for validation of the generator dynamic models cannot be captured with existing measurement systems (e.g., SCADA)[9] because SCADA measurements cannot capture dynamic events accurately and are not time-synchronized. Therefore, present test methods require model validation to be performed at the generator.

In addition to testing at the power plant, NERC[10] and WECC have recommended the installation of PMUs[11] to collect the data necessary for online generator model validation. However, this approach has not been validated by the industry. This technology demonstration showed that PMU data could be collected from the generator and used to support calibration of generator models. PMUs were installed on three large generators at the PG&E Colusa Generating Station. PMU disturbance data was used by a new software tool to compare simulated generator response to actual generator response and modify model parameters to move the curves closer together.

3.2 Project Objectives

To identify the practicality of installing the required PMUs at generating stations and to demonstrate the usefulness and accuracy of the synchrophasor data analysis software, the project had four objectives. These objectives were:

- Install PMUs on up to four PG&E generating stations.
- Test new synchrophasor data analysis software applications (model validation tool).
- Evaluate the practicality and accuracy of performing generator dynamic model validation using the online synchrophasor data collected following transient disturbances on the transmission system.
- Recommend applications for future use if appropriate.

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[7] Initially WECC required validation for generators 10 Megavolt Ampere (MVA) and larger. WECC has changed the size to 75 MVA but PG&E’s policy continues to require validation for generator sizes 10 MVA and larger.

[8] NERC Modeling, Data and Analysis Standards. https://www.nerc.com/pa/Stand/Reliability%20Standards/MOD-026 1.pdf.

[9] Supervisory Control and Data Acquisition (SCADA) is a data acquisition, monitor and control systems covering large geographical areas. SCADA systems are mainly used in industries like power plants, oil and gas refining, water and waste control, and telecommunications.

[10] NERC Reliability Guideline, Power Plant Dynamic Model Verification using PMUs, September 2016.

[11] A PMU is a power system device capable of measuring synchronized voltage and current phasors in a power system. The measurements are called synchrophasors.

3.3 Scope of Work and Project Tasks

This project installed PMUs on three large generators at one PG&E power generating station and developed new generator dynamic models utilizing the new model validation tool (including generator, governor, exciter and PSS). To test the new model, the project team was tasked at simulating grid disturbances and calibrating with synchrophasor disturbance data collected from the PMUs.

There were three major tasks:

1. Identify power generation station(s) for PMU installations
2. Design and install PMU systems and collect data
3. Develop & validate model

3.3.1 Task 1. Identify Power Generation Stations for PMU Installations

The first step was to identify potential power generation stations that could be used during this project. There were four attributes considered:

- Generator size – larger generators have more impact on the system and any discrepancy in the models for these generators would be more likely to be observed.
- The generation facility had adequate existing IT infrastructure to support the application, with a minimal amount of funding to be spent on investing in the IT network infrastructure[12] just for this project.
- The generating plant had a scheduled outage or could schedule an outage within the timeframe for this project.

The milestone for this task was the identification and selection of generation station(s) where PMUs could be installed.

3.3.2 Task 2. Design and Install PMU Systems and Collect Data

This task included the design and preparation of drawings and the associated work plan required to install the PMU units at the plant during a scheduled outage. These drawings were filed at the plant following the installation. The documents included:

- Architecture Drawings
- Network Design Drawings
- Electrical Design Drawings
- Installation Plan

Following the approval of the PMU system design and before the scheduled plant outage, pre-installation work such as the installation of racks, computers and cable, was completed but not connected to the generator. This pre-installation activity was performed to minimize the amount of PMU work required during the actual plant shutdown and reduce the impact of the PMU work on the outage schedule.

During the scheduled generation outage, PMUs were installed and tested at the power generation station to collect frequency, voltage and current data for all three phases, real and reactive power and exciter DC voltage and current data. The generating station consisted of two 181 megawatts (MW) combustion turbine generators and one 349 MW steam turbine. Three PMUs were installed, one for each generator.

Once the PMUs were connected, data was collected and analyzed for disturbances. The project analyzed two instances where various events occurred. The collected data was used to compare simulated generator response

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[12] Adequate IT infrastructure for this project was a local and wide area network with bandwidth capable of transmitting the collected data and spare fiber to transmit collected data from generators to PMUs.

to actual recorded generator response and modify parameters to bring the curves closer together. A complete list of typical PSLF model parameters is provided in Appendix B - Model Parameters.

3.3.3 Task 3. Develop & Validate Model

This step developed and implemented a process for model validation. The generation station models with the latest validated parameters existed in the WECC PSLF system model, however since the PSLF models are derived from a proprietary tool it was not possible to leverage these algorithms, and the project was required to develop new models in the new model validation tool. Following the development of these new generation station models, a grid disturbance was simulated using these new models and compared against the actual data collected from the disturbance.

The milestones for this task were:

- Development of new generator dynamic models using the new model validation tool
- Simulation of an event(s) associated with collected synchrophasor data
- Curve fitting of simulated and actual generator responses

4 Project Activities, Results, and Findings

4.1 Technical results and findings – Task 1. Identify power generation stations for PMU installation

4.1.1 Technical Development and Methods

The PG&E generating stations were evaluated for the four criteria previously mentioned; (1) Generator size; (2) Adequate existing IT infrastructure; (3) Scheduled outage that aligned with the timeframe for this project; and (4) An extended outage would have minimum impact on the transmission system.

After reviewing the PG&E generating stations, three plants were identified as the most likely candidates – Colusa, Gateway and Helms. All three had large generators and excellent IT infrastructure, but only Colusa had an outage schedule that was consistent with the timeline of this project. Colusa was the only plant that satisfied all four criteria. Being the newest PG&E generating station, Colusa also had excellent IT infrastructure and consisted of two 181 MW gas turbines and one 349 MW steam turbine, and the installation of the PMUs did not represent a risk to the system.

4.1.2 Challenges

This task had three challenges to overcome:

- Identifying a plant with an existing adequate IT infrastructure that could be shut down during PMU installation. Older plants, especially hydro, normally do not have much IT infrastructure since they do not have digital control systems. Therefore, the number of plants with an adequate IT infrastructure was limited.
- The applications for PMU data at generating stations are at their infancy and therefore plant operators are not familiar with installation of the PMU devices within the plant and how they may or may not impact plant operations. The Project team made numerous presentations to plant personnel to help provide understanding and create a comfort level with the installation of the PMUs proposed to be installed.
- The PMU installation required a large amount of pre-planning to be compatible with a scheduled plant shutdown which generally has firm start and completion dates. Engineering drawings and installation plans needed to be finalized and approved and material procured prior to the scheduled shutdown date.

4.1.3 Results and Observations

- The number of generating stations, with existing IT infrastructure adequate for collection of PMU data is limited. The older stations, such as many hydro plants, have not been updated to digital control systems and therefore do not have adequate IT capability for transmitting collected PMU data.
- Applications of PMU data in generating stations are just developing. Plant operating personnel are often unfamiliar with the technology and are cautious about their installation in generation facilities. This is expected to change as PMU applications are adapted by the industry.
- Significant advanced planning is required to install the PMU units during a scheduled outage. Each system is different depending on the generating plant design and the architectural network design drawings, and an installation plan needs to be developed, approved and integrated into the scheduled outage timeline.

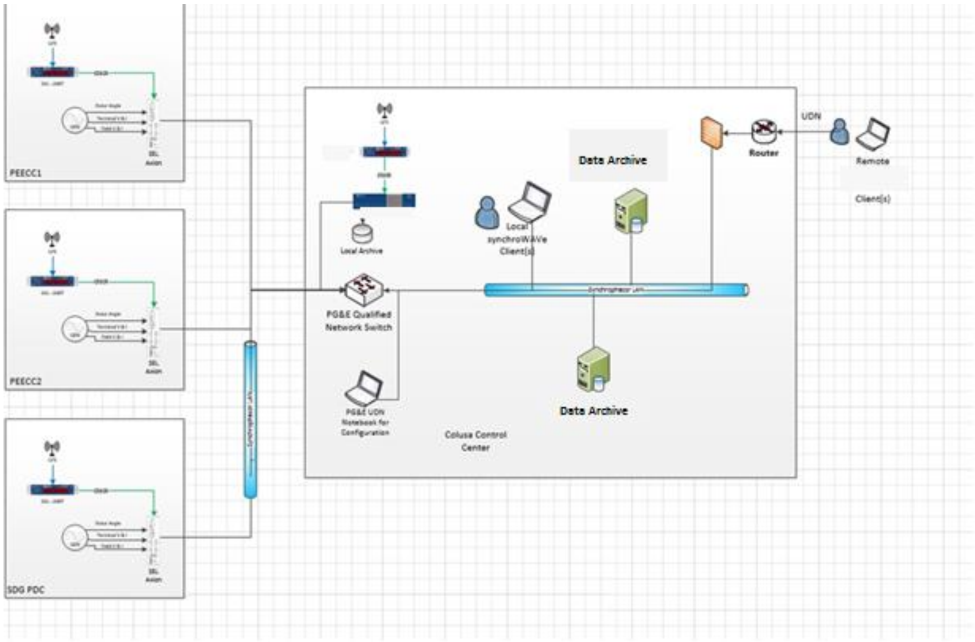
4.2 Technical results and findings – Task 2. Install and test PMUs

4.2.1 Technical Development and Methods

The project installed three PMUs at the Colusa Power Generating Station – one at each generator. The PMU installation required a generation shutdown and was scheduled to be done concurrently with a scheduled plant outage. Prior to the shutdown, design drawings were prepared and approved by the plant. PMU hardware and supporting network equipment were purchased and installed at the plant and configured. The main hardware and equipment, shown in

Figure 1, included PMUs, PDCs, router, switches, and firewall. Pre-testing included establishing communications from PMUs to PDCs, performing tests on PCs and remote connections, and data acquisition.

Figure 1 PMU Installation Architecture

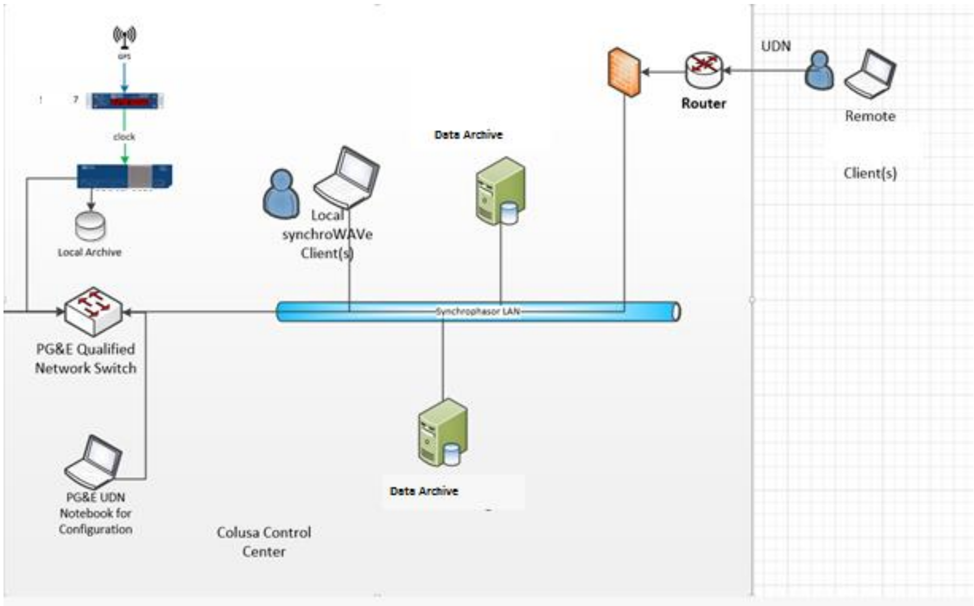


During the generator shutdown, all connections to current transformers and power transformers, shaft angle location signal and exciter measurement signals were connected.

Following the plant shutdown, the data collection started. The data collection process is shown in

Figure 2. The data was received from 3 generators, stored in a local PI server and was accessible locally and remotely. For example, PMU recordings of major grid events, such as frequency excursion, voltage excursion, transmission line trip and Remedial Action Scheme (RAS) activation, could be accessed and used for model validation.

Figure 2 Data Collection Process



4.2.2 Challenges

The primary challenge was getting everything ready in time for the plant shutdown, which included design approvals, installing network fiber, purchasing software and equipment, configuration of equipment, and doing pre-installation of equipment and network cabling where possible.

4.2.3 Results and Observations

- PMUs can be successfully installed at power generating stations during scheduled outages, with minimal impact on the outage activities;
- The risk of extending plant outages was minimized by doing as much pre-installation of the PMU system as possible before the plant shutdown; and
- Coordination with the plant engineering and maintenance personnel is necessary from the beginning of the project, to ensure engineering and installation drawings are completed and approved, and the installation plan is integrated into the overall plant schedule.

4.3 Technical results and findings – Task 3. Develop & Validate Model

The first step in model validation was collecting the PMU data from grid disturbances that resulted in large deviations in generators' frequency and voltage (Frequency measurement data is used for governor model validation and voltage measurement is used for exciter and PSS model validation). A disturbance corresponding to the collected PMU measurement was simulated in the new model validation tool to compare the simulated generator response with the actual recorded generator response In this project, since existing generation models in the WECC PSLF system model could not be imported into the new model validation tool due to proprietary rights, a new generation model was required to be developed.

4.3.1 Technical Development and Methods

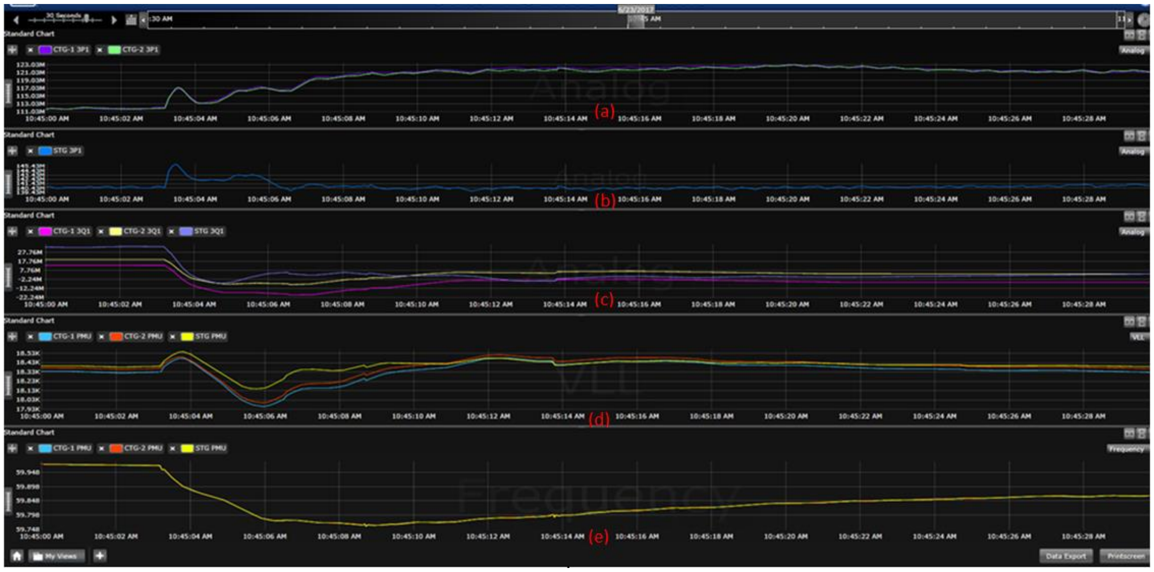
Data Collection*:* after the PMU installation, data was captured for four disturbances. For this project, PMU data from two transmission system events was selected to demonstrate the new model validation tool. These disturbances were selected because they resulted in large voltage and frequency (VF) deviations which are necessary to validate the generation models. The first event occurred on April 6, 2017 at 23:00 and the second event occurred on June 23, 2017 at 10:40. Both events were caused by loss of the PDCI (Pacific DC Intertie) and the subsequent tripping of generation by RAS.

The frequency and voltage responses observed at Colusa, and the generators' real and reactive power responses of three units for the disturbance on April 6, 2017, are shown in Figure 3. This data shows the disturbance, remedial reaction, and stabilization of Colusa's generators.

Figure 3 Generators Active Power (a&b), Generators Reactive Power (c), Voltage (d) and Frequency (e) Responses for April 6, 2017 Event

Figure 4 shows the frequency and voltage disturbance observed at Colusa, and the real and reactive power response of the generators for the disturbance on June 23, 2017.

Figure 4 Generators Active Power (a&b), Generators Reactive Power (c), Voltage (d) and Frequency (e) Responses for June 23, 2017 Event



Model Development: the new model validation tool required dynamic models (generator, exciter, governor and PSS) to simulate the grid disturbances. These models existed in the GE PSLF WECC model but the models could not be imported to the new model validation tool due to proprietary rights. Therefore, the project developed new models in the model validation tool. Dynamic models were developed for the two gas and one steam units at Colusa The developed models could be applicable to other similar generators, e.g., the governor model developed for the Colusa Gas Turbine units is the most common WECC governor model and is used for about 40% of the WECC units.[13]

Model Validation Process: to test the new tool, a disturbance corresponding to the actual outage when synchrophasor data was collected was simulated. PMU data used for forcing the model output were voltage, frequency, and active and reactive power. A set of measurements was replayed and injected into the model as the input, and another set was used for comparison with the simulated model output. If the simulation results show that the model output and the generator's actual response to the disturbance (recorded PMU data) were close enough (based on sum of squared error calculation and engineering judgement), the model was considered accurate. It should be noted that no documented standards exist that state the modeled results are required to be within a specific tolerance of the disturbance.

If the model outputs were deemed to not reflect the results of the disturbance event, the model needed revision. The parameters of the dynamic models were optimized to minimize the difference between the simulated and actual response. This process was repeated until a more representative model was found. If a close match could not be obtained, the structure of the model was considered invalid and needed to be revised using engineering troubleshooting processes and judgement. Three of the replay options (or paradigms) available in the commercial tool are listed below (V stands for voltage, F for frequency, P for active power and Q for reactive power measurements):

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[13] L. Pereira, J. Undrill, D. Kosterev, D. Davies, and S. Patterson, "A New Thermal Governor Modeling Approach in the WECC," IEEE Transactions on Power Systems, May 2003, pp. 819-829.

1. VF replay – compare simulated active power and reactive power (PQ) responses with PQ measurements: VF measurement data are imported to the generator models as the model input, and the simulated results for PQ are compared with the measurement data;
2. PQ replay – compare simulated VF responses with VF measurements: PQ measurement data are imported to the generator models as the model input, and the simulated results for VF are compared with the measurement data; and
3. Active power, reactive power, voltage and frequency (PQVF) replay – compare simulated VFPQ responses with VFPQ measurements in two stages: This replay is a combination of PQ and VF. First PQ replay is implemented to optimize the parameters and the parameters are applied to the model. Then VF replay is implemented on the updated model.

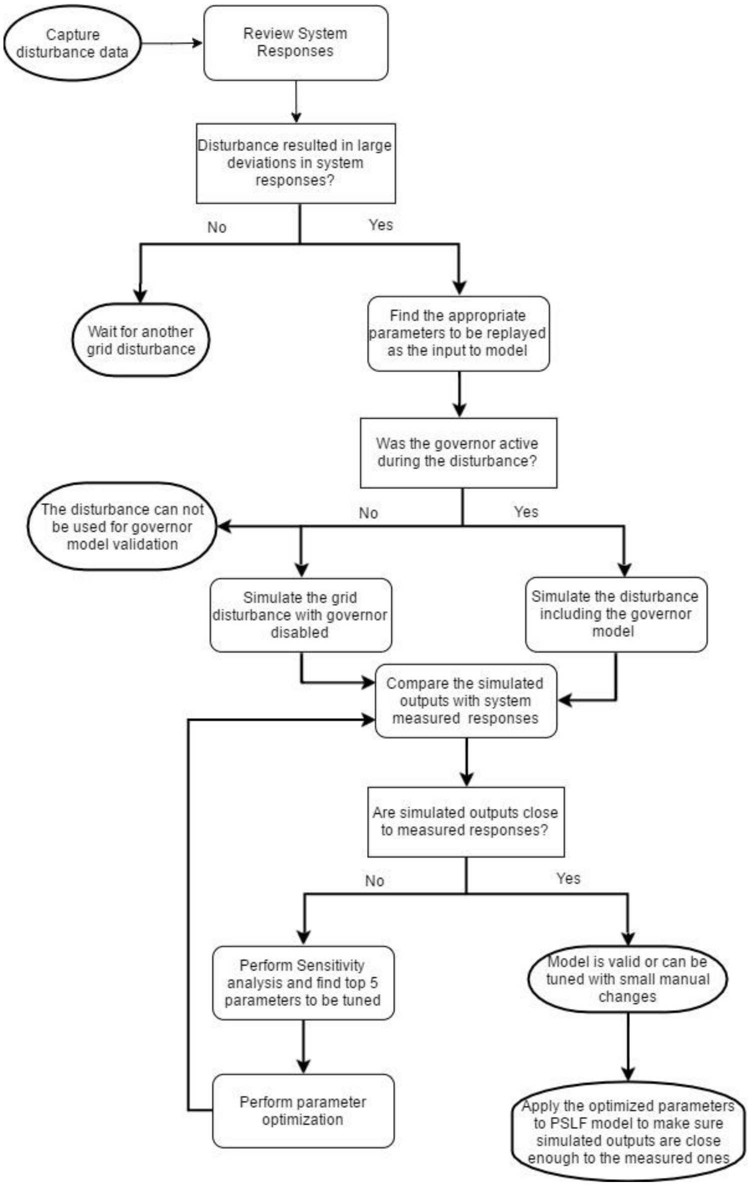
Selection of replay methods is based on visual observation of the recorded disturbance data and engineering judgment.

Recorded disturbances were also selected for model validation based on engineering judgement. A disturbance with noticeable transient responses in both VF is more appropriate for model validation. However, it is important to make sure that the F response is from the governor and not from Automatic Generation Control. The governor model can be validated only if the F response is the result of governor action. Also, if the unit was operating at the maximum capacity, there would be no room for the governor to react and the disturbance was not useful for governor model validation. A disturbance with only a V transient response could be used for exciter and PSS model validations but not for the governor model.

Before the parameter estimation, a sensitivity analysis was run to find the parameters with the highest impact on the model output. This method requires sound engineering judgement because not all generator parameters should be adjusted from their baseline values. The parameters with little or no impact were identified and not included in the validation process to limit the number of parameters to be considered for revision.

A workflow diagram of the validation process is shown in Figure 5 followed by the model validation tests performed for this project.

Figure 5- Model Validation Workflow Diagram



TESTING AND CALIBRATION: the new model validation tool was tested using the collected PMU data for the two RAS events. Measurements used in the tool for validation were pairs of VF and active and reactive power (PQ). Depending on the replay method selection, one pair of measurements (VF or PQ) was injected to the model to replay the measurement data as the model input, and the other pair was used for comparison with the model simulated outputs. The new model validation tool was used to simulate the disturbance and optimize parameters to minimize the difference between the simulated and actual outputs.

4.3.2 Challenges

There were several challenges in validating the models:

- It took longer than expected for the vendor to develop the new generation models in the new model validation tool, because algorithms were required to be re-developed since they could not be imported from the existing proprietary GE PSLF models.
- Models need to be continuously tested against various grid events to ensure that the models are robust. A robust model is valid with all types of grid events and ultimately delivers better predictions of the plant's response over a wide range of grid events.
- Records from grid disturbances with noticeable generator response (for VF) are required for parameter estimation and validations of models. For this project, two events with noticeable generator response were recorded. However, the collected data was not adequate to evaluate all replay methods in the validation tool. Additional disturbance data is required to confirm the robustness of the models.

4.4 Results

Results for the two RAS events that were used to calibrate and validate the dynamic generator models are presented in this section. The generating station included two gas turbine and one steam turbine units. One of the gas turbines was selected for model validation since the gas turbines include governor, exciter and PSS, and was a good choice for testing the validation tool. However, an initial observation of the recorded system response for the first event, April 6, 2017, showed that the governor was not active during the disturbance and therefore the event could not be used for governor parameters validation. Simulated responses were close to the measured responses and only a small manual tuning by engineers was required to more closely align the parameters. However, to evaluate the performance of the power plant validation tool for this event (for generator, exciter and PSS), some of the model parameters were purposely changed to invalidate the model. These changed parameters are referred to as "dirty parameters". For the second event on June 23, 2017, it was found that the governor was active and this event could be used to teset the governor model as well as generator, exciter, and PSS. With the "dirty parameters", the simulated responses were not close to the measured ones and the model required tuning via parameter estimation.

To estimate model parameters for the two events, a sensitivity analysis was first performed to find the top 5 parameters with the highest impact on the results for each event. Then the parameter optimization was implemented to tune the selected parameters. In addition, a comparison of the parameter optimization with and without the sensitivity analysis was performed. Detailed results for parameter estimation of the two events are presented in the following. It should be noted that there remains many questions on how best to utilize optimization routines. Additional work in evaluating use cases and potential benefits from the use of optimization routines is recommended to help streamline the model validation process.

4.4.1 Technical Development and Methods

4.4.1.1 Results for the First Event:

For the first event on April 6, 2017, the F and active-power responses from the measured data from the Colusa plant, shown in Figure 6, were reviewed to make an initial observation on the appropriate replay method. It was seen that while F dropped by only 0.25% following the grid event, active-power dropped approximately the same relative amount. There were two observations at this stage: (1) the very small perturbation in both F and active-power suggests that fitting governor parameters would be problematic as there was not a large enough perturbation in the system to exercise the governor dynamics and (2) it could be assumed the governor was not active as there was no clear governor response. For either of these observations, a reasonable conclusion was that the governor model could be removed for further validation process for this event, to simplify the problem and reduce computational effort for subsequent parameter sensitivity and parameter estimation tasks.

Another observation from Figure 6 was that the active-power response had more dynamic content than the F response. Since the more dynamic content in the output response will result in better parameter estimation, this was an early indicator that PQ replay will not be as effective as VF replay for this particular data set, therefore, VF replay was selected.

Figure 6 Frequency and Active Power Response for April 6, 2017 Event

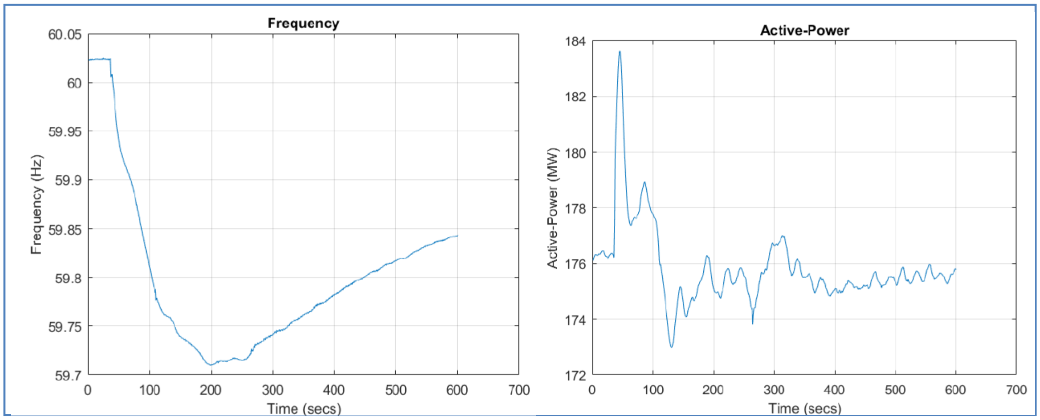


Figure 7 shows the result from the VF replay model for the baseline parameters. Visually it could be seen that the responses were fairly good, but reactive power could be improved based on engineering judgement.

shows the normalized responses and the sum-squared error for VF replay.

Figure 7 Measured Results With VF Replay and Original Parameters for April 6, 2017 Event

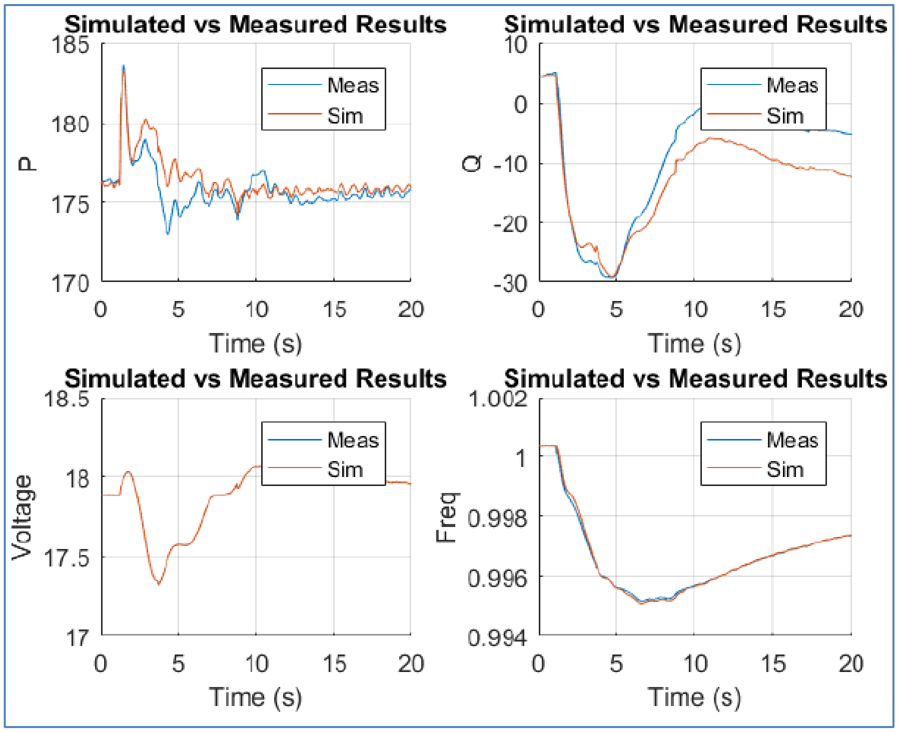


Figure 8 Normalized Responses and Sum-Squared Error for Baseline Parameters for April 6, 2017 Event

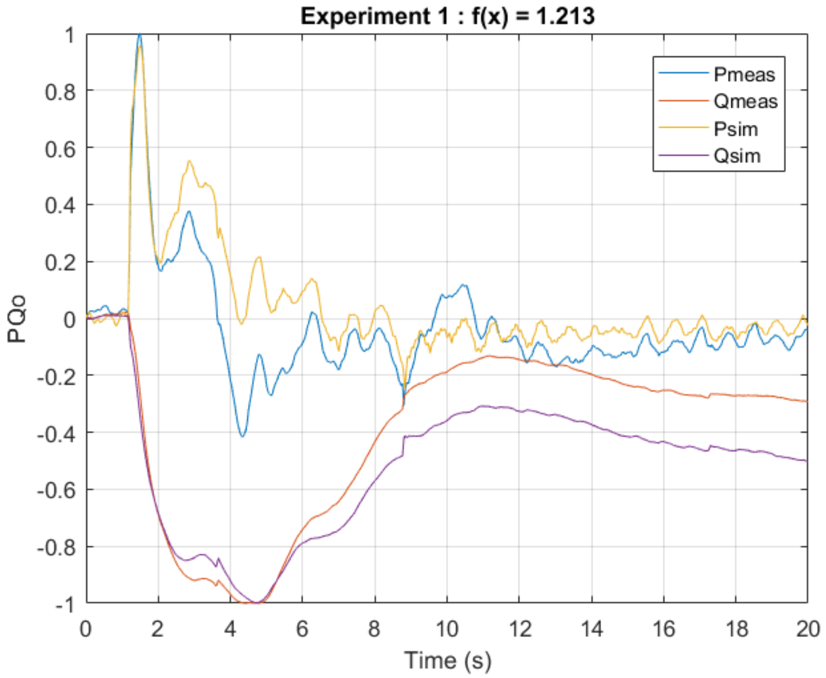
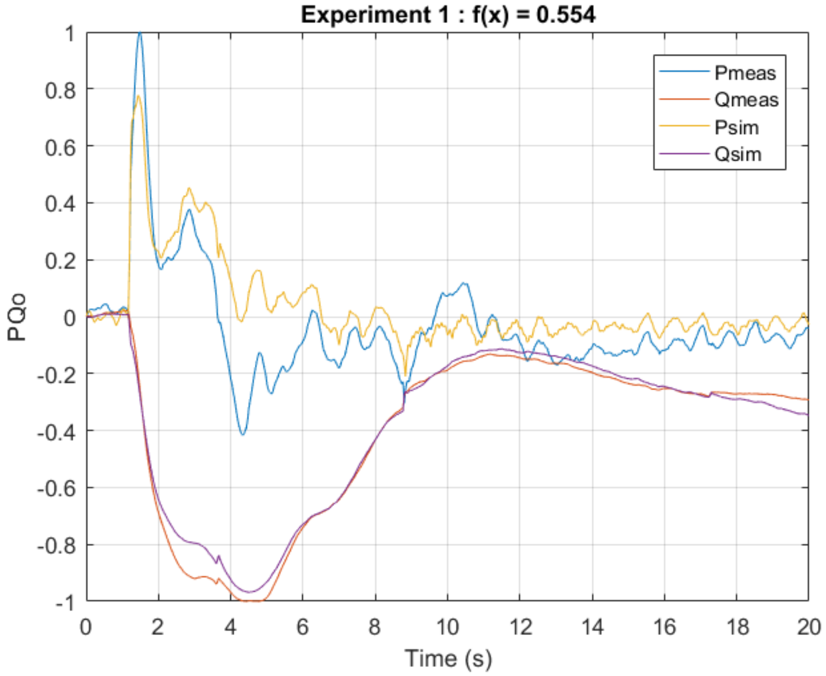


Figure 9 Normalized Responses and Sum-Squared Error With Fitted Parameters for April 6, 2017 Event



Parameter Estimation With Sensitivity Analysis

Automated sensitivity analysis could help identify whether there were parameters which were strongly correlated with the objective function. Figure 10 shows correlation for the dirty parameter values. It is shown that three of PSS and two of AVR parameters were strongly correlated. Parameter estimation with the selected parameters was performed and the results are shown in Figure 11 and fitted parameters are shown in **Table 1**. It can be seen that the result shown in Figure 11 was very close in value to the result of Figure 9 but with fewer adjusted parameters.

Figure 10 Correlation of Parameters With Objective Function for Dirty Values for April 6, 2017 Event

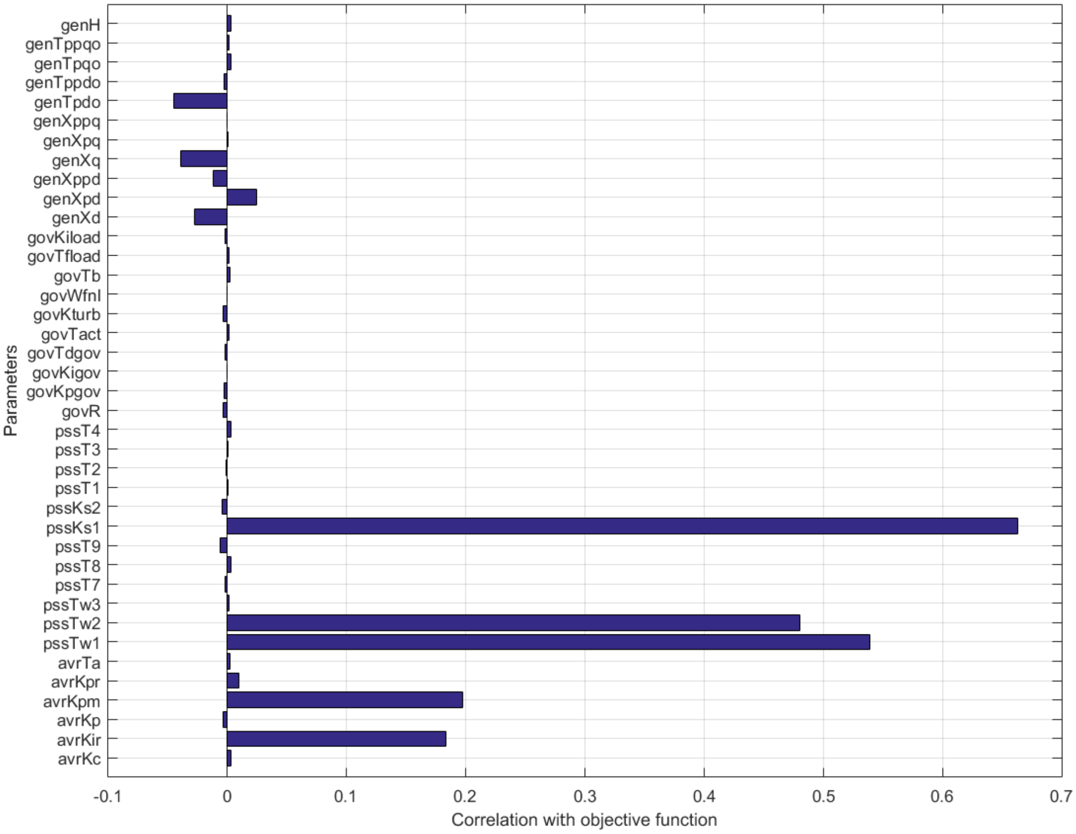


Figure 11 Normalized Responses and Sum-Squared Error With Fitted Parameters Selected Through Sensitivity Analysis for April 6, 2017 Event

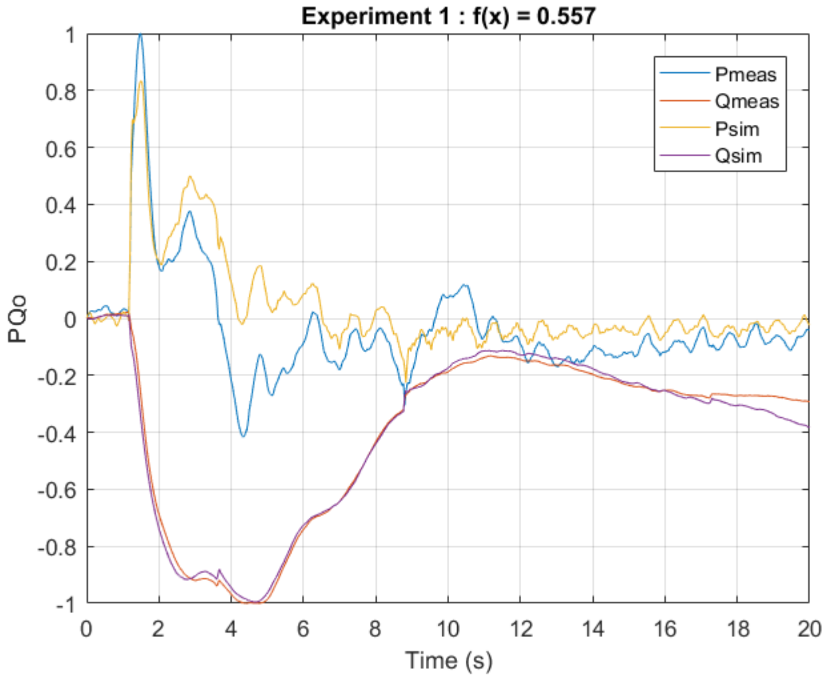


Table 1 Parameter Values and Sum-Square Error for Original, Dirty and Fitted Parameters Selected Through Sensitivity Analysis

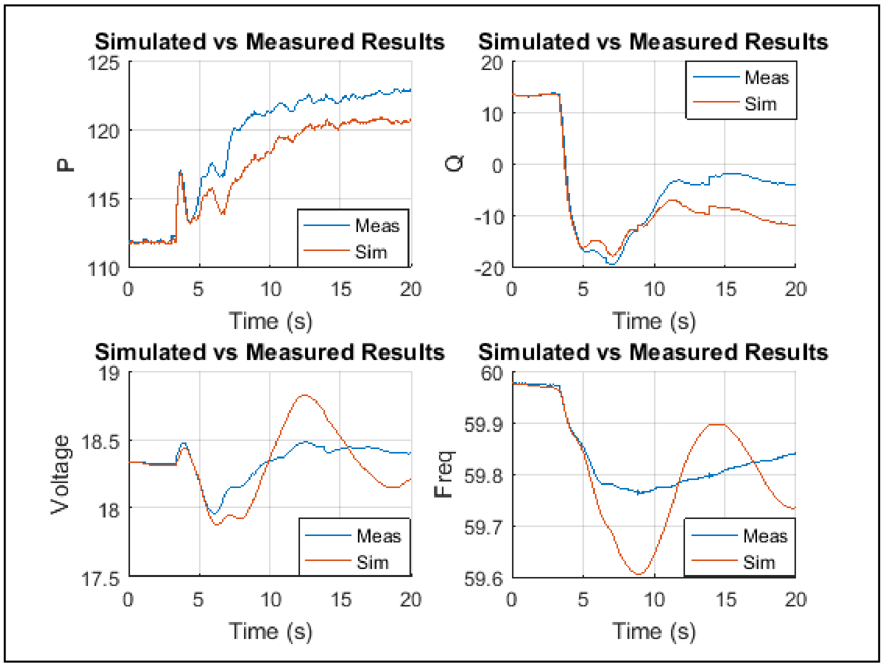
	Original	Dirty	Fitted
Parameter f(x)	0.633	75.322	0.557
pssKs1	8.0	8.0	8.205
pssTw1	4.9	5.5	4.332
pssTw2	4.9	6.25	5.315
avrKir	2.98	2.98	2.998
avrKpm	1.0	1.0	0.886

Note that PSS parameters were initially calibrated, but it was determined that for a digital control system, PSS parameter values should not be changed. For the provided dataset and the second event, VF replay was deemed to be the most appropriate replay paradigm for reasons discussed in this report. It was also demonstrated that arbitrarily selecting parameters for estimation did not provide a rigorous and traceable approach, and so engineering judgment and automated parameter sensitivity analysis provided additional insights to help the engineer arrive at the most reasonable solution.

4.4.1.2 Results for the Second Event:

For the second event, the PQVF paradigm was implemented. The measurements and original model outputs for P, Q, V and F are shown in Figure 12. It can be seen that there is a significant difference between measurement and simulated outputs. For the VF, additional dynamics exists in the simulated output.

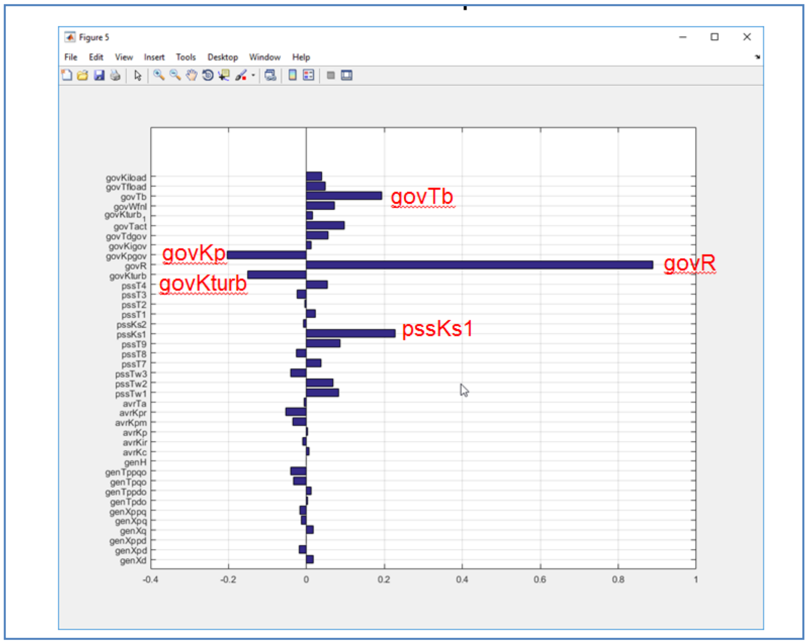
Figure 12 Measured Results With Original Parameters for June 23, 2017 Event



Sensitivity Analysis

Before implementing the parameter estimation, a sensitivity analysis was performed to find the top five most sensitive parameters for this disturbance. Four governor parameters and one PSS parameter were selected for parameter estimation, as shown in Figure 13. The PQVF paradigm was then implemented to update the five parameters.

Figure 13 Sensitivity Analysis Results for June 23, 2017 Event



Parameter Estimation

Measurements and simulated outputs after parameter estimation are shown in Figure 14. It can be seen that the simulated outputs were very close to measurements and the additional dynamics in the VF were removed.

Normalized results and sum-squared error for original and optimized parameters are shown in Figure 15.

Figure 14 Simulated vs. Measured Results With PQVF Optimized Parameters for June 23, 2017 Event

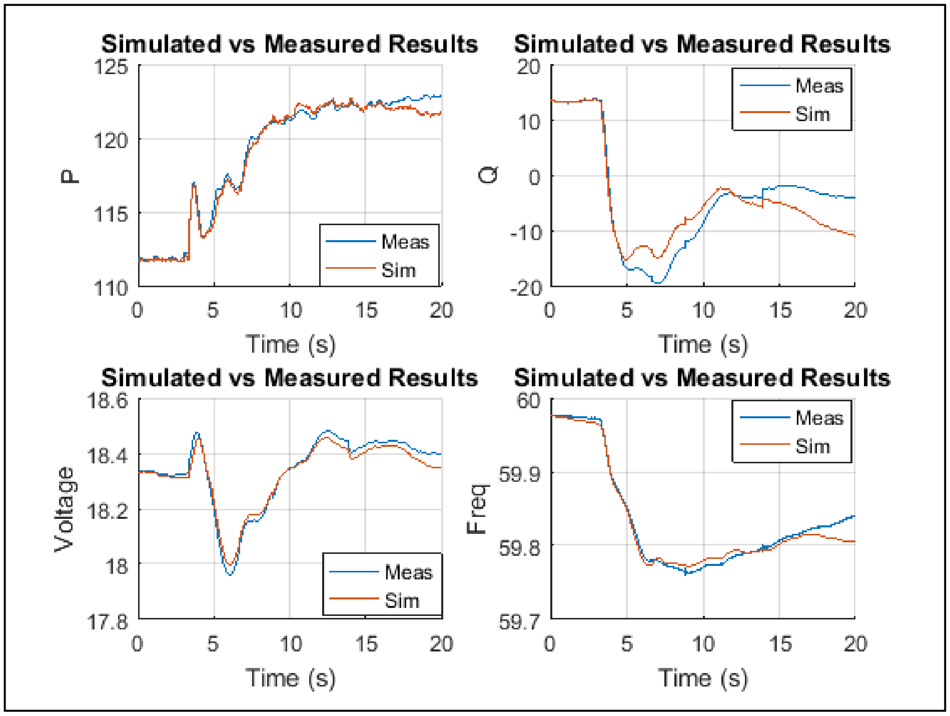
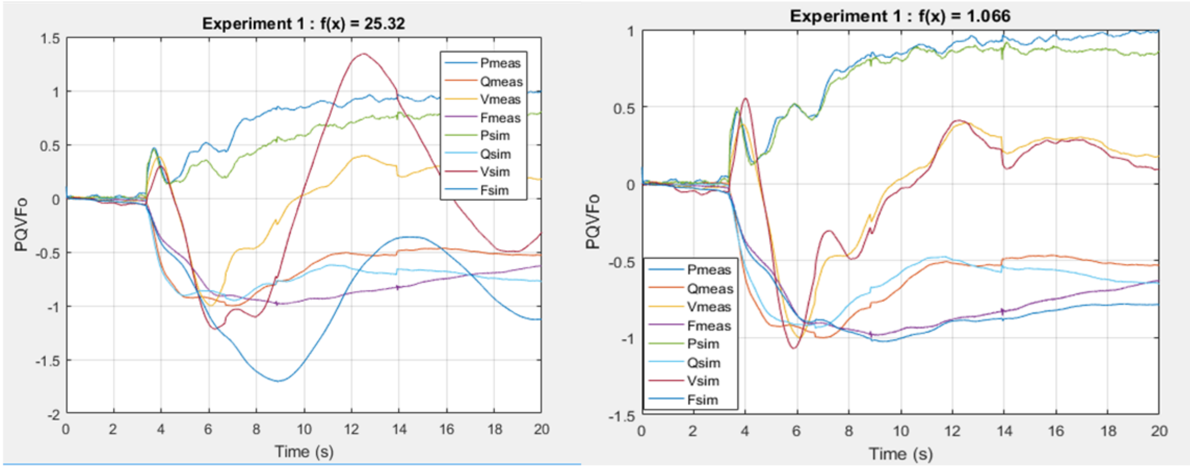


Figure 15 Normalized Responses and Sum-Squared Error With Optimized Parameters for June 23, 2017 Event



(Original parameters) (Optimized parameters)

4.4.2 Observations

This project tested the concept of using synchrophasor data for NERC-mandated dynamic parameter estimation. To develop models in the new tool, a large modeling effort was required since the existing PSLF models (proprietary) could not be directly imported into the new tool, which would help expedite this effort.

The tool helps streamlines the parameter estimation process using an automated sensitivity analysis function. However, the tool does not replace the need for engineers to review the output of the results to ensure that the model is valid against all typical grid disturbances (i.e., models fit vs. actual data). Model validation relies heavily on engineering judgement and there currently are no documented standards that specify a specific tolerance between the actual generator’s response to the disturbance.

5 Value Proposition

Primary EPIC Guiding Principles			Secondary EPIC Guiding Principles
Safety	**Reliability**	**Affordability**	**Efficient Use of Ratepayer Monies**
	✓		✓

5.1 Primary Principles

This project addressed the following two primary principles:

- *Reliability* – The project demonstrated the use of synchrophasors and associated software tools to perform parameter estimation for generator dynamic models remotely using collected disturbance data. Current processes require testing at the power plant. More accurate generator models will result in more accurate grid reliability studies. The tool and methodology tested did not conclusively demonstrate that it could be replace current test methods based on the reasons covered in section 6.2 of this report .

5.2 Secondary Principles

- *Efficient Use of Ratepayer Monies* – The collection and use of synchrophasor data, to perform NERC-mandated generator dynamic model calibration, potentially reduces the need to perform tests at the power plants. This could reduce costs and is an efficient use of ratepayer monies. As noted in the report, the cost savings was not proven sufficient to justify the cost of installing generator PMUs.

6 Accomplishments and Recommendations

6.1 Key Accomplishments

The following summarizes the key accomplishments of the project:

- Three generation plants (Colusa, Helms and Gateway) were identified with an adequate IT infrastructure for the collection of PMU data.
- A PMU system was designed, approved, procured and installed on the three generators at the Colusa Power Generating Station during a scheduled generator outage with minimum impact on the schedule for the generation maintenance work performed.
- Generator station models were developed using the new commercial software.
- Four disturbances were captured by the PMUs. Two of the disturbances were used to test the new tool for parameter estimation.

6.2 Key Recommendations

Based on the findings of this report, PG&E does not recommend installing PMUs at other generating stations for model validation purposes alone. The new model validation software developed in EPIC 2.15 did not result in a tool that is production ready and that could be used in current form for model validation purposes. In addition, the cost of PMU installation at generators was not found to be cost effective for model validation purposes.

The demonstration was a proof of concept that identified several gaps that would need to be addressed by the market before this technology could be used to support operations. These gaps include:

- Investigate methods to streamline the model validation process, for accuracy and ease of use in addition to potentially improving the process for developing generator models in the validation tool using existing PSLF models.

- The new validation tool demonstrated that it could be used to identify potential problems with model parameters, however it is not capable of assessing the accuracy of any single parameter. This added capability would provide added functionality beyond what the current PSLF modeling tools can provide.

- Traditionally Voltage (V) and Frequency (F) are played into a model and the Active Power (P) and Reactive Power (Q) response is observed and compared to measured VF to validate a model. It is also possible to reverse the inputs (play P&Q and compare to V&F measured data), which may improve model accuracy.

- The benefits of PMU data is to continually tune and refine existing models for improved accuracy for multiple events. Functionality of a tool to calibrate model parameters based on running multiple disturbance events would support improved model accuracy.

Although this project is not recommending the installation of PMUs for model validation purposes alone, additional learnings can be realized by maintaining the installation of PMUs at Colusa to provide data for post event analysis and possible future applications. PG&E will continue to evaluate new and existing tools using data from transmission disturbances. In addition, other use cases might be developed in the future which could utilize synchrophasor data from the plant.

7 Technology Transfer Plan

7.1 Investor-Owned Utility's (IOU) Technology Transfer Plans

A primary benefit of the EPIC program is the technology and knowledge sharing that occurs both internally within PG&E, and across the other IOUs, the CEC and the industry. In order to facilitate this knowledge sharing, PG&E will share the results of this project in industry workshops and through public reports published on the PG&E website. Specifically, below are information sharing forums where the results and lessons learned from this EPIC project were presented or plan to be presented:

7.2 Information Sharing Forums Held

- WECC JSIS Meeting
  Vancouver, WA, September 13, 2016
- WECC JSIS Meeting
  Salt Lake City, UT, May 23, 2017
- NASPI (North American Synchrophasor Initiative) Meeting
  Springfield, MA, September 26, 2017
- WECC JSIS Meeting
  Westminster, CA, October 10, 2017

7.3 Adaptability to other Utilities / Industry

The following findings of this project are relevant and adaptable to other utilities and the industry:

- The cost of PMU installation at generators was not found to be cost effective for model validation purposes alone.
- Synchrophasor data can theoretically improve generator model validation at other utilities, however this has yet to be demonstrated and gaps need to be addressed by the market before this technology could be used to support operations. These gaps include streamlining the model validation process, tuning models leveraging multiple disturbance events, and assessing the accuracy of any single model parameter for calibration.

8 Data Access

Upon request, PG&E will provide access to data collected that is consistent with the CPUC's data access requirements for EPIC data and results.

9 Metrics

The following metrics were identified for this project and included in PG&E's EPIC Annual Report as potential metrics to measure project benefits at full scale.[14] Given the proof of concept nature of this EPIC project, these metrics are forward looking.

D.13-11-025, Attachment 4. List of Proposed Metrics and Potential Areas of Measurement	Reference
1c. Potential energy and cost savings (Avoided procurement and generation costs)	5.1
3a. Economic benefits (Maintain / Reduce operations and maintenance costs)	4.2, 4.3
5a. Safety, Power Quality, and Reliability -Equipment, Electricity System (Outage number, frequency and duration reductions)	4.3
7b. Identification of barriers or issues resolved that prevented widespread deployment of technology or strategy (Increased use of cost-effective digital information and control technology to improve reliability, security, and efficiency of the electric grid (PU Code § 8360))	4.2

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[14] 2015 PG&E EPIC Annual Report. Feb 29, 2016. http://www.pge.com/includes/docs/pdfs/about/environment/epic/EPICAnnualReportAttachmentA.pdf.

10 Conclusion

The integration of PMUs on generators for dynamic model validation is a new technology and the installation at Colusa was the first in PG&E territory for this application. The new model validation software developed in EPIC 2.15 did not result in a tool that is production ready and that could be used in current form for model validation purposes. In addition, the cost of PMU installation at generators was not found to be cost effective for model validation purposes alone. These are the primary reasons PG&E is not currently pursuing the installation of PMUs for model validation alone at other plants.[15]

PG&E recommends that installation of PMUs at generating stations continue to be evaluated as applications evolve which could enhance generator testing or provide other reliability benefits. PG&E will continue to utilize and refine the new model validation tool to perform model validation updates at Colusa, Diablo Canyon, and possible future installations using PMU data.

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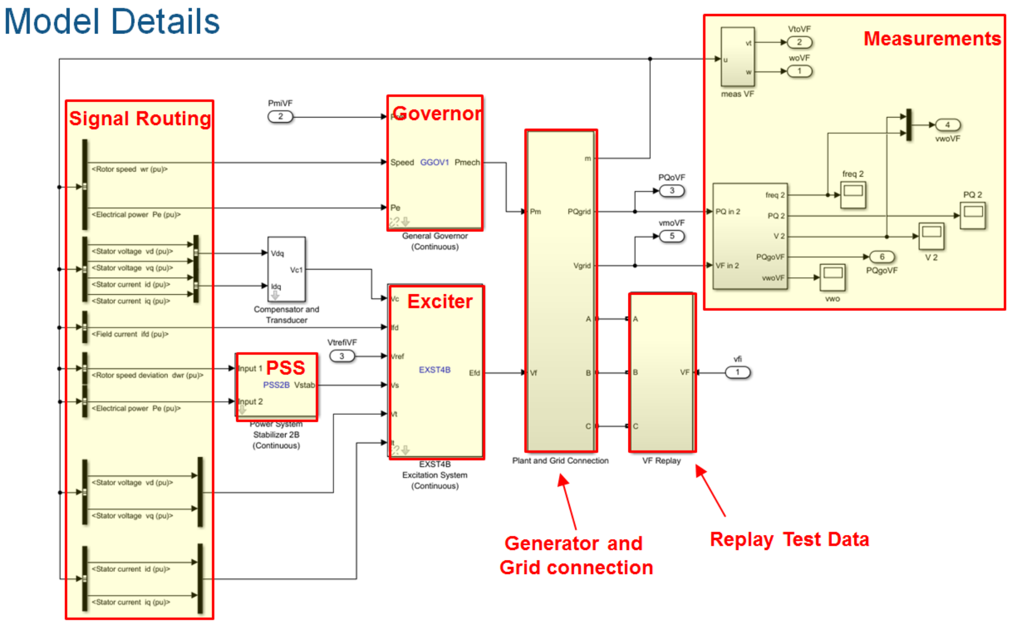
[15] PG&E’s 2020 General Rate Case (GRC) (Exhibit 5, Chapter 4) mentioned potentially installing the PMUs pending the conclusion of EPIC 2.15; which differ from the close out report’s findings. Due to the complexity, magnitude and long-lead time needed to compile the GRC, the GRC description was based on an earlier and thus more open-ended outlook for the project.

Appendix A - Generating Station Models

- COLUSGT1
  - Governor: GGOV1
  - Generator: GENTPJ
  - Exciter: EXT4B
  - Stabilizer: PSS2B
- COLUSGT2
  - Same as COLUSGT1, but with a different parameter set
- COLUSST1
  - Same as COLUSGT1, but with GGOV1 removed



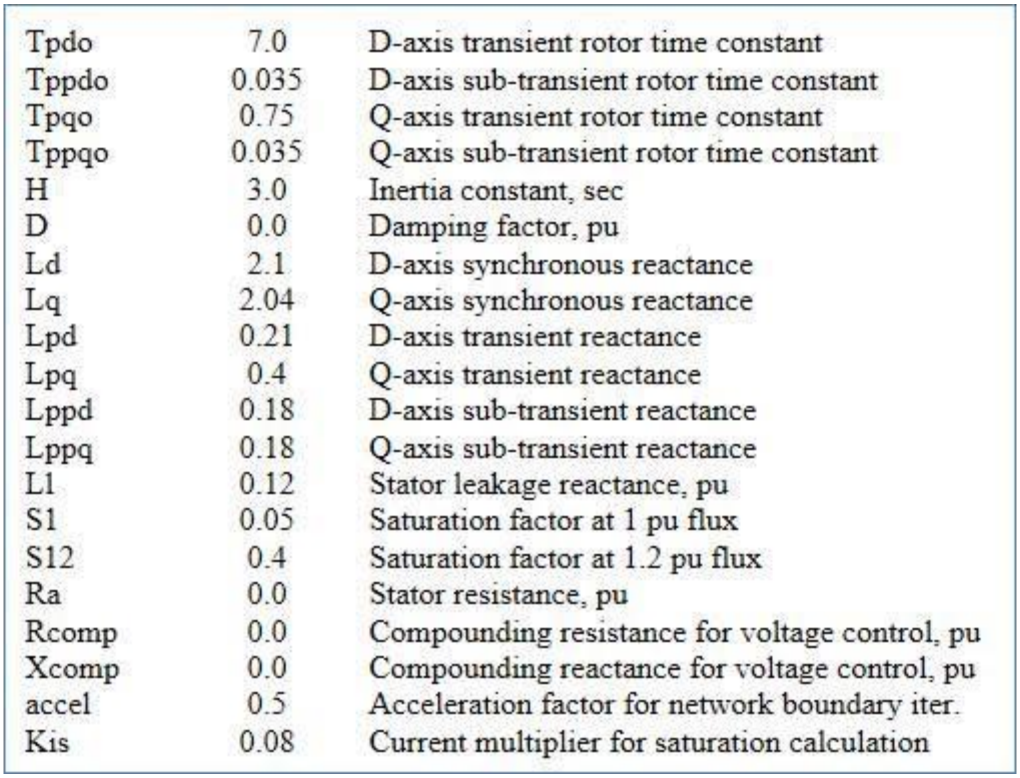
Appendix B - Data Collected and Model Parameters

1. PMU data collected

Frequency
Frequency Rate of Change
Phase A Current Magnitude
Phase A Current Angle
Phase B Current Magnitude
Phase B Current Angle
Phase C Current Magnitude
Phase C Current Angle
Line-to-Line Voltage
Positive Sequence Voltage Magnitude
Positive Sequence Voltage Angle
Positive Sequence Voltage Rate of Change
Phase A Voltage Magnitude
Phase A Voltage Angle
Phase A Voltage Rate of Change
Phase B Voltage Magnitude
Phase B Voltage Angle
Phase B Voltage Rate of Change
Phase C Voltage Magnitude
Phase C Voltage Angle
Phase C Voltage Rate of Change
Real Power
Reactive Power
Exciter Volts DC
Exciter Current DC

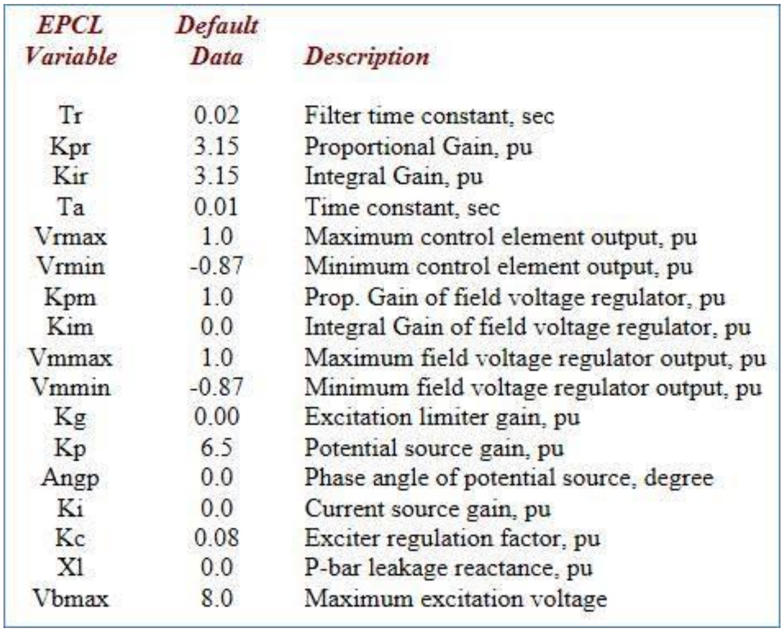
2. Default Model parameters

Generator gentpj model parameters



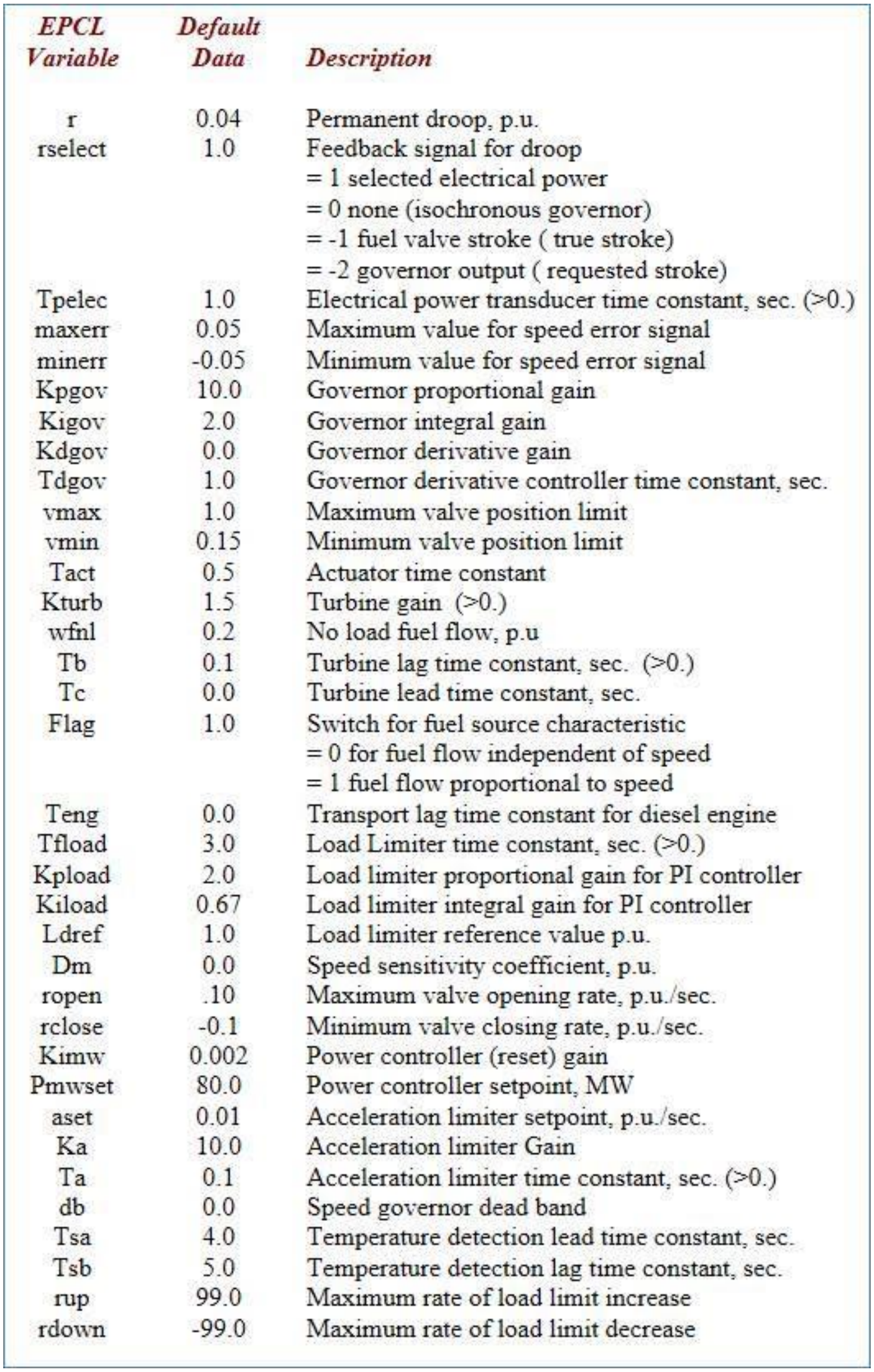
Tpdo	7.0	D-axis transient rotor time constant
Tppdo	0.035	D-axis sub-transient rotor time constant
Tpqo	0.75	Q-axis transient rotor time constant
Tppqo	0.035	Q-axis sub-transient rotor time constant
H	3.0	Inertia constant, sec
D	0.0	Damping factor, pu
Ld	2.1	D-axis synchronous reactance
Lq	2.04	Q-axis synchronous reactance
Lpd	0.21	D-axis transient reactance
Lpq	0.4	Q-axis transient reactance
Lppd	0.18	D-axis sub-transient reactance
Lppq	0.18	Q-axis sub-transient reactance
Ll	0.12	Stator leakage reactance, pu
S1	0.05	Saturation factor at 1 pu flux
S12	0.4	Saturation factor at 1.2 pu flux
Ra	0.0	Stator resistance, pu
Rcomp	0.0	Compounding resistance for voltage control, pu
Xcomp	0.0	Compounding reactance for voltage control, pu
accel	0.5	Acceleration factor for network boundary iter.
Kis	0.08	Current multiplier for saturation calculation

Exciter exst4b model parameters



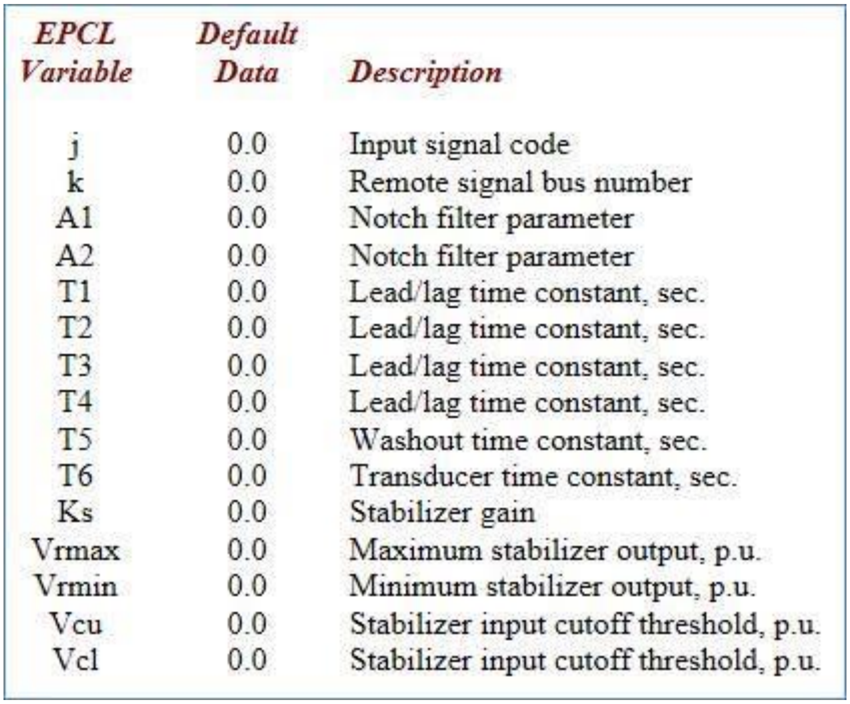
EPCL Variable	*Default Data*	*Description*
Tr	0.02	Filter time constant, sec
Kpr	3.15	Proportional Gain, pu
Kir	3.15	Integral Gain, pu
Ta	0.01	Time constant, sec
Vrmax	1.0	Maximum control element output, pu
Vrmin	-0.87	Minimum control element output, pu
Kpm	1.0	Prop. Gain of field voltage regulator, pu
Kim	0.0	Integral Gain of field voltage regulator, pu
Vmmax	1.0	Maximum field voltage regulator output, pu
Vmmin	-0.87	Minimum field voltage regulator output, pu
Kg	0.00	Excitation limiter gain, pu
Kp	6.5	Potential source gain, pu
Angp	0.0	Phase angle of potential source, degree
Ki	0.0	Current source gain, pu
Kc	0.08	Exciter regulation factor, pu
Xl	0.0	P-bar leakage reactance, pu
Vbmax	8.0	Maximum excitation voltage

Governor ggov1 model parameters



EPCL Variable	***Default Data***	***Description***
r	0.04	Permanent droop, p.u.
rselect	1.0	Feedback signal for droop = 1 selected electrical power = 0 none (isochronous governor) = -1 fuel valve stroke (true stroke) = -2 governor output (requested stroke)
Tpelec	1.0	Electrical power transducer time constant, sec. (>0.)
maxerr	0.05	Maximum value for speed error signal
minerr	-0.05	Minimum value for speed error signal
Kpgov	10.0	Governor proportional gain
Kigov	2.0	Governor integral gain
Kdgov	0.0	Governor derivative gain
Tdgov	1.0	Governor derivative controller time constant, sec.
vmax	1.0	Maximum valve position limit
vmin	0.15	Minimum valve position limit
Tact	0.5	Actuator time constant
Kturb	1.5	Turbine gain (>0.)
wfnl	0.2	No load fuel flow, p.u
Tb	0.1	Turbine lag time constant, sec. (>0.)
Tc	0.0	Turbine lead time constant, sec.
Flag	1.0	Switch for fuel source characteristic = 0 for fuel flow independent of speed = 1 fuel flow proportional to speed
Teng	0.0	Transport lag time constant for diesel engine
Tfload	3.0	Load Limiter time constant, sec. (>0.)
Kpload	2.0	Load limiter proportional gain for PI controller
Kiload	0.67	Load limiter integral gain for PI controller
Ldref	1.0	Load limiter reference value p.u.
Dm	0.0	Speed sensitivity coefficient, p.u.
ropen	.10	Maximum valve opening rate, p.u./sec.
rclose	-0.1	Minimum valve closing rate, p.u./sec.
Kimw	0.002	Power controller (reset) gain
Pmwset	80.0	Power controller setpoint, MW
aset	0.01	Acceleration limiter setpoint, p.u./sec.
Ka	10.0	Acceleration limiter Gain
Ta	0.1	Acceleration limiter time constant, sec. (>0.)
db	0.0	Speed governor dead band
Tsa	4.0	Temperature detection lead time constant, sec.
Tsb	5.0	Temperature detection lag time constant, sec.
rup	99.0	Maximum rate of load limit increase
rdown	-99.0	Maximum rate of load limit decrease

Power System Stabilizer pss1a model parameters



EPCL Variable	*Default Data*	*Description*
j	0.0	Input signal code
k	0.0	Remote signal bus number
A1	0.0	Notch filter parameter
A2	0.0	Notch filter parameter
T1	0.0	Lead/lag time constant, sec.
T2	0.0	Lead/lag time constant, sec.
T3	0.0	Lead/lag time constant, sec.
T4	0.0	Lead/lag time constant, sec.
T5	0.0	Washout time constant, sec.
T6	0.0	Transducer time constant, sec.
Ks	0.0	Stabilizer gain
Vrmax	0.0	Maximum stabilizer output, p.u.
Vrmin	0.0	Minimum stabilizer output, p.u.
Vcu	0.0	Stabilizer input cutoff threshold, p.u.
Vcl	0.0	Stabilizer input cutoff threshold, p.u.