Nontraditional Approach to Generator Measurements and Model Validation

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***Abstract*—This paper discusses a rotor angle measurement system that was installed and commissioned at San Diego Gas & Electric (SDG&E). This installation provides real-time monitoring and recording of generator rotor angle as well as field excitation quantities. Measurements of signals associated with a generator beyond the traditionally measured terminal voltage and current are receiving more attention recently due to their promise of increased insight into the operation and dynamic responses of the generating units. Mechanical measurements such as speed, vibration, shaft strain, pressure, and other physical quantities are already used for turbine protection and monitoring, but the use of mechanical quantities for generator protection has not been investigated in detail. One promising measurement, rotor angle, has historically been of limited use due to a lack of synchronization of the measurement to electrical system events. Present high sampling rate data acquisition technology allows for the highly accurate measurement of machine rotor angle, and when coupled with IEEE C37.118 for synchrophasors, such a measurement can be synchronized with other power system measurements to gain a broader understanding of the relationship between the electrical and mechanical systems.**

Measurements from generator terminals can effectively provide a powerful technique to validate the generator (mechanical or electrical) model and the combined power system stabilizer (PSS) and exciter system parameters separately. The underlying theory of an extended plant model validation technique such as this is similar to that of the plant model validation technique that has been proposed by Bonneville Power Administration (BPA) and used by Western Electricity Coordinating Council (WECC). However, new phasor measurement unit (PMU) data are providing additional capability for validating each dynamic model separately and not just the entire plant. Similarly, the rotor speed and angle measurements can be used to validate the combined governor control and mechanical model separately from the electrical part of the generator model. Because field and rotor measurements are very instrumental for the online validation of the dynamic models that are employed in the simulation, we are considering other measurements that can also validate the PSS and governor control models, independent of the exciter and the mechanical part of the generator. Accurate estimates of PSS and governor control settings will be crucial for credibility of the stability study results.

I. Introduction

San Diego Gas & Electric (SDG&E) has always been interested in improving visibility of the operation of the generation assets in their system. This has led SDG&E to begin installing monitoring equipment that can acquire time-synchronized measurements of various generator electrical and mechanical real-time data. While capturing time-synchronized synchrophasor data from power systems is not new in the industry, SDG&E was particularly interested in obtaining similarly time-synchronized data of other ancillary generator measurements. Three widely understood, yet seldom captured, measurements are rotor angle, field current, and field voltage. These three quantities and their role in the generation of electric power are well understood but are seldom integrated into traditional machine protection equipment. However, modern high-speed data acquisition and synchronized time-stamping techniques enable the integration of these data into protection and control schemes more easily than in the past. Given this access to data that was previously difficult to leverage, we are in a position to develop deeper levels of understanding of the generating units and possibly to turn from passive protection to proactive monitoring and more advanced incipient fault detection.

This paper outlines the process SDG&E followed to upgrade and install this monitoring equipment and addresses some of the challenges faced during the Real-Time Generator Monitoring project. It introduces the components being monitored, their role in the machine, and how SDG&E went about instrumenting their generating units to capture the data. In addition, initial results are presented to highlight the capabilities of the generator monitoring system that SDG&E installed. The paper concludes by discussing applications SDG&E is using today and future implementation on the remainder of the power plants in their system.

II. SDG&E System Overview and Project Needs

Fig. 1 shows the major interconnections of the SDG&E transmission system. SDG&E is connected to Southern California Edison (SCE) to the north and the Comisión Federal de Electricidad (CFE) to the south. The eastern interconnections include the Imperial Irrigation District (IID) and Arizona Public Service (APS). Palomar is one of the major generation plants in their service area.

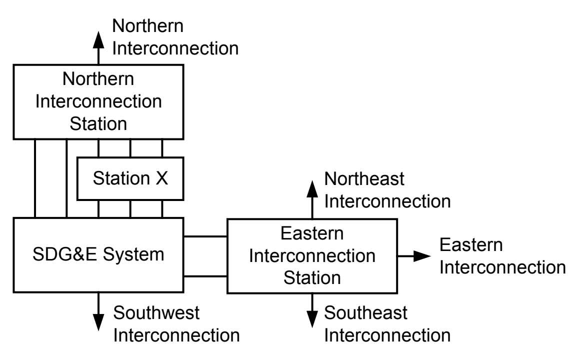

Fig. 1. Major Interconnections of the SDG&E Transmission System

North American system stability limits are changing because of the integration of renewable sources; thus, monitoring the physical parameters of the system is increasingly more important. As such, synchrophasors for monitoring generators and the electric grid are very critical for SDG&E. Some additional justifications for this project include the following research goals [1]:

- Acquiring field quantities for generator model validation.
- Analyzing the interaction of mechanical and electrical quantities.
- Estimating generator parameters [2] [3].
- Developing real-time condition assessments based on physical parameters.

Baseline models are usually required for commissioning of generators before the commercial operating date (COD). However, the North American Electric Reliability Corporation (NERC) Standards MOD-026 and MOD-027 require periodic revalidation of the plant dynamic models. This is performed by taking the units offline for generator testing, which is generally costly and risky. MOD-026 addresses the generator exciter and MOD-027 the governor control. The details of the MODs are listed in Table I and Table II [4]. The cost of missed generation opportunities and the risk of damaging equipment during testing are pushing the energy industry to look for alternative ways of revalidating the dynamic models for MOD-026 and MOD-027. Several researchers from industry and academia have been working on developing online model revalidation of generation plants that does not require taking the generating units offline. These techniques are based on measuring plant dynamic responses to system events at the generator terminal or interconnection point and comparing them with the simulated responses. The parameters of the dynamic models can be validated if the software simulation matches the field measurements reasonably well. This model validation method has minimal cost and the least impact on plant operation.

Fig. 2 shows combustion turbine plant subsystems including: the generator (block 1), the excitation system (block 2), the unit shaft dynamics (block 3), and the turbine-governor (block 4). For this study, SDG&E measured generator shaft speed, field voltage and current, and phasor measurement unit (PMU) data at the generator terminals.

During model validation, if measurement and simulation do not match, some forms of parameter identification methods must be employed. Recently, Western Electricity Coordinating Council (WECC) and Bonneville Power Administration (BPA) have been collaborating on a staged test that introduces a certain controlled bus fault to the system that helps to identify the plant model under different system loading conditions. In this technique, a brake resistor is applied at a high-voltage bus for a short time. The shock of this disturbance is harmless to the system; however, it is sufficient for identifying major dynamic modes of the machine. The details of this approach are outside of the scope of this paper and may be found elsewhere [4] [5] [6] [7].

TABLE I
WECC DEFINITIONS FOR MOD-026 AND MOD-027

Standard	MOD-026	MOD-027
System event	Voltage excursion from a measured system disturbance—size not specified, should have noticeable perturbation to terminal voltage	Frequency excursion event, with unit operating in frequency responsive mode $\Delta f \geq 0.5$ hertz
Staged event	Voltage excursion from a staged test—for example, voltage reference step test with unit online and power system stabilizer (PSS) on/off	Speed governor reference change with unit online (partial load rejection test)

TABLE II
WECC RESOURCES AND CONTROLS

Resource	Excitation Control System	Turbine/Governor Control
Synchronous machine	Includes generator, exciter, voltage regulator, impedance compensation, and PSS	Includes turbine/governor and load control
Aggregate generating plant	Includes voltage regulator and reactive power control system controlling and coordinating plant voltage and associated reactive capable resources	Includes active power/frequency control

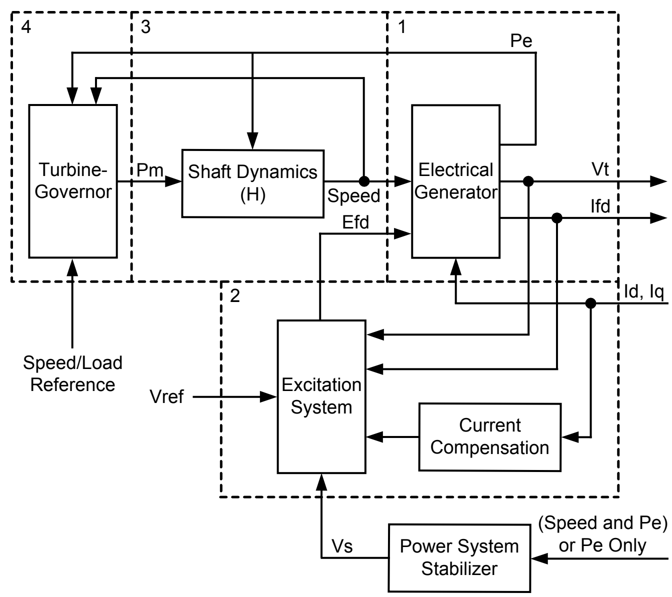

Fig. 2. Typical Generator Plant Subsystems [4]

After the 1996 disturbance, WECC mandated that owners of generators (both new and existing, synchronous and non-synchronous) with units connected to the transmission grid at 60 kilovolts or higher with single unit capacity of 10 megavolt-amperes and larger, or facilities with aggregate capacity of 20 megavolt-amperes and larger, should provide model validation reports that include exciter, governor, PSS, and voltage stabilizer responses.

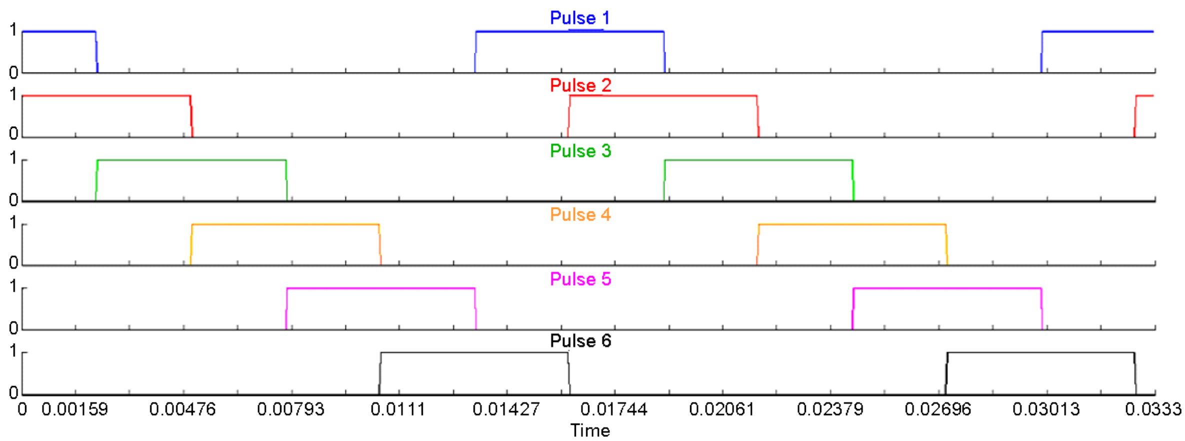

Fig. 3. SCR Gate Pulses

III. Newly Monitored Machine Values

Synchronous machines require a rotating magnetic field to induce voltage in their armature windings. For most electric power generators, this rotating field resides on the rotor and is realized through an electromagnet created by energizing a field circuit with a dc source. Thus, the field voltage and current are important quantities when considering the performance and response of the machine. The intensity of the current through the field winding dictates the strength of the magnetic field created on the rotor and is partially responsible for the strength of the magnetic coupling between the field and armature windings. The machines at the SDG&E power plant are excited by what is known as a static excitation system, where three-phase power from the machine terminals is stepped down and connected to a six-pulse rectifier bridge composed of silicon-controlled rectifiers (SCRs). The six-pulse rectifier bridge is controlled by the excitation controller to fire each SCR at a predetermined time to conduct or inhibit current flow through the SCRs to create a voltage that is dc on average. The voltage across the dc bus represents the voltage applied across the field circuit.

Textbooks explain that the voltage applied to the field is a pure dc value; however, when deciding what equipment to use to measure this quantity, it is important to understand how the rectifier bridge operates. Fig. 3 illustrates the architecture of the rectifier bridge.

An important concept to understand regarding the operation of the six-pulse rectifier is that, while synchronous machines are excited by a dc signal, the particular form of dc the field circuit experiences is likely not actual dc. Fig. 4 illustrates this concept and the waveform looks like a sawtooth wave. Simple analysis shows that the period of the waveform is 360 hertz, which is consistent with the ripple associated with a six-pulse rectifier. So, while the waveform is dc on average, when instrumenting the machine to capture this waveform, it is necessary to account for the instantaneous measurements, not just the average value.

The current signal has a similar characteristic, though it is measured through slightly different means. Where the voltage signal can, with proper isolation, be safely connected to the measurement device, the current flowing through the field winding can be several hundreds to thousands of amperes, so direct connection of measurement equipment is out of the question. Instead, most excitation systems have a small-value resistor (see Fig. 5) installed in series with the positive dc bus (see Fig. 6). The resistor is sized to produce a small voltage (typically between 50 and 150 millivolts) when the field is at full current. In this way, a device can measure a small voltage and internally scale that voltage to reproduce a digital representation of the current flowing through the winding.

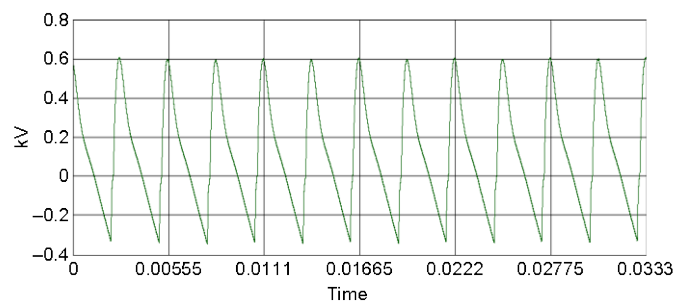

Fig. 4. Real-Time Field Voltage Measurement

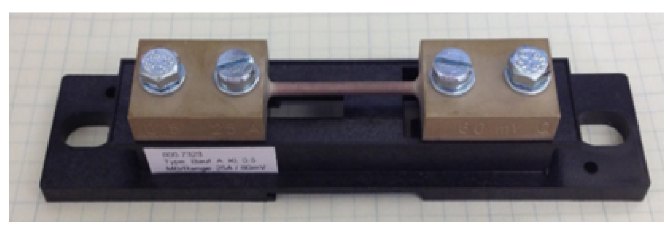

Fig. 5. Shunt Resistor

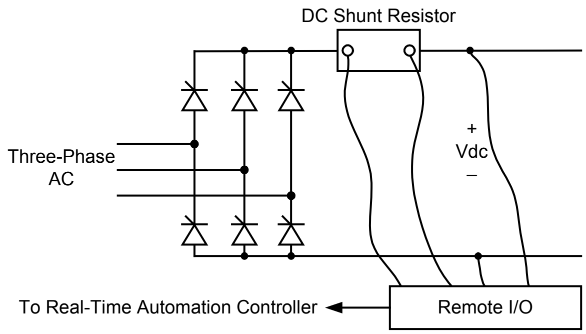

Fig. 6. Generator Field Circuit With Remote Data Acquisition

By combining rotor speed, field voltage, and field current measurements, along with the terminal voltages and currents, we can measure almost every practical electrical signal that is of consequence to the operation of the machine. This gives us—short of the damper winding currents—a complete picture of the machine while it is running and under load, during steady-state and transient conditions. Moreover, these data can be captured using precision time-stamping and included in synchrophasor data streams.

Rotor angle is the position of the rotor relative to the terminal voltage. The relative angle between these two sinusoidal varying quantities has a direct relation to the power output of the generating units. In addition, the rotor angle is necessary for the development of the mathematical model of the machine in terms of what have become known as Park's equations [8] [9]. The top illustration in Fig. 7 shows the rotor, a toothed wheel, and a notch or indentation on the shaft called a keyway. These objects rotate on a common shaft, and the toothed wheel and keyway are monitored using sensors mounted near, but not touching, the surface of the wheel and shaft, as shown in Fig. 8.

Each time the keyway passes the sensor, the sensor outputs a pulse, similar to what is illustrated in the lower plot on the right side of Fig. 11. The terminal voltage illustrated in the upper plot is used as the reference voltage. Each pulse from the keyway sensor and each positive-going zero crossing is time-stamped. Under a no-load condition, the time between the zero crossing and the keyway pulse is constant. If the keyway notch is aligned exactly with the rotor direct axis of the machine, the voltage zero crossing and the keyway pulse occur at the same point in time. However, because this is not likely, we normally see some difference between the two signals, which we document and refer to as the no-load reference angle or offset reference. As the unit is loaded, we can track the angle of the rotor pulse relative to the no-load reference angle, and this provides us with an absolute rotor angle.

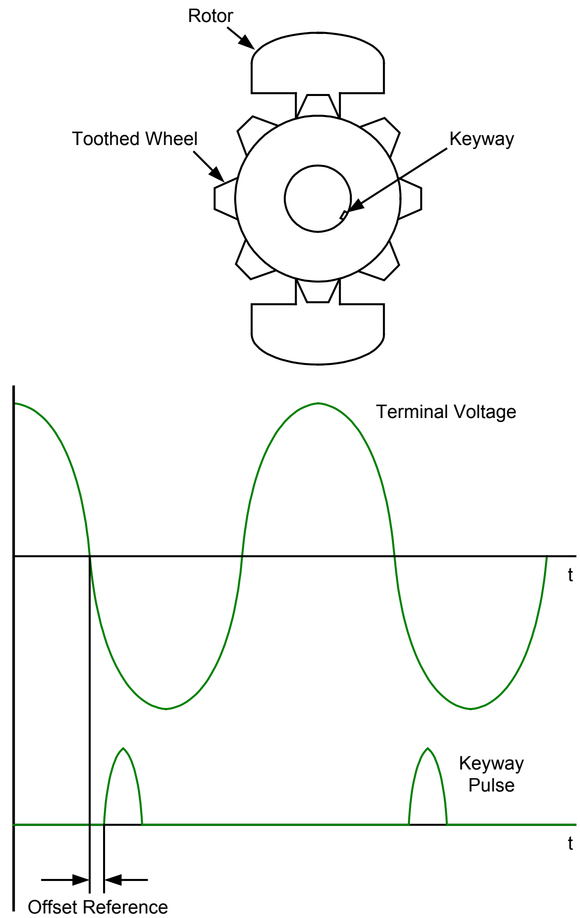

Fig. 7. Rotor and Voltage Physical Relationship

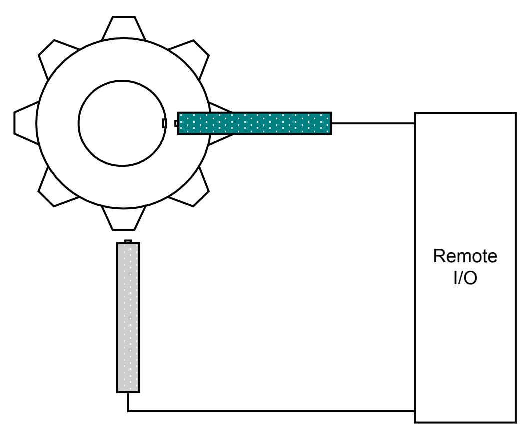

Fig. 8. Toothed Wheel Data Acquisition

IV. Monitoring Solution Architecture

With the fundamental concepts regarding the quantities that SDG&E is monitoring addressed in the previous section, we will now discuss how SDG&E implemented the hardware and software to collect these data. The solution consists of data acquisition of the field quantities, rotor angle, and terminal quantities; manipulation of these data in an automation controller provides synchrophasor data that includes collection, concentration, and storage of these data in various phasor data concentrators (PDCs).

As for the field quantities, both field current and field voltage are measured using voltage signals. The connection point for both of these signals resides within the exciter control houses.

Fig. 6 depicts a simplified portion of the machine field circuit. The field voltage is measured directly from the Vdc bus, and the field current is measured using the voltage across the dc shunt resistor. Both signals are captured using equipment that maintains proper isolation from the field circuit in the event that a fault occurs on the field. The data acquisition equipment is mounted within the excitation controller cabinet to reduce the length of the cabling needed to bring the signal to the measuring device.

The rotor angle measurement is obtained using a mechanical speed measurement. The mechanical speed of the rotor is related to the electrical speed of the machine, which is to say that under steady-state conditions, the mechanical speed and the electrical speed of the machine are equal and there is no change in the rotor angle of the machine. When the units are loaded, the mechanical and electrical systems are coupled through a magnetic interaction, which is not rigid, thus allowing some deviation in speed between the two systems. Change in the rotor angle manifests itself through this speed deviation. If one system is momentarily moving faster than the other system (e.g., the rotor is moving faster than the electrical system), this causes the rotor angle to advance relative to the electrical system (i.e., the rotor angle increases).

The multitoothed wheel is a common apparatus installed on most machines and is used by the speed governor as the feedback mechanism to control the speed of the machine. SDG&E had an additional sensor mounted and wired to a remote I/O module to detect the speed from the toothed wheel. In addition, SDG&E wired a one-pulse-per-revolution signal to the same I/O module as the multiple-pulse signal from the toothed wheel. The single pulse per revolution represents a more straightforward approach to obtaining the rotor angle because each pulse occurs exactly once every electrical cycle (in a two-pole machine). This allows for easy alignment of this pulse to the terminal voltage for direct comparison and tracking of the rotor position relative to the voltage. The multitoothed wheel requires a bit more thought and a slightly more sophisticated algorithm to determine the rotor angle [9].

Overall, the system consists of two remote I/O devices, one to capture the field voltage and current and the other to capture the mechanical speed of the unit. These two modules are connected to an automation controller using high-speed real-time Ethernet communications over a fiber-optic network. Fig. 9 shows the architecture.

These data are collected in an automation controller, converted to IEEE C37.118 format, and sent over a local-area network to a PDC. This allows any accurately time-stamped signal to be included in the data stream and collected and visualized along with other phasor data.

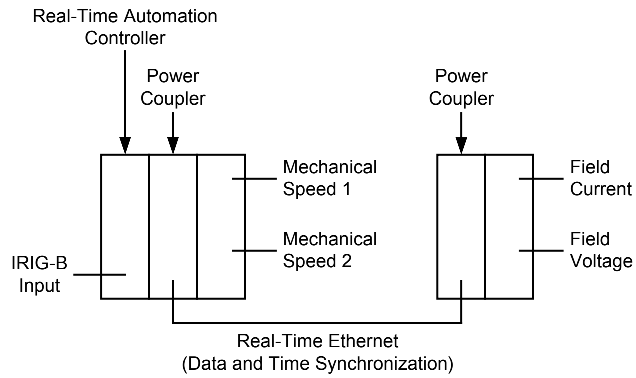

Fig. 9. Generator Monitoring System Architecture

V. Field Data and Results

The generator monitoring equipment were installed during a scheduled plant outage and was online when the machines returned to service. The initial data captures recorded the generating units as they returned to service and synchronized with the grid.

Fig. 10 shows a capture of the rotor angle and frequency of the steam unit during a synchronizing event. The upper plot shows the rotor angle of the machine, where the abscissa is time. Note that for the first half of the top capture, the rotor angle is constant. This represents the time before the generator breaker is closed; thus, the machine is unloaded (i.e., the rotor angle is zero). At the point at which the breaker is closed; there is a large uptick in the angle and then small oscillations as the rotor is brought into synchronism with the system. Note that the angle then begins to increase, which implies that the machine is being loaded.

The bottom half of Fig. 10 shows the system electrical frequency and machine electrical and mechanical frequencies. The relatively flat line in the lower half of the plot represents the system electrical frequency, while the more jagged purple line represents the machine mechanical frequency. The green line closely following the purple line is the machine electrical frequency. It is easy to see the point in time where the machine is synchronized to the grid (i.e., where the electrical and mechanical frequencies snap to the system frequency). It is interesting, albeit not surprising, that the frequencies do not immediately lock to the system frequency but oscillate a little before being pulled into synchronism. This demonstrates the concept that the electromagnetic coupling between the rotor and stator is not rigid but is more consistent with that of a spring, where any perturbation of the system causes a slight oscillatory effect between the stator and rotor.

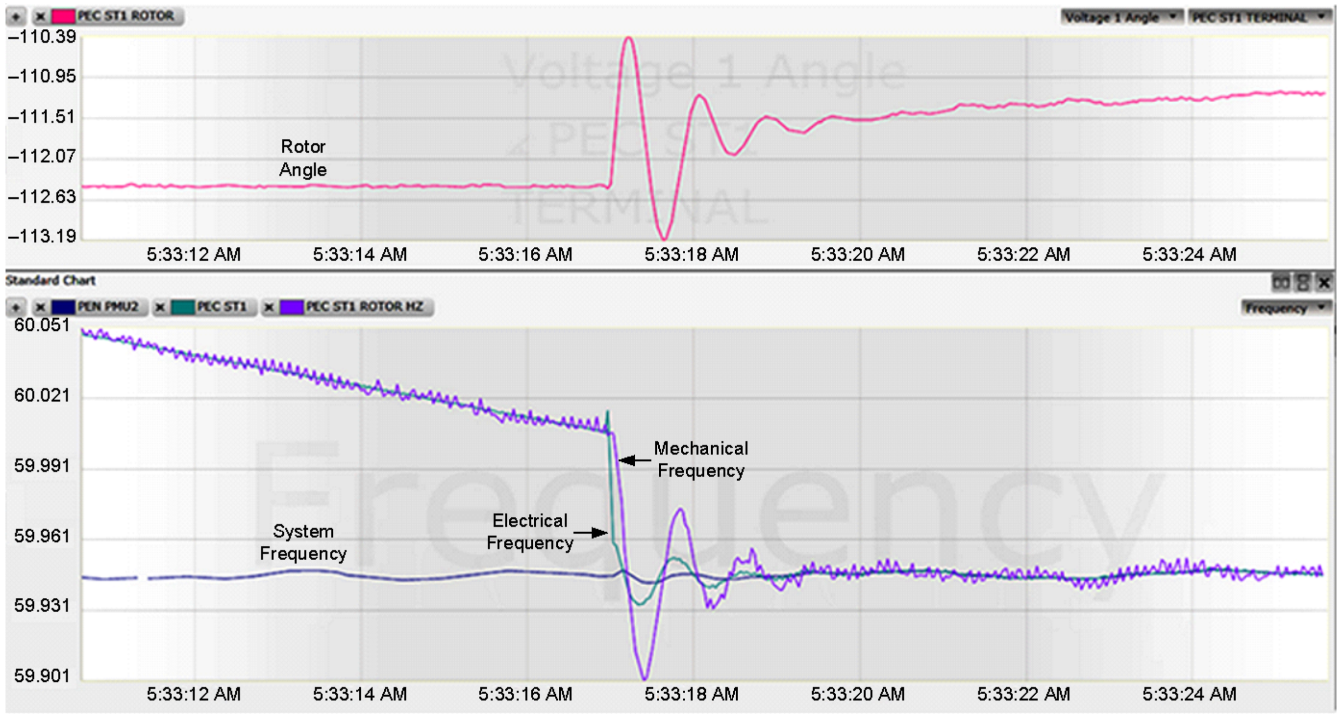

Fig. 10. Rotor Angle Capture During Synchronizing Event

SDG&E is using the disturbances in the system to verify the models meet the MOD-026 and MOD-027 requirements. As discussed under Section II, Fig. 11 and Fig. 12 show the comparison of exciter and governor response from the field data and simulation. Fig. 11 shows the exciter responses with and without PSS. Fig. 12 shows the governor responses with and without governor with different droop settings. Fig. 13 shows the frequency responses from the field measurements and simulations. These results show that field data can be used to meet the NERC and WECC requirements for model validation.

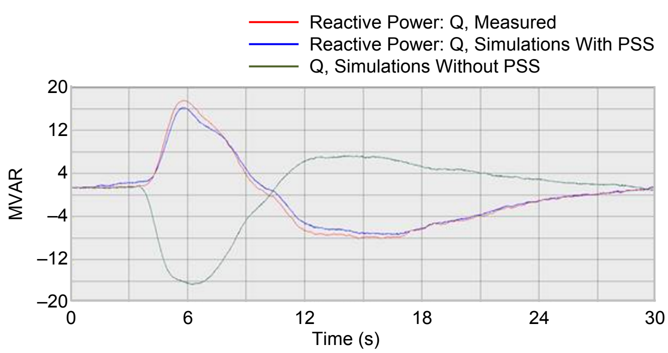

Fig. 11. Exciter Response Benchmarking

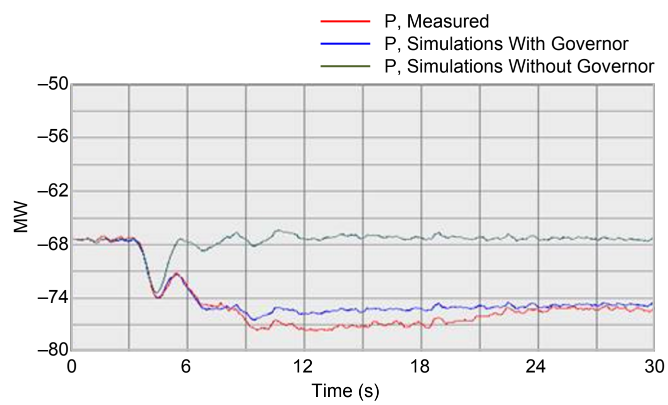

Fig. 12. Governor Response Benchmarking

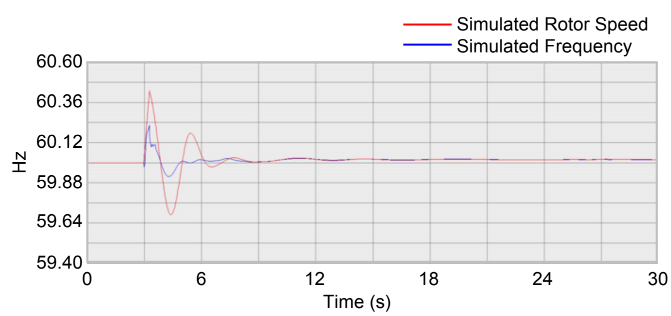

Fig. 13. Frequency Response Differences

Fig. 14 shows the startup of a typical combustion turbine generator load commutated inverter (LCI) [10]. The process begins by accelerating the LCI from turning gear to purge speed of approximately 0.3 per unit (pu) in 4.5 minutes. From purging, it goes to coast speed of approximately 0.15 pu, and subsequently the LCI accelerates the machine to a speed of 0.9 pu. The volts per hertz during the starting of the LCI is maintained at 0.8 pu or below. Fig. 15 shows the LCI results from the field. The top graph shows real power, the middle graph shows electrical and mechanical frequency, and the bottom graph shows field current and voltage. The results for the LCI start were verified using another independent system. From the results, it is easy to establish purge, coast, and acceleration to full speed. These results can be used for LCI start validation because typical protection relays cannot track frequencies below certain limits. However, calculating the rotor speed and converting into frequency enables us to monitor frequencies even during the purge and coast stages.

It is clear from Fig. 15 that the speed increases to 14.15 hertz during purge, which is 14.15/60 = ~0.24 pu speed for this machine. If multiple LCI starts show any drift, we can use this information for additional analysis and troubleshooting. Typical LCI protection includes volts per hertz and overcurrent.

It may be possible to add additional monitoring for LCI protection using nontraditional measurements as mentioned previously. These results show that additional data (i.e., field current and voltage) can be used for model validation and additional protection and machine parameters.

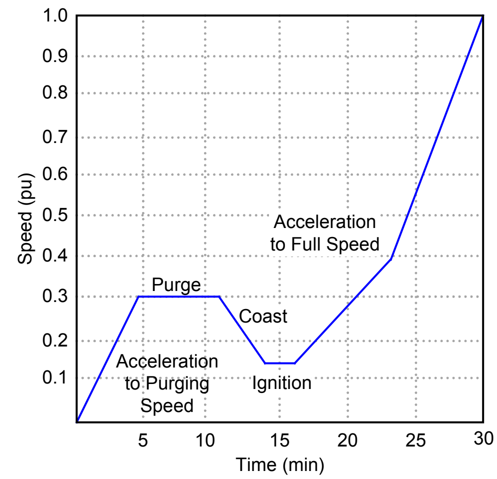

Fig. 14. LCI Start Results Standard

Fig. 15. Starting Curve for LCI Start

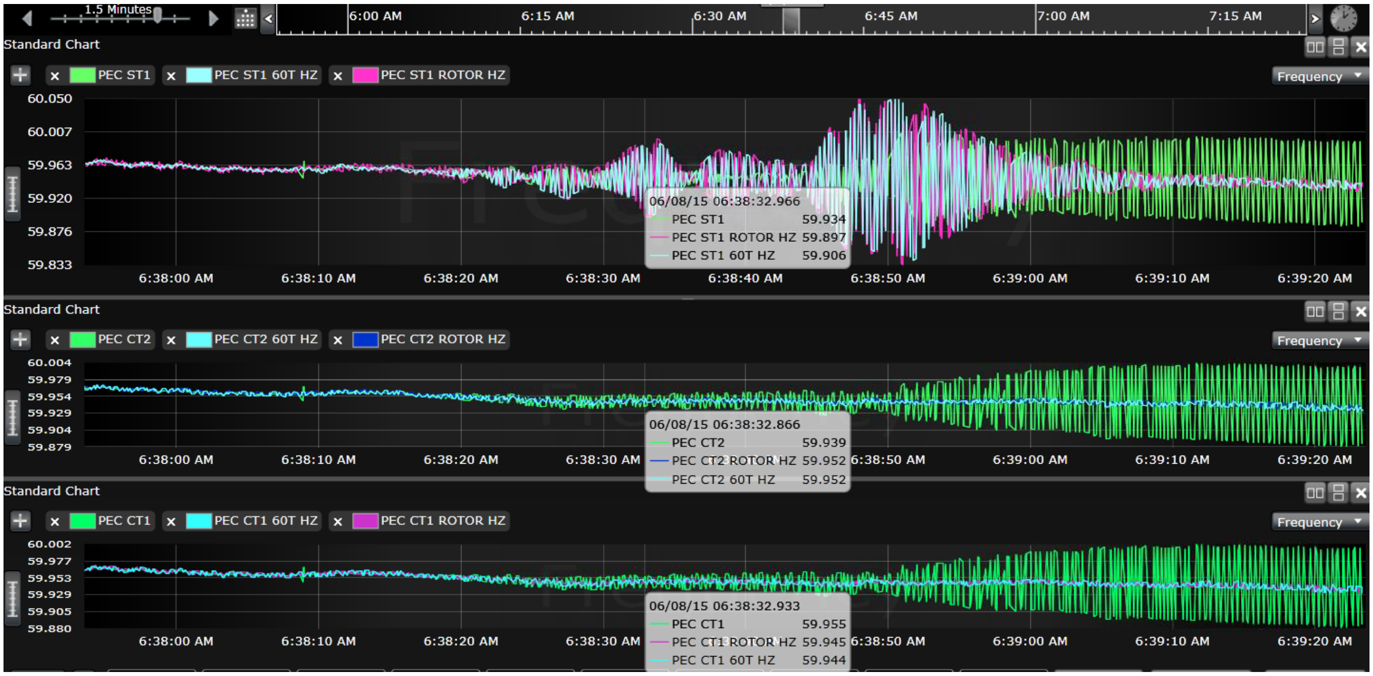

Fig. 16. Mechanical Oscillations System Disturbance

Fig. 17. Voltage Oscillations System Disturbance

Fig. 16 and Fig. 17 show electrical and mechanical frequency for the three generating units for an external event in the SDG&E system. The steam unit first experienced some mechanical oscillations for the disturbance nearby. Subsequently, the oscillations appear in the terminal electrical measurements, including terminal voltage and frequency for all three units. It was determined that the steam turbine had some mechanical oscillation, which may be due to the units' multi-mass system. The oscillation frequency for the electrical quantities is approximately 11 hertz. Some of the information from this pilot project can be used for investigating the subsynchronous resonance and mechanical oscillations.

VI. Conclusion

As discussed in Section V, the proposed solution to measure field current, voltage, and rotor angle can be applied for model validation to meet WECC requirements for MOD-026 and MOD-027 validation. WECC and NERC mandate using disturbance of significant magnitude, which may be selected for MOD-026 and MOD-027 validation (see Table I). SDG&E is using these data to fine tune the machine model including PSS, exciter, and governor.

SDG&E is also investigating new ways of using the field quantities and rotor angle measurements. Section V discusses the application for an LCI start for gas turbine and oscillation monitoring on the machines for various system disturbances. SDG&E also anticipates that generator mechanical and field quantities can be integrated into existing relays to provide additional elements for generator protection [11].

VII. Acknowledgments

The authors gratefully acknowledge the contributions of Nic Seeley and Joe Casebolt of Schweitzer Engineering Laboratories, Inc. during various stages of this project and paper.

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IX. Biographies

Tariq Rahman is a principal engineer in the Electrical Transmission and Distribution Engineering Department at San Diego Gas & Electric (SDG&E). Prior to joining SDG&E, Tariq worked with Long Island Lighting Company in New York and the Sunflower Electric Power Corporation in Garden City, Kansas. He obtained his B.S.E.E. in 1980 and his M.S.E.E. in 1985. Tariq has 30 years of experience working in the electric utility industry. During this time, he has worked in electric operations, generation planning, and system protection and control engineering. In addition to his system protection engineering functions, he is leading the Transmission Synchrophasor Project at SDG&E. He is a licensed professional engineer in the states of New York and California and is a member of IEEE.

Hassan Ghoudjehbaklou (IEEE SM'91) received his B.Sc. in Mathematics, graduating as valedictorian of his class, from Tehran University, and received his M.Sc. in Information and Computer Science, M.Sc. and Ph.D. in Electrical Engineering from Georgia Institute of Technology. He joined Harris Corporation, Controls Division in Melbourne, Florida, after graduation, working on security constrained dispatch and optimal power flow. Later, he joined Isfahan University of Technology, Iran, teaching and researching different applications of artificial intelligence and optimization in power systems. He supervised many master and several Ph.D. dissertation theses. Hassan spent his sabbatical leaves with University of Toronto and University of Calgary, Canada, working on different applications of fuzzy logic, neural networks, and expert systems in power systems. He also worked on modeling of arc-furnaces for voltage stability and simulation studies. In 2001, he joined Open Systems International, Inc. (OSI), in Minneapolis, Minnesota, working on the development of advanced power systems applications for different energy management and distribution management systems. These applications included power flow, state estimator, optimal power flow, unit commitment, and operator training simulator. He later served for several years as the technical manager of the power systems development team at OSI. Since 2010, Hassan has been with San Diego Gas & Electric (SDG&E), working with the transmission planning and generation interconnection group, involved in NERC/FERC reliability studies of the future CAISO/SDG&E renewable projects. Hassan's recent interests include smart grid, energy storage systems, and dynamic model validation using phasor measurement unit data. Hassan has also been a certified professional engineer in the state of California since 2011.

Isaac West received his B.S.E.E. in 2011 and M.S.E.E. in 2013 from Montana Tech in Butte, Montana. He has been a power engineer at Schweitzer Engineering Laboratories, Inc. since 2013, working in the control and monitoring group in research and development.

Kamal Garg received his M.S.E.E. from Florida International University and India Institute of Technology, Roorkee, India, and his B.S.E.E. from Kamla Nehru Institute of Technology, Avadh University, India. Kamal worked for POWERGRID India and Black & Veatch for several years at various positions before joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2006. Presently, he is a senior protection engineer at SEL Engineering Services, Inc. Kamal has experience in protection system design, system planning, substation design, operation, remedial action schemes, synchrophasors, testing, and maintenance. Kamal is a licensed professional engineer in the United States and Canada.

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