

Capturing Generator Rotor Angle and Field Quantities – SDG&E Experience and Approach to Using Nontraditional Generator Measurements

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Capturing Generator Rotor Angle and Field Quantities – SDG&E Experience and Approach to Using Nontraditional Generator Measurements

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Abstract—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 of the machine and electrical system during transient conditions. 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 data acquisition technology allows for the highly accurate measurement of machine rotor angle, and when coupled with IEEE C37.118 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. In addition, taking time-synchronized measurements of the field voltage and current allows us to gain greater insight into the operation of the machine and has implications beyond traditional generator protection. Such measurements bring greater insight into mechanical transients occurring within the machine during electrical system events and can provide us with a deeper practical understanding of the electromechanical relationship between the generator and the power system.

This paper discusses a first-hand experience with the installation and commissioning of a rotor angle measurement system installed on the generators in a 740 MVA combined cycle plant. This installation provides real-time monitoring and recording of the generator rotor angle as well as field excitation quantities. This paper discusses the lessons learned and possible applications using these measurements.

I. INTRODUCTION

Over the past two years, San Diego Gas & Electric (SDG&E) has been involved in an effort to improve visibility into the operation of the generation assets in their system. This has led them to begin installing monitoring equipment that can acquire and time-synchronize various generator electrical and mechanical data. While the capturing of time-synchronized synchrophasor data is nothing new to the industry, SDG&E was 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, yet they are seldom integrated with traditional machine protection equipment. However, modern data

acquisition and synchronized time-stamping techniques allow us to integrate these data into protection and control schemes much more easily than before. Given this access to data that was previously difficult to leverage, we are in a position to develop deeper levels of understanding of our machines and possibly turn from reactive protection to proactive monitoring and incipient fault detection.

This paper discusses the process SDG&E followed to upgrade and install this monitoring equipment and some of the challenges and opportunities confronted during the project. It introduces the components being monitored, their role in the machine, and how SDG&E went about instrumenting their machines to capture the data. In addition, initial results are presented to highlight the capabilities of the generator monitoring system SDG&E installed. The paper finishes by discussing applications SDG&E is considering for future implementation on the rest of the machines in their system.

II. SDG&E SYSTEM OVERVIEW AND PROJECT NEEDS

Fig. 1 shows a high-level overview and one-line diagram of the SDG&E system.

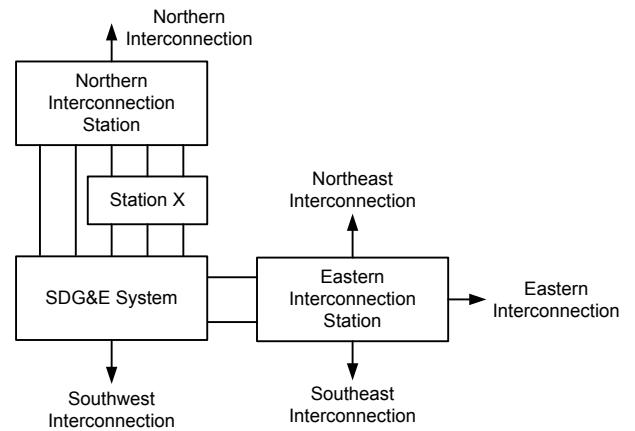


Fig. 1. Major Transmission Lines and Interconnections

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 the area. System stability limits are changing due to the integration of renewable sources, thus,

monitoring the physical parameters of the system is more important. As such, synchrophasors and generation monitoring 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].
- Continuous condition assessment.
- Developing real-time condition assessments based on physical parameters.

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 voltage across and current through the field circuit 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. It seems intuitive then, given the relative importance of the field voltage and current in regards to their role in the function of the machine, that monitoring these field quantities can provide value to engineers and operators.

These data are collected and archived using the same system that archives SDG&E synchrophasor data: a system-wide phasor data concentrator (PDC) known as the Central PDC. SDG&E has local PDC archiving at the plant level in addition to the Central PDC. Such a system allows the plant-level PDC to capture data at higher rates and pass lower-rate data to the Central PDC for long-term archiving.

Capturing the field quantities at the SDG&E power plant posed some interesting challenges, but overall proved to be relatively easy to accomplish. As described previously, the field windings of synchronous machines are excited by a dc

quantity. 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 in order to create a voltage that is dc on average. The voltage across the dc bus represents the voltage applied across the field circuit.

While textbooks teach us that the voltage applied to the field is a pure dc value, when deciding what equipment to use to measure this quantity, it is important to understand how the rectifier bridge operates. Fig. 2 illustrates the architecture of the rectifier bridge.

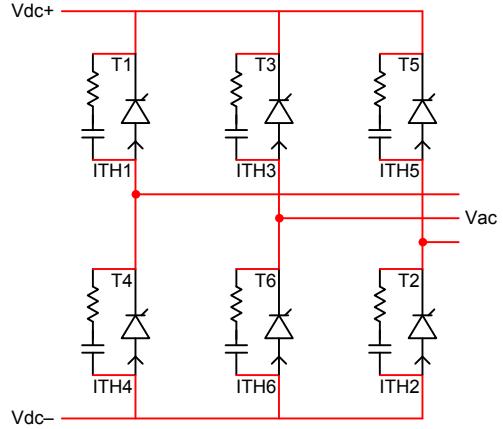


Fig. 2. Six-Pulse Rectifier Bridge

Each phase of a three-phase ac voltage is connected at the midpoint of a branch in the rectifier bridge. Each branch is connected in parallel, where the potential between the top and bottom of the branch represents the voltage for the dc bus. The SCRs permit or inhibit the flow of current based on a gating signal. The operational theory behind the gating signal is beyond the scope of this paper; however, the plot in Fig. 3 illustrates when and in which order the pulses are fired. In general, when the bridge circuit is laid out as shown in Fig. 2, the firing order is simply in numerical order (i.e., T1, T2, T3, T4, T5, T6, T1, T2, and so on).

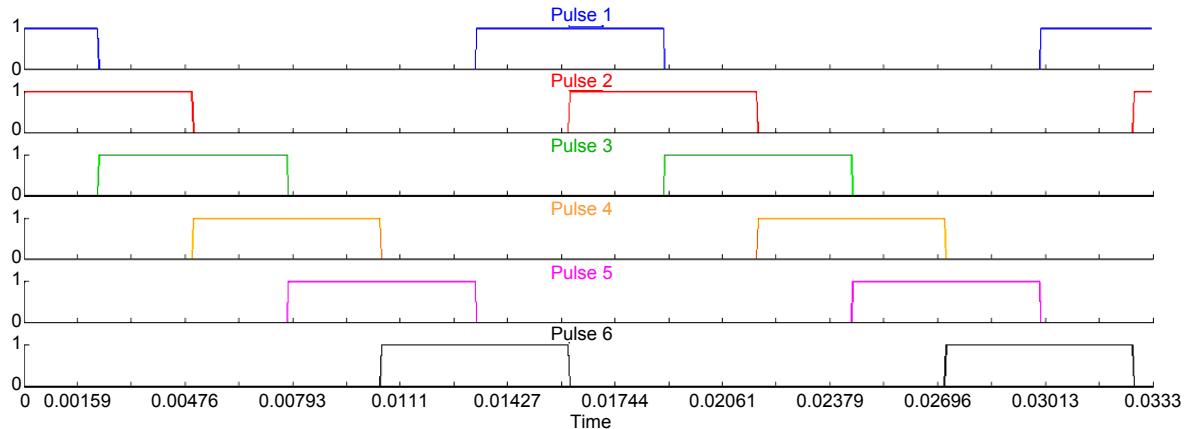


Fig. 3. SCR Gate Pulses

As is apparent in Fig. 3, the pulses overlap, with two SCRs conducting at all times. This makes intuitive sense considering that two SCRs must be conducting in order to have a complete circuit between the dc buses. The overarching philosophical premise of the six-pulse rectifier bridge is that, because we are starting with three-phase ac, we can control the switching of each phase so that the resulting signal on the dc bus is dc on average.

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 sees is likely not actual dc. Fig. 4 illustrates this concept. While we would normally expect and envision the voltage of a dc circuit to appear mostly flat and constant over time, the waveform in Fig. 4 looks like a sawtooth waveform. Simple analysis tells us that the period of the waveform is 360 Hz, 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 we need to account for the instantaneous measurements, not just the average value. Suffice it to say, when choosing data acquisition equipment, it is critical to understand what the signal being acquired looks like and how it behaves.

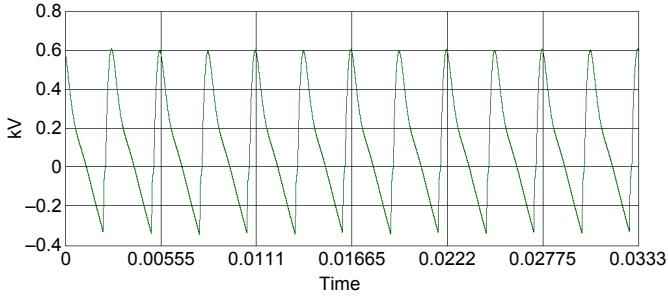


Fig. 4. Field Voltage Oscillograph

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 (as shown in Fig. 5) installed in series with the positive dc bus (as shown in Fig. 6). The resistor is sized to produce a small voltage (typically between 50 and 150 mV) 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.

By combining the field voltage and field current measurements, along with the terminal voltages and currents, we measure 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 so the data are time-aligned to all other synchrophasor system data. Details on the architecture of such a system are described later in the paper.



Fig. 5. Shunt Resistor

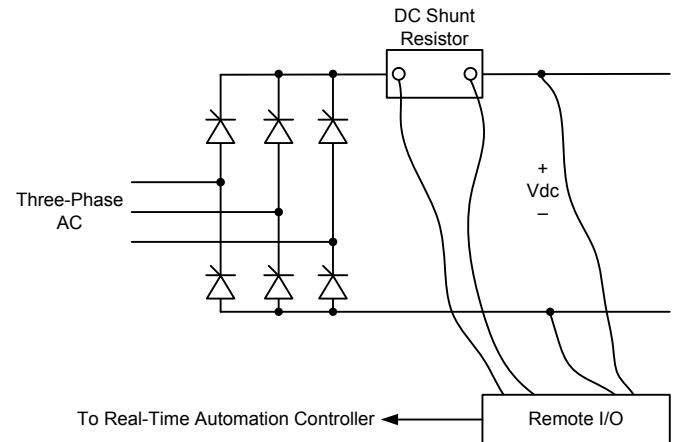


Fig. 6. Generator Field Circuit With Remote Data Acquisition

Rotor angle is the position of the rotor relative to the terminal voltage. The relative angle between these two sinusoidally varying quantities has a direct relation to the power output of the machine. 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.

In order to ease the burden of calculations necessary to model the response of a machine to external events, such as system faults, it is convenient to use the Park's machine model (also referred to as the dq model). The difficulty in calculating the response of a machine to an external fault is caused by time-varying inductances inherent to rotating machinery. In all machines there are mutual inductances that exist between the rotor and the stator. Because the rotor is constantly rotating under normal operation, the value of these inductances changes depending on the position of the rotor relative to the phase windings. These changing inductances make analysis of the machine much more difficult. In an effort to simplify the analysis of machines, Robert Park developed a method to transform the ordinary phase quantities to a set of quantities independent of the rotor position. This method became known as Park's transformation, and the equations resulting from the transformed data that are used to analyze machines are known as Park's equations. The entirety of synchronous machine modeling stemming from the Park's transformation and subsequent equations hinges on the rotor angle, as do modern concepts of power system stability.

Despite the relative complexity of the dq machine models that stem from Park's equations, the physical concept of rotor angle has a relatively simple explanation. To understand the concept, we first revisit the basic operation of a generator. A typical power system generator is nothing more than a magnet spinning inside a coil of wire. The magnet has a north and a south pole. Faraday's law tells us that voltage is induced in a coil of wire based on the rate of change of magnetic flux (i.e., the speed of the spinning magnet) multiplied by the number of coils in the wire.

$$e = N \cdot \frac{d\phi}{dt} \quad (1)$$

Because of the physical relationship between the spinning of the rotor (i.e., the magnet) and the production of voltage in the stator winding (i.e., the coil of wire), it stands to reason that the position of the rotor has some relation to the voltage at any given point in time. Noting such an obvious relationship helps us establish the important concept that when each phase winding on the stator sees the peak magnetic flux from the rotor, the voltage is at a zero crossing.

This is intuitive considering that the ϕ term (flux) in (1) is expressed as a sinusoid. With the flux represented as a sinusoid, the voltage is then expressed as the derivative of that flux sinusoid, which itself is a sinusoid lagging the original by 90 degrees (see Fig. 7). The physical result of this relationship is that when the flux is at its peak, the voltage is at zero (Fig. 8), and vice versa (Fig. 9). In the lexicon of power engineers, under no-load conditions the q axis of the rotor and phase winding axis are aligned when the voltage is at a peak. As such, the phase winding axis of the machine is defined as the reference point by which to measure rotor angle. Specifically, in three-phase systems the established nomenclature uses the A-phase winding axis of the stator winding to represent the reference for rotor angle measurements.

In an open-circuited (i.e., no-load) machine, the only flux that exists in the circuit is that which is provided by the rotor field circuit. As the machine is loaded, current begins to flow in the stator winding and develops armature reaction flux. The vector sum of the armature reaction flux and the field flux produces a composite flux, and this composite flux is responsible for the production of the machine terminal voltages. As shown in Fig. 10, δ defines the rotor angle, which is the angle between the q axis (i.e., the internal voltage axis) and the terminal voltage, where the terminal voltage phasor generally corresponds to the A-phase voltage.

The payoff for understanding the nuances of what rotor angle actually means and how it is developed and defined is that we can instrument a machine to provide a signal we can use to measure the rotor angle. This actually turns out to be a rather trivial exercise because all we need to know is when the rotor rotates one electrical cycle. Given a single pulse for each physical rotation of one electrical cycle, we can compare a time stamp of that pulse to a point on the A-phase of the terminal voltage—likely a zero crossing or any other arbitrary

threshold. As the machine is loaded, the time between the rotor pulse and the voltage threshold increases. This behavior occurs because the rotor angle is physically advancing in time relative to the terminal voltage. While the pulse obtained from the rotor may not correspond directly to the q axis of the rotor, it does not need to as long as we can establish a reference offset between the pulse and the voltage zero crossing when the machine is in a no-load condition.

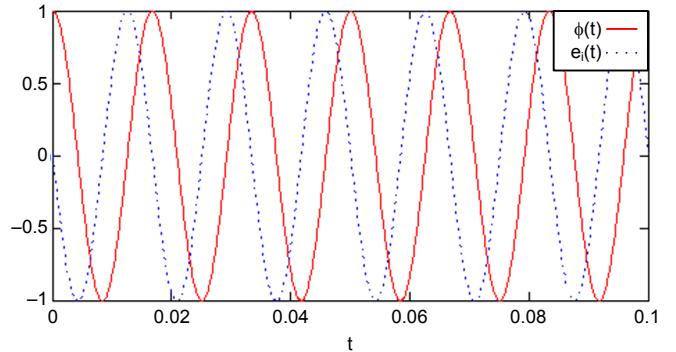


Fig. 7. Relationship Between Voltage and Flux

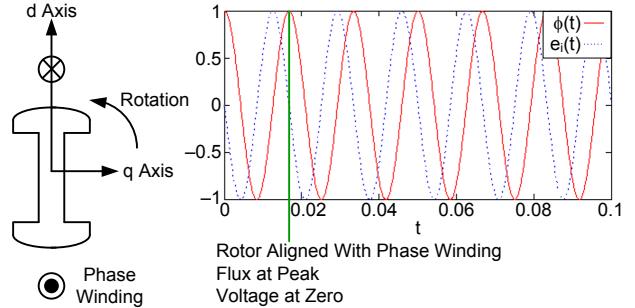


Fig. 8. d Axis Aligned With Phase Winding

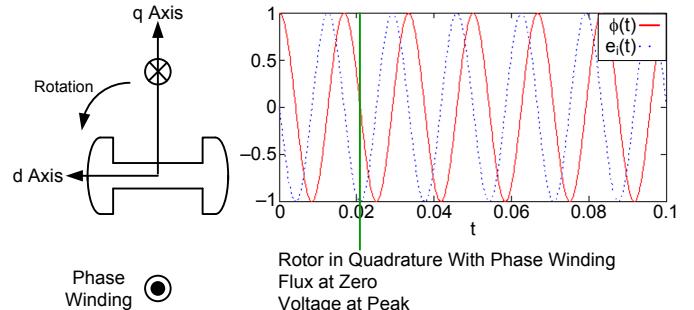


Fig. 9. q Axis Aligned With Phase Winding

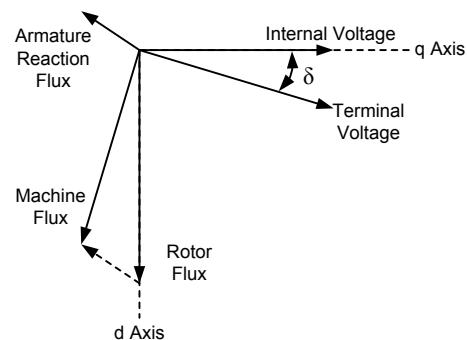


Fig. 10. Flux and Voltage Vector Diagram

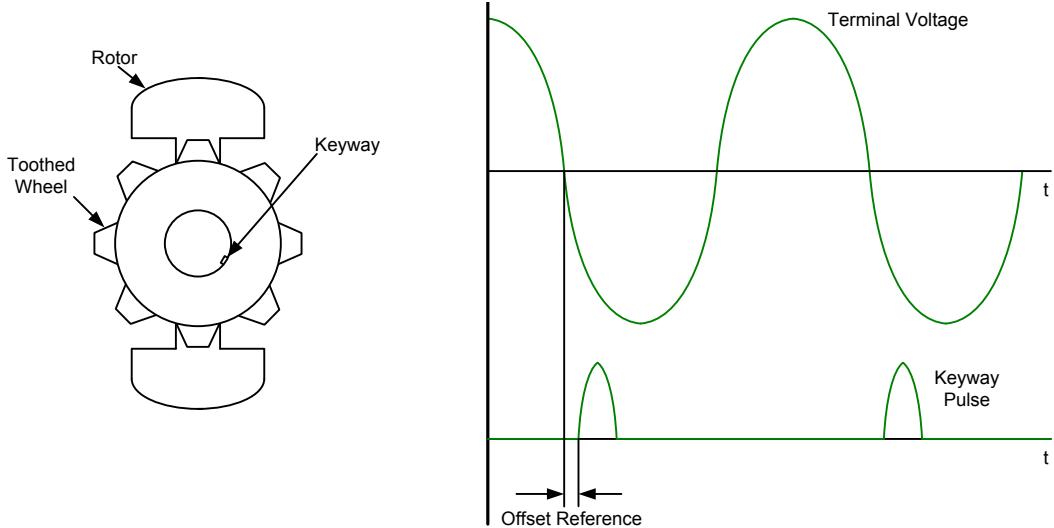


Fig. 11. Rotor and Voltage Physical Relationship

Fig. 11 illustrates this concept. The illustration on the left 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 (see Fig. 12).

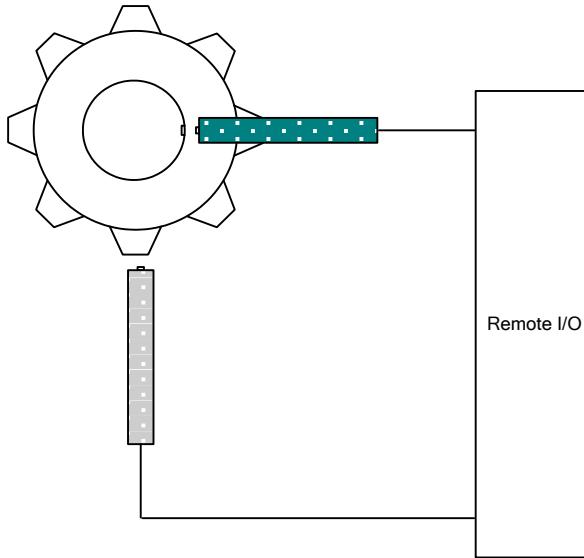


Fig. 12. Toothed Wheel Data Acquisition

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, and these time stamps are compared. 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 d axis of the machine, the voltage zero crossing and the keyway pulse occur at the same point in time. But, 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 machine is loaded, we can track the angle of the rotor pulse relative to the no-load reference angle, and this provides us with our absolute rotor angle.

IV. MONITORING SOLUTION ARCHITECTURE

With the fundamental concepts regarding the quantities that SDG&E is monitoring addressed in the previous section, we can move on to 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 a real-time automation controller to provide synchrophasor data, and the collection, concentration, and storage of these data in various 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 at the plant.

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 machine is loaded, or during system transients, the mechanical system and electrical system are coupled through a magnetic interaction, which is not rigid and allows some deviation in speed between the two systems. Change in the rotor angle of the machine 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 multoothed wheel is a common apparatus installed on most machines, from hydroelectric and gas turbines to diesel engines, and in each case 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. 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 (as shown in Fig. 12). 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's position relative to the voltage. The multoothed wheel requires a bit more thought and a slightly more sophisticated algorithm to determine the rotor angle.

The actual gear and bracket attached to the gas turbine at SDG&E is shown in Fig. 13. The toothed wheel has 60 teeth, and there are a number of sensors detecting the passage of the teeth. The majority of these sensors are wired directly to the turbine speed controller. One sensor was wired to the remote I/O module for rotor angle measurement for use in a real-time automation controller.

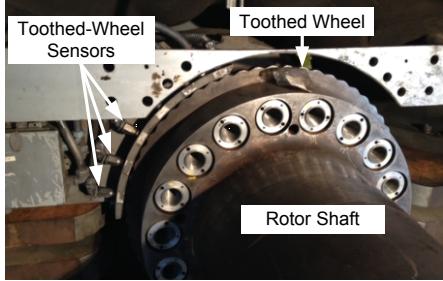


Fig. 13. Toothed Wheel and Associated Sensors

Overall, the system consists of two remote I/O devices, one to capture the field quantities and one to capture the mechanical speed of the machine. These two modules are connected to a real-time automation controller using high-speed real-time Ethernet communications over a fiber-optic network. The deterministic nature of the communications makes it possible to capture the remote data and time-align them as required for use with the standard synchrophasor protocol. A major benefit of the real-time Ethernet communications is the ability to synchronize the data sampling on the remote cards. In this way, the data received at

the real-time automation controller are guaranteed to have been sampled at identical instants regardless of the placement of the remote I/O modules. Fig. 14 shows the architecture.

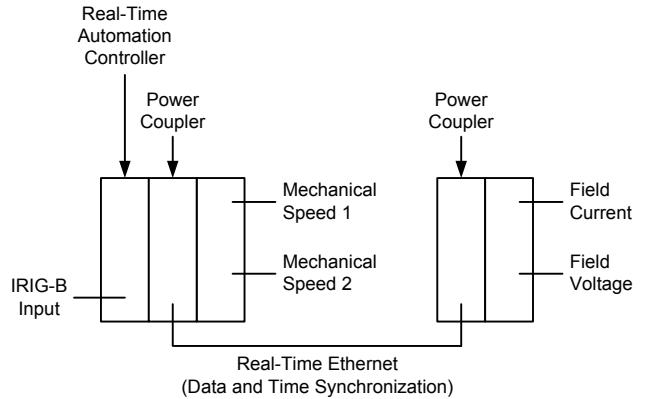


Fig. 14. Generator Monitoring System Architecture

The connection diagram in Fig. 14 represents the basic architecture of the data acquisition system. It is quite simple, yet very powerful considering the time-synchronized sampling of the data acquisition cards.

These data are collected in a real-time automation controller and sent to an IEEE C37.118 server for transmission over a local-area network to a PDC. The PDC resides in the plant control center and collects phasor data for the entire plant, not just the generator. While the field quantities and rotor angle information are not technically phasors, it should be noted that the IEEE C37.118 standard allows non-phasor data to receive time stamps similar to phasor data, which allows them to exist in the same data stream. This allows any accurately time-stamped signal to be included in the data stream and collected and visualized along with other phasor data. The benefits of such a feature should be apparent; the collection of phasor and non-phasor data alike allows us to visualize the entire system (electrical and mechanical) or multiple systems within a single time-coherent construct. For some time now, GPS time-stamping has been an important tool in the diagnosis and analysis of fault conditions. With the addition of mechanical quantities and non-phasor-based signals, we are able to extend this concept to include more pieces of the overall system, allowing us to correlate the impact of faults on the mechanical system as well as the electrical system.

V. FIELD DATA AND RESULTS

The generator monitoring equipment was installed during a scheduled plant outage and was online when the machines returned to service. The initial data captures recorded the machines returning to service and being synchronized to the grid.

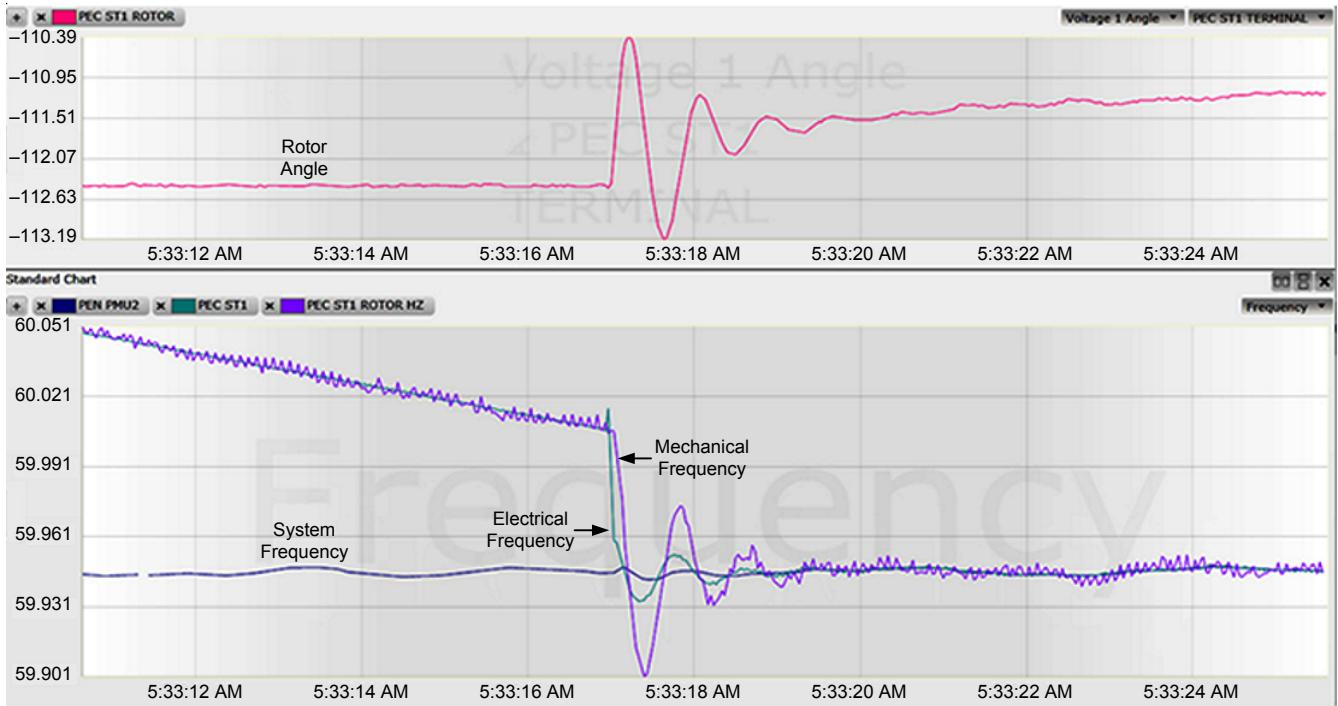


Fig. 15. Rotor Angle Capture During Synchronizing Event

Fig. 15 shows a capture of the rotor angle and frequency of a machine 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. 15 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 more consistent with that of a spring, where any perturbation of the system causes a slight oscillatory effect between the stator and rotor.

Fig. 16 shows a capture of the field voltage (bottom) and current (top). Note the sawtooth nature of the waveform. While we know that synchronous machines are excited by a dc current, Fig. 16 shows what the dc current actually looks like.

This should not be surprising when considering the field circuit as discussed in Fig. 2. The rectifier bridge is only capable of switching on and off and cannot shape the waveform. What ends up being applied to the field circuit are rectified sections of the three-phase source connected to the bridge, hence the sawtooth-shaped waveform. Fig. 16 shows an oscillography capture of the field quantities; of particular use is the root-mean-square (rms) value of these quantities. The waveforms shown in Fig. 16 are dc on average, so the rms value represents what the machine is working with in terms of magnetic field and flux generation.

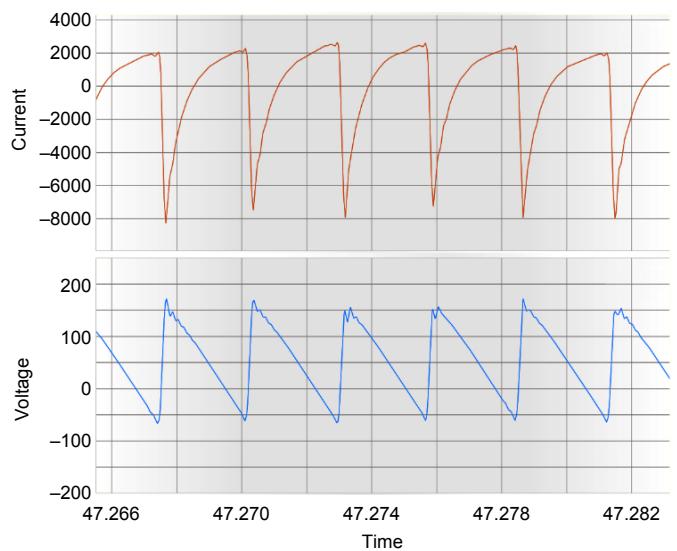


Fig. 16. Field Voltage and Current Plot Captured by the Monitoring Equipment

VI. FUTURE USE CASES

Capturing the data presented in this paper presents a specific technical challenge, but the actual use of the data in practical applications, other than just visualization and analytics, represents a completely different type of challenge. Applying these data in a form other than analytics, for machine protection for example, represents a departure from the way generator protection has traditionally been accomplished. Methods of generator protection have been fairly consistent for many years, wherein the biggest change has been transitioning from electromechanical relays to digital protection, notwithstanding the fact that most microprocessor-based relay protection is nothing more than digital implementations of electromechanical protection.

Machine model validation is likely the best and most easily implementable use of field and mechanical quantities. Anyone who has perused Anderson's text, *Power System Control and Stability* [4], has likely felt the differential equation and linear algebra-induced pain such models can instill. For the purposes of this paper, we will ignore the mathematical rigor behind such equations and instead use them at a high level to understand how monitoring and capturing field quantities and the rotor angle can help us.

Looking at a modified version of Park's synchronous machine model in terms of current measurements, we can use a generalized form, as shown in (2).

$$\begin{bmatrix} V_0 \\ V_d \\ V_q \\ V_F \\ V_D \\ V_G \\ V_Q \end{bmatrix} = [Z1] \cdot \begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix} - k \cdot [Z2] \cdot \begin{bmatrix} I_0 \\ I_d \\ I_q \\ I_F \\ I_D \\ I_G \\ I_Q \end{bmatrix} \quad (2)$$

Equation (2), while not useful for calculation purposes in the form shown, does serve as an important learning tool for our purposes in that the entire function of the machine can be boiled down to the interaction of the voltages and the currents with impedance matrices $Z1$ and $Z2$. In this case, the voltages are used as the state variables and the currents are multiplied by the impedance matrices. The important feature to recognize is that the machine is described through the use of the dq equations. The main requirement in the use of the dq equations, by definition, is the rotor angle of the machine. The rotor angle is what makes the dq equations possible, and without it the transformation to the dq reference frame is useless. This fact highlights the importance of obtaining the rotor angle measurement for use in model validation. Considering that the models of machines are almost universally described in terms of the dq equations, rotor angle is necessary for the proper analysis of these models.

In addition, the field quantities (V_F and i_F) are used throughout the model in (2). By measuring the field quantities

directly, we eliminate the need to indirectly calculate these values. The more quantities we can directly measure, the better we can implement our model.

The impedance matrices $Z1$ and $Z2$ represent the parameters of the machine that are unknown or in need of verification. With the measuring of the voltages and currents, estimating the values of the impedance parameters becomes easier. There are several methods of determining the parameters, and there is actually an entire subset of engineering analysis dedicated to the concept of parameter estimation. Most methods involve some sort of least squares error minimization technique, but these methods are beyond the scope of this paper. The important thing to note is that SDG&E and other utilities are aware when obtaining these measurements of the possibilities regarding their ability to implement parameter estimation schemes. As North American Electric Reliability Corporation (NERC) and Federal Energy Regulatory Commission (FERC) mandates progress, the requirement of utilities to provide accurate models of their machines is becoming more stringent. For this reason alone, parameter estimation and model validation are becoming more important in the industry. However, beyond the regulatory requirement, the general ability to understand how a given machine behaves is a powerful tool in ensuring proper and stable operation of the machine itself as well as the greater electrical grid.

As an extension to model validation, condition-based monitoring and protection could become a new protection paradigm as a benefit of capturing previously underused machine quantities. Traditional protection requires a failure of some sort. In machines, this failure typically manifests itself through insulation failure. The insulation protecting the windings from other windings, or the core of the machine, gradually begins to fail and eventually reaches a point where a phase-to-phase or phase-to-ground fault triggers the machine protection. In this manner, the machine has already failed and the protection is reactive, ensuring that the damage is limited. The concept of condition monitoring is to not wait until the machine reaches a point of failure but rather to monitor the health of the machine while it is in service, looking for gradual changes in operating conditions that signal imminent failure. By identifying incipient fault conditions, system operators will likely have enough time to plan an outage to repair or replace the affected machine rather than be forced to take an unplanned outage to respond to an unforeseen failure.

These concepts of condition monitoring are not new. However, our present ability to capture data from several different points of interest (on both the electrical and mechanical sides of machines) with coherence between the measurements, in addition to the computing power and sophistication of modern-day real-time automation controllers, allows for the implementation of any number of algorithms of varying levels of complexity to identify incipient faults and help operators and plant personnel improve the reliability of their systems.

VII. CONCLUSION

SDG&E is investing in new ways of monitoring and visualizing the performance of their machines. At present, these projects are an effort to promote applied research for enhanced diagnostic and monitoring capabilities for the generators on their system. The first step has been to begin acquiring machine quantities that, while useful and important in understanding the overall performance of the machine, have yet to be used widely by industry. In this effort, SDG&E has successfully implemented field quantities monitoring and rotor angle measurement on three machines in their generation fleet. These measurements are made in real time, running all day every day at 60 samples per second, while being archived through the SDG&E system-wide PDC. All machine and system events are captured and stored on the PDC, and the effects of these events on the machine are preserved in the PDC and the higher-frequency data event captures.

SDG&E is considering model validation as a next step. With the capture of system events and the machines' responses to these events, it is possible to implement these disturbance data for the validation of machine models. Given the response of a machine to a system disturbance, a model of that machine should behave similarly when simulated on a computer. If the machine model as simulated does not match the response of the actual machine as recorded by the PDC, then the parameters of the model need to be adjusted.

Overall, SDG&E is just beginning to embark on this effort to enhance the monitoring and protection capabilities for their machines. They have had initial success with the capturing of the data and are now planning to apply these data to use them to their full potential.

VIII. REFERENCES

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IX. BIOGRAPHIES

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Kamal Garg is a protection supervisor in the engineering services division of Schweitzer Engineering Laboratories, Inc. (SEL). He 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 for seven years and Black & Veatch for five years at various positions before joining SEL in 2006. 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.