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# Protection Modeling and Dynamic Model Validation – A Real-World Case Study for Puerto Rico

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## SUMMARY

Power system dynamic models are commonly used in the industry to simulate different events and faults that occur in the system. Precise models of protective relays are an imperative part of dynamic modeling and simulation, especially in island networks. This paper investigates the protection schemes and studies the contributions of governors during some real-world events that occurred in the Puerto Rico power system. The existing relays in the field are fully modelled in the PSS/E dynamic model using both standard library models and a user-defined model. The main focus of this paper is to simulate the system's frequency obtained from SCADA measurements following an event using accurate relay models and adjusted governor parameters such as droop and deadband.

Due to the importance of the generators on the island, the study started by providing the accurate under/over frequency relay models for the generators based on available data, the transmission and distribution system operator in Puerto Rico. For the rest of the generators without sufficient protection data, standard settings based on the requirements of the applicable regulation [9] have been utilized in the dynamic file. Apart from the generator relays, a reliable load shedding scheme can maintain the frequency of the system and maximize the load served in case of an emergency. Underfrequency relays in PSS/E are used for the load shedding scheme when the frequency or rate of change of frequency violates some settings as found in the field. The system also utilizes protection schemes that trip select line sections automatically in underfrequency conditions, but they are not available in the standard library of PSS/E. Therefore, a user-defined underfrequency line tripping (UFLT) model has been developed based on field settings to trip all the facilities between the two buses of interest.

After modeling all the existing relays, two generation tripping events are used to assess the reliability of the relay and governor models. Then the impact of different generators' dispatch on the load shedding scheme and on the governors of the in-service units is studied. We observed that there is a meaningful difference in the amount of load shedding and governor compensation in different dispatches considering the current model of governors and relays. When the reliability of the system is highly dependent on load shedding, accurate relay settings play an important role. Two different dispatches are tested with larger time delays in the relay models. Simulations revealed that the frequency becomes unstable with inaccurate relay settings for the case that is more dependent on load shedding than governor actions. Finally, the impact of changes in the governor's parameters is investigated to show the improvement in the frequency response. The purpose of the governor adjustment study highlights the importance of having accurate models for both the governors and protective relays.

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**KEYWORDS**

Generator Protection, Governor, Load Shedding, Underfrequency Relay.

## 1. Introduction

Power system protection is an important part of the reliable and safe operation of the grid. Modeling the protective relays for generators, load shedding, and transmission lines and then performing a system-wide simulation is a common practice for planning purposes. Furthermore, precise relay settings are crucial to avoid blackouts. An important lesson learned from previous industry events and blackouts is that too conservative or too generous time delays adversely affect the reliability of the power system. Therefore, standards have been created to guide planning engineers in improving their models for relay and governor settings. Additionally, the models can also be checked against the real-world device settings, but this is often an expensive undertaking in terms of cost and time. To verify the dynamic model's accuracy, it should be validated with measurements from real events. NERC mandates generator owners and utilities to adopt PRC-024-1 for generator frequency and voltage protective relay settings [1], and PRC-006-NPCC-2 for automatic underfrequency load shedding [2].

Underfrequency load shedding is a common practice to protect the system from instability by disconnecting some of the loads. This includes disconnecting blocks of load when certain frequency points are met. Due to the high penetration of renewable energy sources and lower inertia, frequency deviations are much faster. Under these circumstances, the rate of change of frequency (RoCoF) relay becomes critical. While the window between two frequency points is normally fixed in simulation tools, the authors in [3] proposed a RoCoF estimation method with a flexible window size based on the Least Squares.

Unlike similar works that used standard relay settings [4,5], this paper makes use of the real relay settings and locations. The proposed models for the existing relays are tested against different events, and the impact of the generation's dispatch on the frequency trace is also studied. Although different configurations and relay settings might be of interest, this paper focuses on the relays and their settings as they exist in the real system. In lieu of confirmed in-field governor settings, measurements from events can be used to estimate the settings with some assumptions. High resolution data from events, such as from phasor measurement units (PMU), provides excellent data to perform a thorough validation of the dynamic models [6,7]. However, the absence of PMU data in the Puerto Rico system made us to use lower resolution data from the supervisory control and data acquisition (SCADA) system. Different software tools have been utilized for dynamic simulation and testing of the protection system. For instance, the authors of [8] exploited GE PSLF for protection system dynamic simulation using generic relay models and settings. In this paper, all the simulations are performed in PSS/E. It is noted that our planning team has made several reasonable assumptions during the process due to a lack of data or other considerations. These assumptions do not limit the generality of the study and are clearly stated in different sections of the paper.

The rest of the paper is organized as follows: The protection scheme is discussed in Section 2. Details about the under/over frequency relay models for the generators, the underfrequency load shedding model of the loads, and a user-defined model for tripping the lines are all clarified in this section. Various case studies are considered in order to test the relay models and governor parameters in Section 3. Finally, section 4 concludes the paper and gives the research path for future study.

## 2. Protection Schemes

In this section, three types of frequency relays, which are utilized in the protection system in the PSS/E dynamic file, are discussed in detail. These relays are under/over frequency trip relays for the generators and underfrequency load shedding relays for the loads. A user-defined relay model is also added to strengthen the underfrequency load shedding plan elaborated in section 2. C.

### 2. A. Generator Protection

Generator protection is a critical part of the protection system. Under/Over Frequency Generator Trip Relays (FRQTPAT) relay models are commonly used in PSS/E to demonstrate the generator under/over frequency protective relays. The critical settings for the FRQTPAT relay model are the under and over frequency thresholds as well as the tripping time delay. One of the limitations which was observed during the work is that this model accepts only one over-frequency and one under-frequency setting. For more than one under frequency setting, which was the case for most generators, more than one relay model is needed to cover all the frequency points. The relay settings for roughly 35% of the generators were provided to the team. Therefore, the settings for the rest of the generators have been selected based on the standard values [9].

### 2. B. Load Shedding Scheme

Load shedding schemes are designed in a way to maintain the system's frequency in order to serve the maximum amount of load without passing the frequency threshold. If the lower frequency threshold is violated, the load shedding scheme trips feeder breakers based on the time delays and the pre-set thresholds of each relay. In this study, the LDSHBL relay model, which is an underfrequency load shedding protective relay in PSS/E has been utilized. This model has three frequency points, and there is a load shed percentage setting according to each frequency point that determines the amount of load that should be shed if the corresponding frequency point is violated. When there is a rate of change of frequency (RoCoF) setting for the relays, the DLSHBL relay type is available in the PSS/E standard model library. In addition to the LDSHBL settings, in the DLSHBL model, three rates of frequency shedding points are also available.

### 2. C. Under Frequency Line Tripping Relays

In some instances, entire taps and/or lines between the buses or substations are the targets of the load shedding. To this end, all the circuits and loads between the two ends of the desired section are disconnected after a specified time delay when the underfrequency threshold is met. To model this type of relay, a user-defined relay model, namely, the UFLT relay, has been employed. Thus, *From Bus*, *To Bus*, frequency threshold, and time delay are the necessary inputs for this model.

## 3. Simulation Results and Discussion

In this section, several case studies are considered to investigate the effectiveness of the relay models and the load shedding scheme. Also, the effect of changing the governor parameters and the deadband is studied in the last subsection. SCADA measurements with a scanning time of two seconds are used to assess the accuracy of simulation results. Before presenting the simulation results, two important remarks are brought up:

*Remark 1:* Although the relay modeling and testing are highly interconnected with the models of the governors, having precise governors' models and the corresponding parameters was not possible considering the limitations of the industry projects. So, estimating and fine-tuning the parameters of the governor through online or offline tests is out of the scope of this paper. As a result, there might be small differences between the simulations and SCADA measures.

*Remark 2:* In this study, automatic generation control (AGC) has not been modeled. It is noted that the time frame of the underfrequency relays is in the order of cycles or seconds at most. Thus, the AGC will only impact the steady-state frequency and will not impact any short-term transients or load shedding. So, inaccuracies in the settling frequency do not affect the generality of our simulations.

### 3. A. Case I: Historical Event of Two Large Generation Units Tripping

In a historic system event, two critical generation units generating 254 MW and 180 MW tripped simultaneously, totaling 434 MW of generation loss. Figs. 1 and 2 show the real power of both units in MW, respectively. The blue curves in both figures indicate the SCADA measurements, the red ones show the ideal active power of the tripped units, and the green ones are the simulated power outputs using PSS/E. Immediately after the event, the in-service units began to adjust their generation considering their governor's dead band and droop settings. Based on the simulations, a large number of in-service units responded to the generation loss through their governor actions. However, only three units had considerable governor contributions based on SCADA data. So, the governors of the rest of the units were disabled in PSS/E to mimic the reality of the event.

Fig. 3 represents the frequency trace of the system for Case I. The total generation drop in this event is 434 MW. The SCADA measurements show that only 59 MW of this loss is compensated by generation increase, implying that almost 375 MW of the generation loss is compensated by load shedding actions. The updated underfrequency relay models in PSS/E with the existing UFLT models resulted in a load shed of 248.5 MW, which is less than the MW load shed obtained from SCADA. While the total generation of the system increases by 59 MW based on the SCADA, the simulation results in an 185.4 MW increase in the total generation of the system.

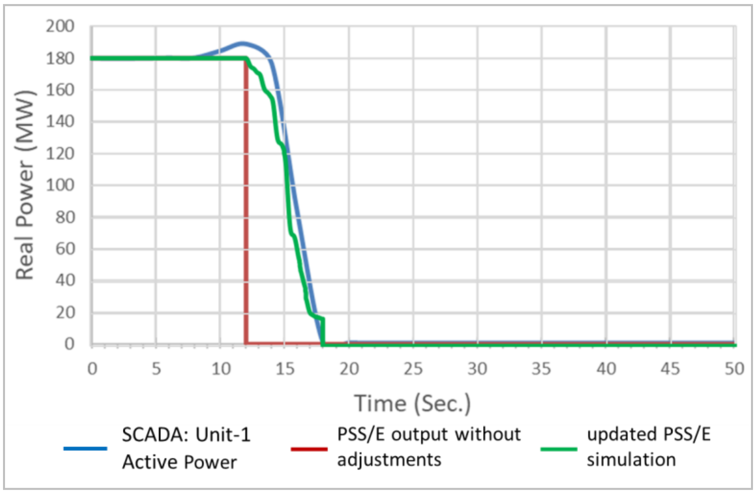


**Fig. 1. Unit 1 MW: SCADA Measurement (blue), PSS/E Simulation Instantaneous Trip Without Adjustments (red), Updated PSS/E Simulation with the Latest Relay Models (green)**

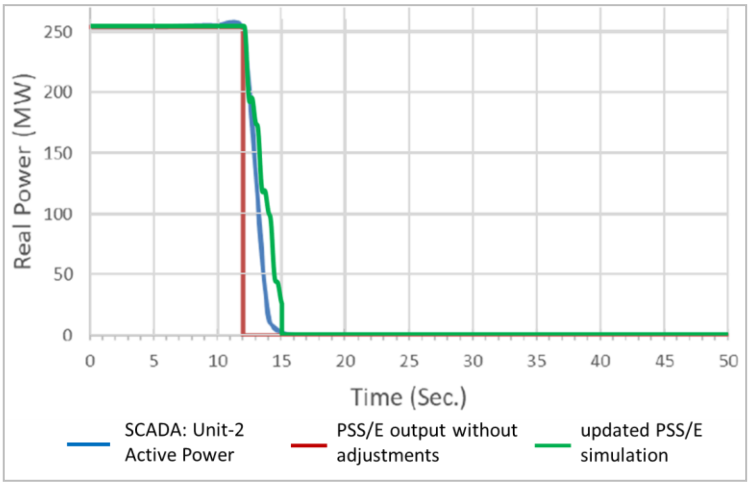


**Fig. 2. Unit 2 MW: SCADA Measurement (blue), PSS/E Simulation Instantaneous Trip Without Adjustments (red), Updated PSS/E Simulation with the Latest Relay Models (green)**

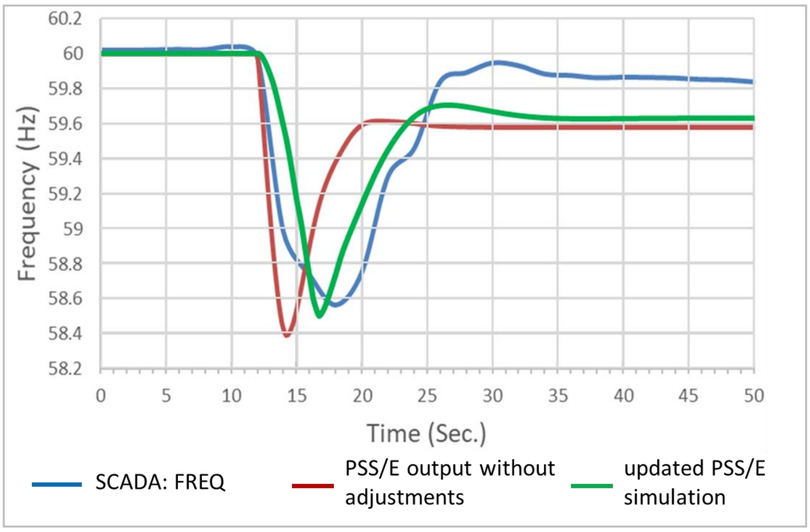


**Fig. 3. Case I Frequency Trace: SCADA Measurement (blue), PSS/E Simulation Instantaneous Trip Without Adjustments (red), Updated PSS/E Simulation with the Latest Relay Models (green)**

### 3. B. Case II: Historical Event of a Large Generation Unit Tripping

In this event, one of the critical units which was generating 300 MW, tripped. The real power of the tripped unit is shown in Fig. 4. Like in the previous case, the blue curve shows the SCADA measurements, the red one shows the ideal active power of the tripped unit, and the green one is the simulated power output using PSS/E.

Fig. 5 represents the frequency trace of the system for Case II. The total generation drop in this event is 297.9 MW. At the same time, the SCADA measurements show that only 49.6 MW of this loss is compensated by a generation increase, implying that almost 248.3 MW of the generation loss was compensated by load shedding actions. The updated underfrequency relay models in PSS/E resulted in 100 MW of load shed, which is less than the amount reported by SCADA records. While the total generation of the system increases by 49.6 MW based on SCADA, the simulation results show a 197.1 MW increase in the total generation. It is noted that matching the frequency recovery requires tuning the parameters of the active governors obtained from machine datasheets or field tests.

### 3. C. Case III: Dispatch Impact Analysis on the Frequency Stability

This section investigates the impact of a three-phase fault at a critical substation followed by the whole substation outage on the grid stability. The system is in a steady state until t = 2 sec. at which time a three-phase fault occurs at the substation. The fault remains on the bus for seven cycles until the entire substation (all voltage levels) is disconnected. This event is simulated on the latest dispatch of the system and the dispatch of Case I. Total generation and load before and after the event are shown in Fig. 6, where the left picture is related to the new dispatch and the right picture shows the same quantities for Case I dispatch. Total generation loss, active power compensated by the governors of the in-service units, and load shedding amounts are shown in Fig. 7, where the left figure is related to the new dispatch and the right one shows the same quantities for Case I. As can be seen in Fig. 6, the load drop due to the load shedding scheme is roughly 445 MW during this event for the new dispatch. As can be seen in Fig. 7, the load drop due to the load shedding scheme is roughly 445 MW during this event for the new dispatch, whereas the load shedding in Case I dispatch is roughly 913 MW. Also, the amount of power that is compensated by the governors is 351 MW and 141 MW for the new and Case I dispatch, respectively. Thus, maintaining the frequency in the Case I dispatch relies more on the load shedding scheme. The system's frequency for this phenomenon is simulated in Fig. 8. The left figure shows the frequency trace of Case I dispatch with the updated relay time delays and the right-hand side figure shows the frequency of the system when larger time delays are selected. In the latter case, frequency destabilized a few cycles after the event due to the sensitivity of the case to the load shedding scheme.

### 3. D. Case IV: Generator governor validation using SCADA measurements

Detailed generator validation requires field testing and takes significant time and effort to complete. It is not uncommon for power grid models to differ from settings in the field because detailed testing has not been conducted. Instead, a more practical approach using SCADA measurements is applied to validate machine governor parameters and build more confidence in PSS/E dynamic models. The governor validation process in this section focuses on the droop and deadband settings.

SCADA measurements are available for a third case of loss of generation. The frequency nadir reaches 59.02 Hz but does not trigger any automatic load shedding which makes it a reasonably pure generation trip event. Of the machines with recorded output during the event, only seven of them have a governor response following the loss of 175 MW.

Since the power flow snapshot used is not the same as the pre-event power flow, the case must first be validated prior to the dynamic models. First, the load and generation are scaled in the power flow case

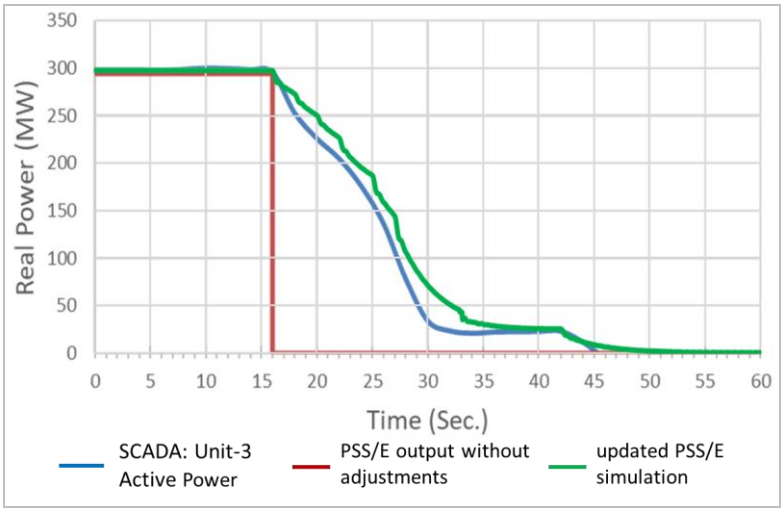


**Fig. 4. Unit 3 MW: SCADA Measurement (blue), PSS/E Simulation Instantaneous Trip Without Adjustments (red), Updated PSS/E Simulation with the Latest Relay Models (green)**

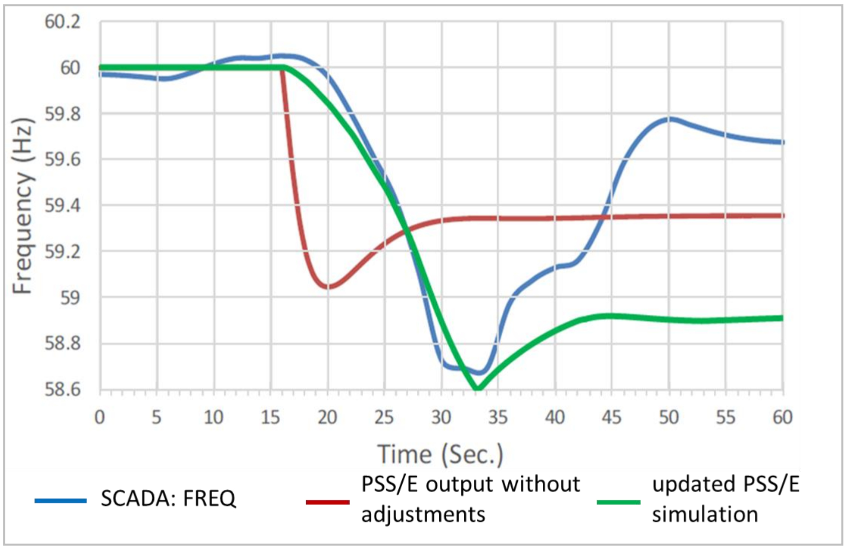


**Fig. 5. Case II Frequency Trace: SCADA Measurement (blue), PSS/E Simulation Instantaneous Trip Without Adjustments (red), Updated PSS/E Simulation with the Latest Relay Models (green)**

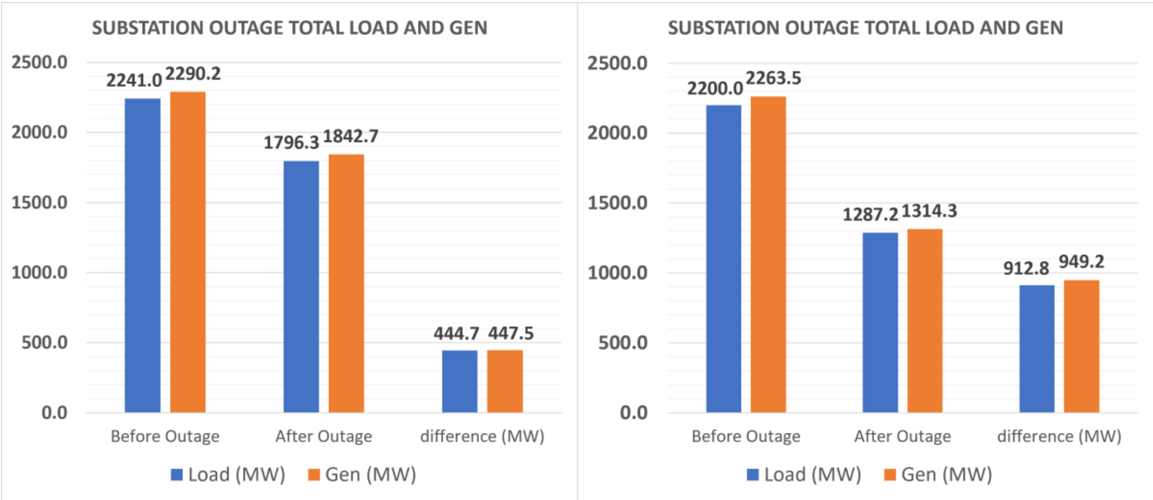


**Fig. 6. Gen and Load before/after the Substation Outage – left: Case III dispatch, right: Case I dispatch.**

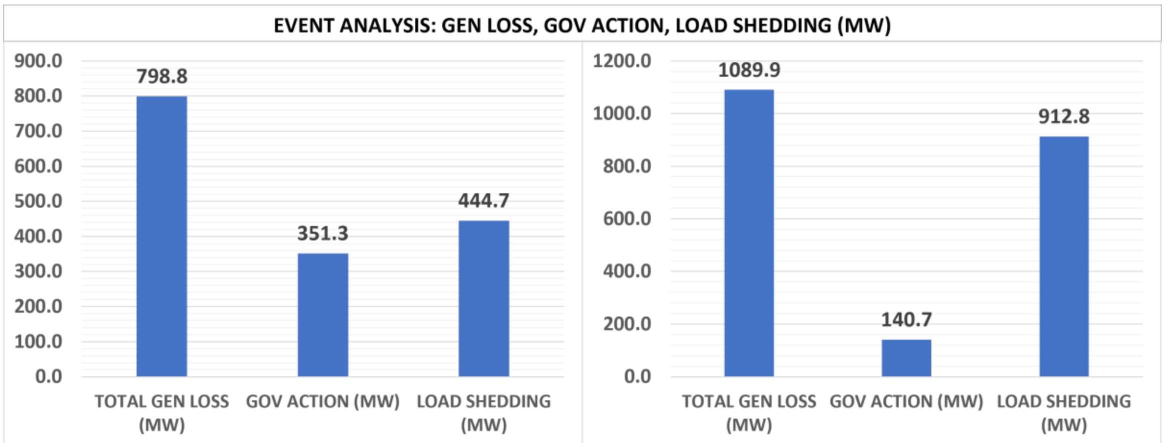


**Fig. 7. Gen Loss, Gov Action, Load Shedding Values – left: Case III dispatch, right: Case I dispatch.**

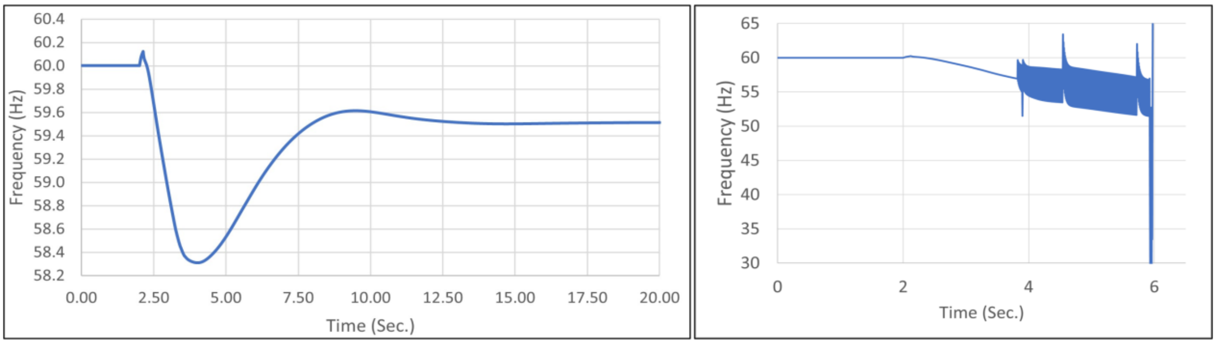


**Fig. 8. Frequency Trace – left: Case III dispatch, right: Case I dispatch.**

using a ratio of the pre-event total generation to the total generation in the power flow case. The generation ratio is used for scaling the load since the actual pre-event load is not known. Next, the generation output of all machines with SCADA measurements are adjusted and all other machines are turned off in the case. Using this method, the converged power flow differed by roughly 3 MW from the measurement at the swing bus. The active power for all machines in the converged power flow case closely matches the measurements. The reactive power of the machines is not validated since it is reliant on the accurate distribution of load throughout the system and cannot be verified with the limited data available.

After validating the power flow case, there are five machines in the base case dynamic simulation with a governor response that is not present in the measurement and whose governors are consequently disabled in the validated dynamic model. Additionally, based on the recommended settings by FERC order 842, the governor deadband is adjusted to 36 mHz for four machines whose initial deadband values are either 0 mHz or 498 mHz. This adjustment is based on SCADA measurements showing either a larger or smaller inertial response during the event. Lastly, the droop setting of one power plant is adjusted from 5% to 20% since the machine provided more support in the simulation than what is recorded in the measurement. A 20% droop is already present in the base case dynamic model of a coal power plant. It is important to note that the FERC order 842 recommends setting droop to 5%. The frequency response and a subset of generators' active power output are shown in Fig. 9 and Fig. 10, respectively. The results show a better match between the validated model and measurements for the event. Still, there is a noticeable decrease in accuracy at the swing bus in the validated dynamic case, which has no dynamic model parameters changed. The governor model parameters at the swing bus are not adjusted because there is some inherent error in the PSS/E simulation since the event frequency starts at 59.84 Hz and is offset in the figure to match the 60 Hz starting frequency of PSS/E.

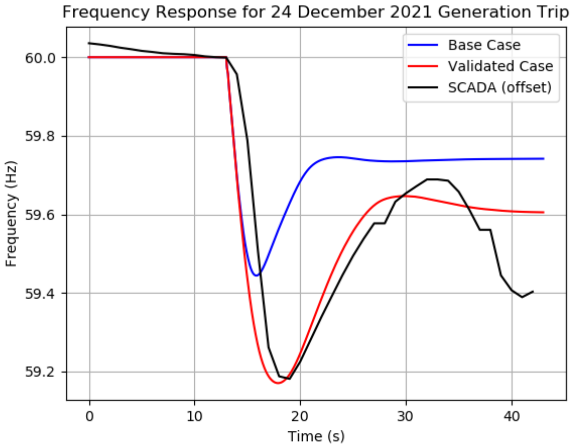


**Fig. 9. Frequency Response for the Validated Event (Case IV).**

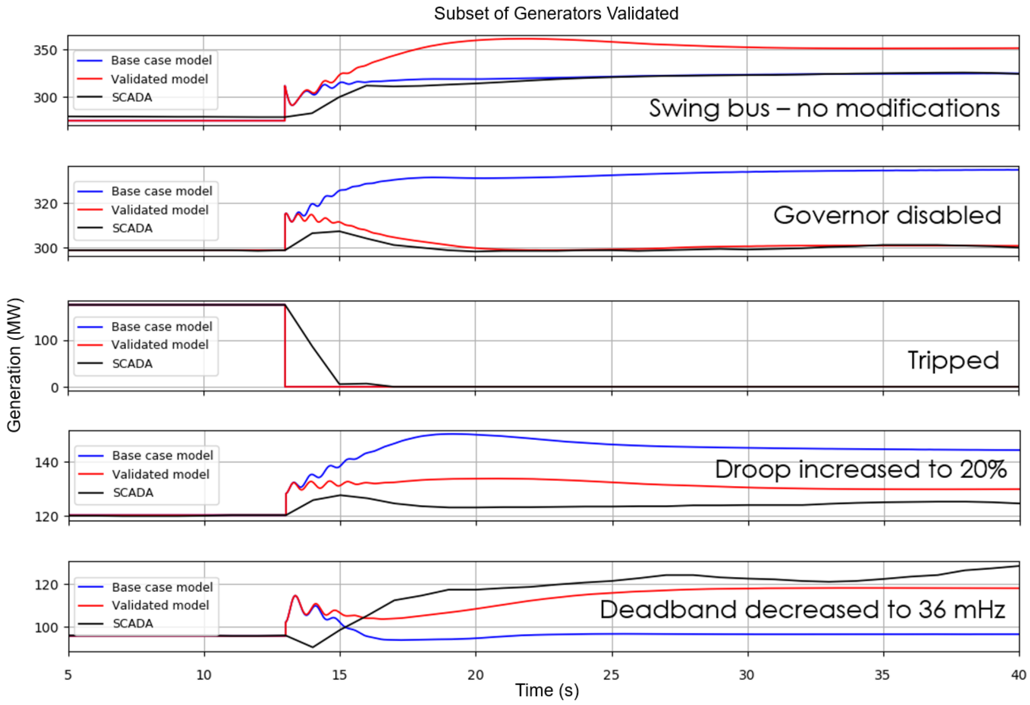


**Fig. 10. Generator Response of the Case IV Validated Event.**

## 4. Conclusion

This paper presents the industry experience related to modeling the protection relays and studying the impact of governor changes on the dynamic response. PSS/E is utilized for the dynamic simulations throughout this paper. Frequency relays are carefully modeled with respect to the actual settings in the field. Both the standard library and user-defined models are used for simulating the protection system in different conditions. Three case studies, including the loss of major generation units and a substation outage, are simulated using the latest relay models. Although there are small discrepancies between the SCADA and PSS/E simulations, the performance of the relays is satisfactory. Since governors are also critical in the dynamic simulation of the power system, the effect of governors' parameters, including droop and deadband, is also investigated as a separate case. Although some effort is made to study the impact of the droop and deadband, no attempt has been made to estimate the accurate parameters of the governor, as this needs extra field tests and effort. This work by no means is considered a complete work, and there are ideas and works which are under investigation by the team. Studying the interaction between updated dynamic models of governors and relay models is a necessary and interesting follow-up study.

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