FEATURE ENHANCEMENTS IN NEW DIGITAL EXCITATION SYSTEM SPEEDS PERFORMANCE TESTING

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ABSTRACT: Minimizing the time required to commission an excitation system will speed the availability of the machine to become a revenue producer. Tests including Voltage Step response, Excitation Limiter verification, and Power System Stabilizer tuning can require an array of external test equipment that can be costly to rent, require downtime to install, and transducers that require insertion in field circuits, VT and CT circuits for test analysis. Today, where NERC and other regulatory agencies are advocating validating of machine and excitation system performance, new technology solutions built into the excitation system can ease the burden of performing required tests and provide permanent records for future analysis.

This paper will discuss performance testing of the excitation system and features available in today's excitation system that eliminates external test equipment and reduce the cost of test verification to comply with the latest agency requirements [1,2,7].

I NEW RULES IN TODAY'S POWER INDUSTRY: TIME IS MONEY, MINIMUM DOWNTIME

In today's electricity market, as the delivery of electric energy to independent system operators (ISO) for transport on the transmission system becomes more prevalent, generator availability and reliability are becoming ever more critical. There is an inherent risk to the participants of having to purchase what they promised, but cannot deliver.

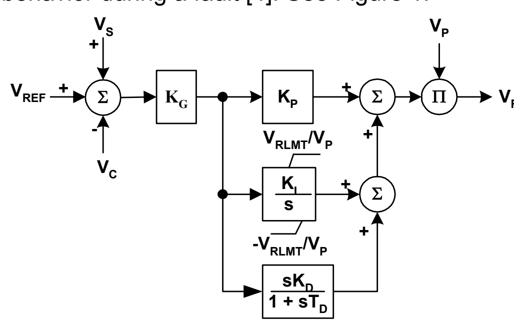
There are two markets with two prices: The Day Ahead Market and the Real Time Market.

Generating companies offer a price, per megawatt hour and quantity of megawatt hours, to sell for delivery into the Day Ahead Market. If it clears the Day Ahead Market (accepted by the ISO), it then becomes an obligation and the generating company must deliver the quantity of megawatt hours at the established market price into the Real Time Market. If a company chooses or is unable to deliver the promised megawatt hours into the Real Time Market, it must fulfill its obligation by purchasing that quantity, at the Real Time Market price.

Should a generator become unavailable, because of an unscheduled outage due to a failure of support equipment, market volatility cost penalties can be imposed for that replacement power. The need for reliable power becomes a priority today, more than ever.

II DATA COLLECTION TO EVALUATE SYSTEM PERFORMANCE

The ability for the excitation system to respond to disturbances and prevent abnormal generator operation such as rotor overheating requires the excitation system to be fully tested. Verification provides important data relative to the behavior of the excitation system with the generator. Testing the excitation system and generator has always been an important criterion to determine the compliance of the voltage regulator and auxiliary functions such as excitation limiters for performance. Today, more than ever, the performance data provides important information that is compared with mathematical model for verification of computer simulations for transmission planners to determine predicted behavior during a fault [4]. See Figure 1.



V_{REF} is generator voltage Reference
V_C is sensed voltage
V_S is stabilizer output
V_{RLMT} is max field forcing
V_p is power input voltage
V_R is voltage regulator output

Figure 1 Simplified Block Diagrams of Automatic Voltage Regulators.

IEEE 421.2 Performance Guide [2] provides testing criteria for the excitation system. These tests include the following:

Small signal voltage step test: A test where the small signal voltage step change is introduced into the summing point input to provide a means of evaluating the response of systems for incremental voltage changes, and changes in synchronous machine rotor speed associated with the initial stages of oscillatory instability. Small signal performance data provide a means for determining or verifying excitation system model parameters for system studies. The voltage step signal is in the range of 2-5% of the generator output.

Open circuit large signal test: The large signal performance criteria related to excitation control systems to determine and permit maximum flexibility in the excitation design. Here field forcing levels are verified and interpreted against the manufacturer promised data. The field forcing maximum is directly related to the secondary voltage available from the power potential transformer. The voltage step change is in the range of 10-20%.

Volts/Hertz Limiter Verification: The Volts/Hertz limiter is used to prevent rotor overheating that may arise from excessive magnetic flux due to underfrequency operation or generator overvoltage operation.

The Volts/Hertz limiter also is used to protect the synchronous machine (and connected transformers) from high flux levels, as may occur with the machine off-line if turbine frequency is reduced or should system voltage rise, prevent overfluxing of the generator and stepup transformer.

The Volts/Hertz limiter is tested by raising the generator voltage above the voltage level it is intended to limit, A 1.08 P.U. value represents 108% maximum generator voltage limit. Conversely, lowering the turbine frequency to a value where the Volts/Hertz limits tests the underfrequency threshold. Figure 2 illustrates the system characteristics of the generator overvoltage limit and an underfrequency operation. Notice how the Volts/Hertz Ratio of 1.99 is maintained in the first column as frequency range and maximum voltage limited is exceeded.

UNDEREXCITATION LIMITER PERFORMANCE

The underexcitation limiter prevents operation beyond the underexcited portion of the synchronous machine capability curve or operation in a region that would approach the steady-state stability limit. The under excitation limiter characteristic is plotted in terms of real vs. reactive power at rated terminal voltage, so that it can be compared with the synchronous machine capability curve or steady-state stability limit. Performance is verified to determine its stability during operation and to ensure the availability of maximum reactive capability available from the synchronous machine. It is important it is properly coordinated with the loss of excitation protection provided for the synchronous machine. The underexcitation limiter should be tested dynamically with a voltage step change in the decreasing direction to verify the reactive stability when pushed into the underexcited region.

Programmed Ratio 1.99 **Check at 1.05 Nominal Vac**	*Frequency*	*PT Instrument System Voltage*	*System Voltage* **Kvac**
1.98	60	119.25	14.31
1.997	59.1	118.18	14.18
2.0	58.5	117	14.04
1.993	58.4	116.4	13.96
2.02	58.3	118.74	14.24
2.0	58.2	116.4	13.96
1.996	58	115.8	13.89
1.994	57.8	115.3	13.83
1.997	57.3	114.43	13.73
2.0	57.2	114.6	13.75
1.987	57	113.3	13.59
1.992	56.7	112.96	13.55
Final Setting of V/Hz Ratio Limiter=2.05 108% Nominal Vac			

Figure 2 Volts/Hertz Limiter Testing

The shape of the under reactive curve also should be checked to verify the desired curve selection. Temporary test settings may be incorporated into the excitation limiter to allow testing without having to demonstrate performance at the extreme value settings to be in compliance with NERC and WECC guidelines.

OVEREXCITATION LIMITER PERFORMANCE:

The overexcitation limiter is used to avoid overheating of the synchronous machine field winding for excursions in field current above the continuous rating. The permissible thermal overload of the field winding is inversely proportional to time and, hence, allowance for delay of action. With high ceiling excitation systems, the overexcitation limiter will have instantaneous current limiting action and or multi-step control incorporated. A cool down feature ensures that repeated field forcing does not occur until the rotor has sufficiently cooled.

The overexcitation limiter is tested by performing a voltage step change into the voltage regulator summing point that causes the generator field current to increase, which results in the field current bumping into the limit. A significant test change may need to be performed to verify the excitation system will bump into the overexcitation limit. Proof that the maximum excitation reaches its limit and is stable

represents an important measurement of the system's effectiveness. Like the underexcitation limiter, temporary test settings may be incorporated into the excitation limiter to allow testing without having to demonstrate performance at the extreme value settings to be in compliance with NERC and WECC guidelines.

Frequency Response Test: A frequency response test is performed to determine the bandwidth of the voltage regulator with the generator and connected system. The frequency response is performed over a range of frequencies from 0.1 to 10 Hertz at 25% real power load. The signal frequency is applied into the summing point of the voltage regulator, and the output of the generator is monitored. Ideally, the output signal frequency will copy the input signal for the range of frequencies being applied. In reality, a lagging phase shift and a roll off of gain will occur as higher frequencies are approached. The lower the phase shift at the higher frequencies, the better the expected excitation system response and faster the voltage recovery. When performing a frequency response, the phase lag is evaluated at 1 Hertz, the typical local mode frequency of the power system. For a voltage regulator driving the exciter field, the maximum desired phase lag measured at 1 Hertz is 135 degrees. For static exciters working into the main generator field, the maximum expected phase lag is 90 degrees for response timing. The faster the excitation system response, the lower the expected phase lags at 1 Hertz.

The results of these tests are used to determine the amount of compensation required for the power system stabilizer. The power system stabilizer compensation, when properly tuned, provides positive damping to mechanical oscillations in the frequency range of 0.1 to 2 Hertz typical.

The tests referenced above can involve substantial equipment that is required to be installed prior to the generator being operated. Equipment including chart recorders, transducers, and a dynamic system analyzer are critical to measuring and performing tests to verify satisfactory operation of the voltage regulator and associated limiters. See Figure 3. The problem however is "Time" - time to schedule the equipment and time to connect the equipment in the appropriate locations. Conversely, the generator may need to be taken offline to remove the temporary equipment to avoid possible machine trips [5,6].

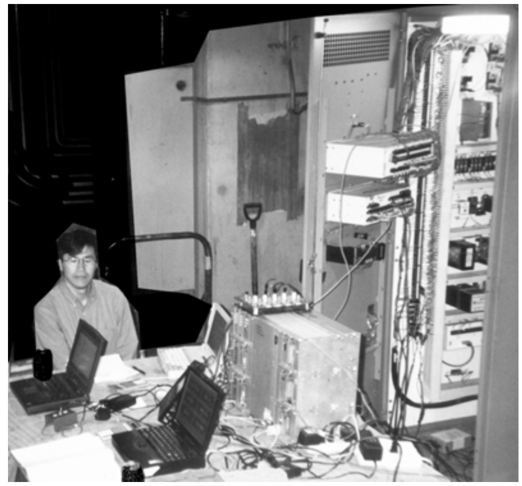


Figure 3 Onsite Testing with Digital Excitation Control System, External Test Equipment and PCs

III NEW FUNCTIONS IN THE DIGITAL EXCITATION SYSTEM SPEEDS TESTING

In the past chart recorders were used to collect data for voltage step changes. Figure 4 illustrates a 5% voltage step change using a chart recorder with external transducers used for recording the generator voltage for a machine rated for 250 MW. In the past few years, oscillography has aid data collection and reduced equipment hardware required at the facility, but this process can be time consuming as data needs to be downloaded into a COMTRADE or log file; stored; then examine through a software viewing program. This may take 5 minutes for each operation during commissioning.

Oscillography is best utilized as a permanent data file for records after desired performance has been satisfied and as a diagnostic tool used to evaluate generator and excitation performance issues after a disturbance.

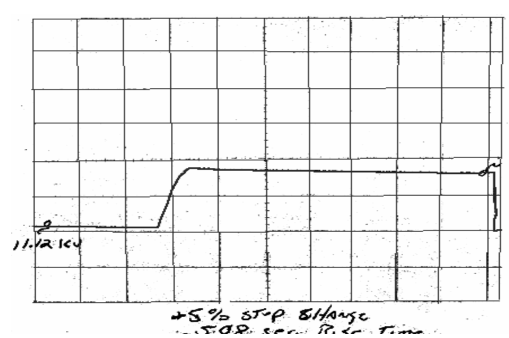


Figure 4 5% Voltage Step Change

Figure 5 New Software Tools Eliminate the Need for an External Dynamic Frequency Analyzer in Favor of Built-in Operating Software Tools Having this Capability

The benefits of a real time chart recorder can speed the process of data collection. Today, programs can be purchased for use with a laptop computer that provide such capability, although it still relies upon external inputs from shunts and PTs and CTs depending upon the type of information being collected.

The best solution is having both a chart recorder and oscillography available with the operating software for the new excitation system. Today, as technology rapidly moves ahead more and more test tools are becoming part of the excitation system setup software. This can eliminate hours or even days of setup and removal unlike test equipment of the past needed for the older vintage excitation systems. One laptop and serial cable are used for onsite testing with digital excitation control system, as shown in Figure 5.

The problem of downtime is money and today, any time to commission an excitation system is too long. To shorten the cycle, manufacturers are creating new testing tools to expedite the process. These include such items as a built-in chart recorder that is capable of measuring quantities from a selection of 2 or more items including functions such as generator voltage, field voltage, and machine MW, MVArs.

Figure 6 highlights a voltage step change that was introduced with operating software provided with the excitation system. Generator voltage is monitored on the top recording while field voltage is monitored in the lower recording. Measured quantities can be scaled. Speed of the data can be adjusted and desired parameter can be selected using dropdown screens. Here a 5% voltage step change is introduced, and a time response is recorded of 8.3 seconds with essentially no voltage overshoot.

Voltage step change is immediately recorded and response is evaluated. As analog meters are being becoming less prevalent, the chart recorder provides a new tool to speed analysis and obtain a visual feedback of the system stability.

Figure 7 illustrates an under excitation test where the upper chart defines response of the reactive power while field current is exhibited in the lower chart. A -3% voltage step change was introduced resulting in the synchronous machine absorbing reactive power up to the limit of the under excitation limiter.

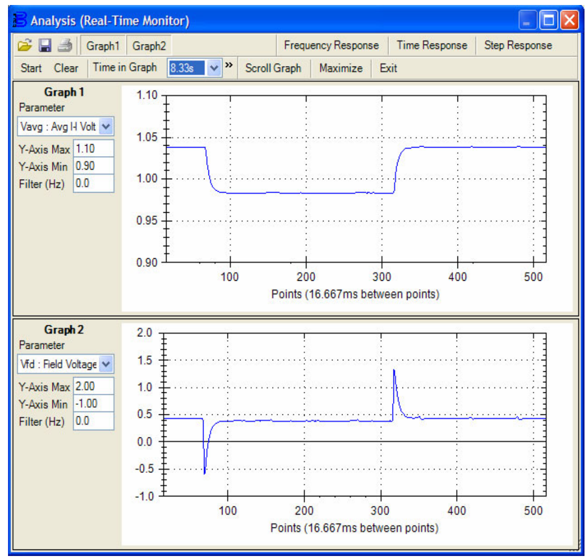


Figure 6 5% Generator Voltage Step Change using Built-in Chart Recorder Software Function

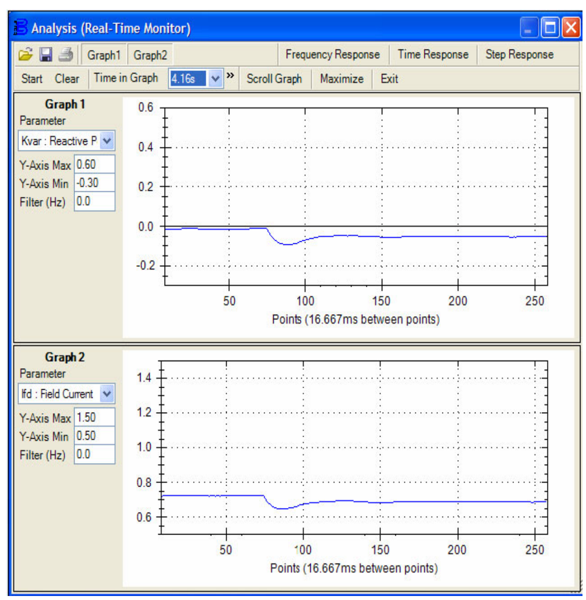


Figure 7 Under Excitation Response
Reactive Power Top- Field Voltage Bottom

Perhaps the most involved testing required is that related to performing a frequency response.

Historically, the frequency response test is a very time consuming process of data collection. The time it takes to perform a frequency response can be tedious, if manual recording is required.

The inclusion of a dynamic system analyzer to perform a frequency response can eliminate the time and speed of testing. Time is shortened from hours to minutes. As shown in Figure 8, selection of the chosen frequency range is identified and the mode selection is set for "Auto". Hours of setup and data gathering are reduced to minutes. Where the excitation system phase lag and gain is desired, for records, a bode plot can characterize the overall response. See Figure 9.

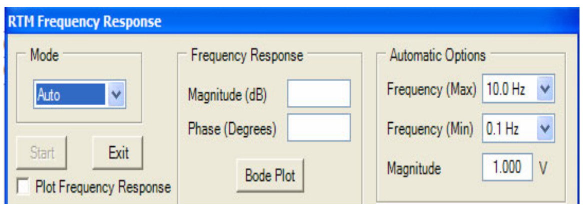


Figure 8 Selection of Parameters for Frequency Response Test

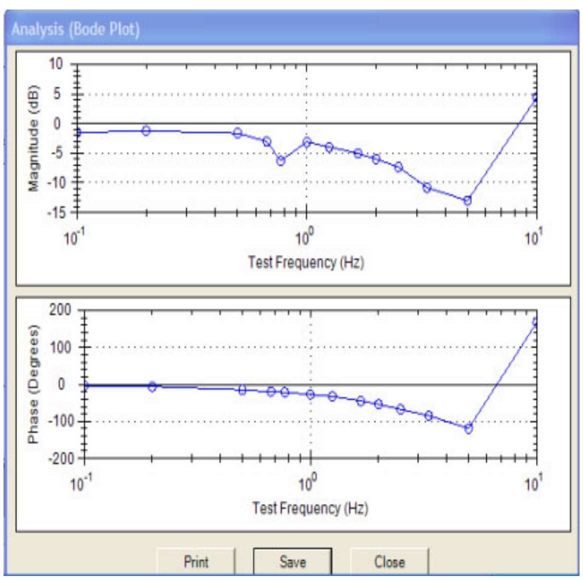


Figure 9 Frequency Response using Built in Dynamic Analyzer

The combined benefit of a frequency response software program and built-in chart recorder allows one to see MWs change as the frequency response is being performed for a visual examination of machine performance during the frequency response test.

IV POWER SYSTEM STABILIZER TESTING PARAMETER SELECTION AND APPLICATION

Integral of accelerating power type PSS is designed to provide robust damping and reduced torsional interaction. It is given in the IEEE standards 421.5 as IEEE type PSS2A [3]. Several different tests were conducted on a 12 MVA hydro turbine generator for Minnesota Power to determine the PSS parameters required for tuning. These parameters include inertia, phase lead-lag time constants, etc.

Estimate of System Gain (Kg) and transient time constant (T'do): The loop gain (Kg) is used to compensate the system gain. The PID gains are per unit gains with a proper loop gain selected. It is calculated based upon a PID controller output and generator voltage measured at a steady state condition. The generator dynamic model data is obtained from a test in which the unit is tripped near zero load and leading power factor while on fixed regulator output. This function was easily accomplished by changing the loop gain (Kg) to zero. (No voltage regulator action). Thus, the change in the generator terminal voltage is solely due to the air gap flux readjusting to its new value in the absence of armature reaction. The generator time constants are measured as 4.5 sec

Generator saturation characteristics: These are measured with the unit offline. The field voltage and currents are recorded as the generator voltage varied. The results are shown in Figure 10. The measured characteristics match the manufacturer supplied characteristics reasonably well.

Selection of Phase Lead-Lag Parameters: Frequency response measurements were made with respect to the input to the voltage regulator. This is easily achieved using built-in dynamic analyzer. Two lead-lag blocks are used with time constants. The phase lead-lag parameters are calculated based on "least squares fit" to required phase compensation obtained from the frequency response data. The calculated time constants of the lead-lag block are T_1=0.1, T_2=0.02, T_3=0.2, and T_4=0.02. Figure 11 illustrates the calculated frequency response of lead-lag block and required phase compensation.

Estimate of Inertia: The unit inertia was confirmed by a partial load rejection test shown in Figure 12. From the figure, the calculated unit inertia value is 2.8 MW-s/MVA. This value matches the provided data by the manufacturer. The inertia is used to scale the active power input to the stabilizer and it was confirmed to produce the correct mixing of the stabilizer power and compensated-frequency inputs. The built-in

voltage step signal is used for verifying excitation system model parameters. With voltage step, the local mode frequency is measured as 1.67 Hz which matches simulation result with Xe=27%, the total reactance between the unit and the infinite bus.

Selection of the PSS gain: With the proper phase compensation, the damping is added as stabilizer gain (Ks) is increased. If stabilizer gain is increased to the value where this mode crosses into the right half plane of the s-domain, it causes system instability. This value is verified during the commissioning of the PSS. The final value gain setting is selected as 15, which is three times less that the instability gain. The PSS performance is illustrated in Figure 13.

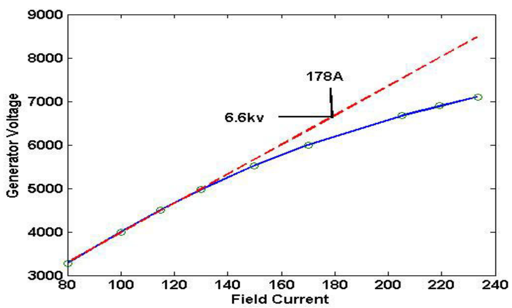


Figure 10 Generator Saturation Characteristics

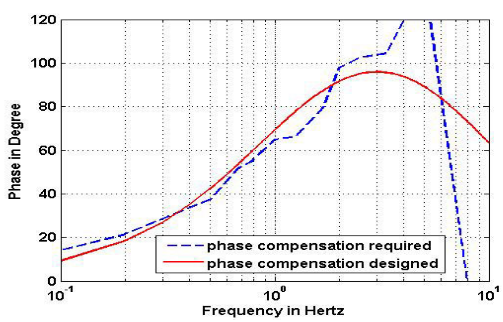


Figure 11 Phase Response of Lead-Lag Block and the Required Phase Compensation

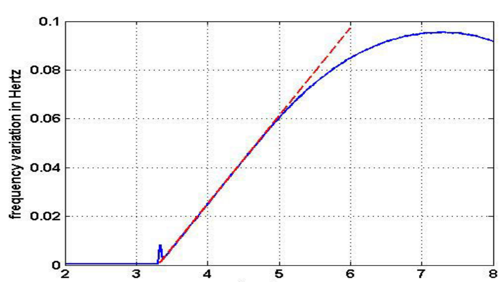


Figure 12 Trip from Load for Inertia Calculation

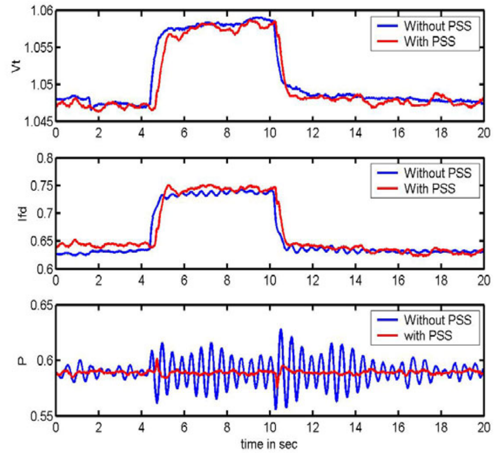


Figure 13 Effectiveness of the PSS with Proper Tuning Parameters.

Figure 14 highlights the real time response of the synchronous machine during commissioning that illustrates immediate effects of the power system stabilizer being commissioned. The top recording highlights the machine MWs without the power system stabilizer and at time equals 5900 seconds the PSS is enabled. The lower recording illustrates the digital controller output that drives the firing circuit for a 6 SCR bridge. Initially the PSS is disabled and the controller output is very stable. Without the power system stabilizer, the combined affect of system impedance and high voltage regulator gain results in a system being marginally stable. At time equals 5900 seconds, the PSS is enabled and the MWs are stable. Note how the digital controller output changes continuously as a result of a supplementary signal being injected into the voltage regulator summing point from the PSS.

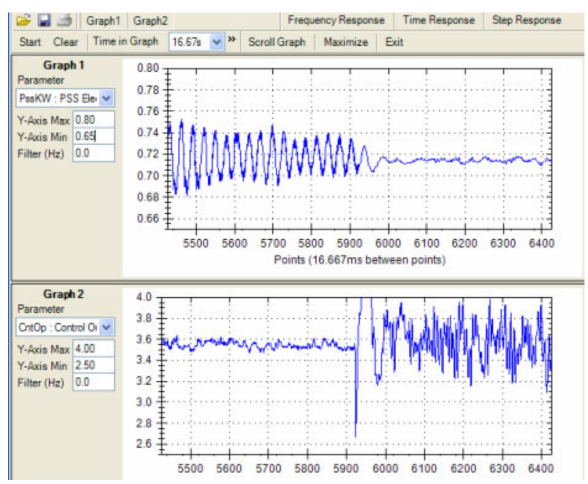


Figure 14 Real Time Chart Recorder, Top Recording MW, Lower Recording Digital Controller Output to Firing Circuit

V. DISTURBANCE DATA COLLECTION

Oscillography has proven its value in protective relaying and has also proven its effectiveness as a tool for data collection for the excitation system. Oscillography allows the operator to understand machine behavior whether it is used during a system disturbance or as a means to help diagnose problems with the excitation system. The oscillography can be set to respond to logic commands such as excitation limiter activity, or by establishing thresholds and monitoring changes in generator voltage, field voltage, or digital controller output and generator breaker trips to name just a few of the many options.

Pretriggers can be established to record events prior to the change of condition. Time resolution can be varied to obtain the maximum amount of useful data practical in a relative period of time. Figure 15 illustrates typical logic that can be selected for gathering data; Figure 16 highlights thresholds that can be set.

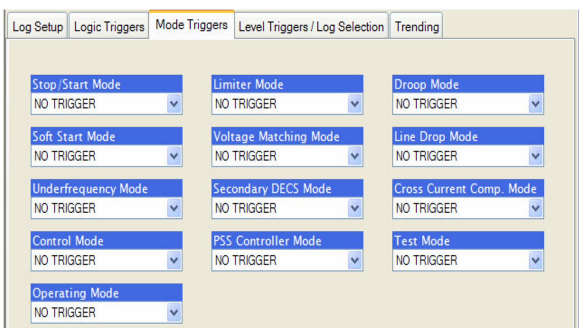


Figure 15 Typical Logic Pickup for Recording Oscillography Record

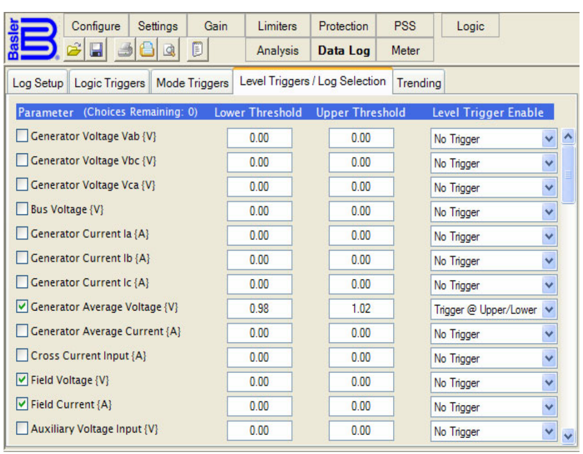


Figure 16 Oscillography Set to Record Based upon Threshold Change

Figure 17 shows typical data collected during a motor start of a 4000 HP induction machine across the line of a three 2500 kW generators. Data was triggered upon a drop of generator voltage of 2%. Notice the excitation system response, voltage dips to 12% momentarily and voltage recovered within 0.2 seconds, while the motor reaches pull-in speed within 3 seconds. Information recorded includes reactive power, line current, field voltage, and generator voltage that provided data for the engineer to evaluate system performance after the new excitation system was installed during a motor start.

Another provision provided with new excitation systems today is sequence of events. Time stamps and dates are applied relating to activity of the excitation system. From the moment the excitation system is turn on. Word descriptions are provided that identifies the type of activity that has transpired and time stamped. Such items may include an excitation limiter operation, On/off status, upper and lower limits stop or transfer from voltage regulator mode to manual control. Sample of Partial Sequence of Events Download is shown Figure 18.

The accumulation of oscillography and sequence of events information provides valuable diagnostic resources to examine and understand problems quickly to resolve them and minimize machine down time.

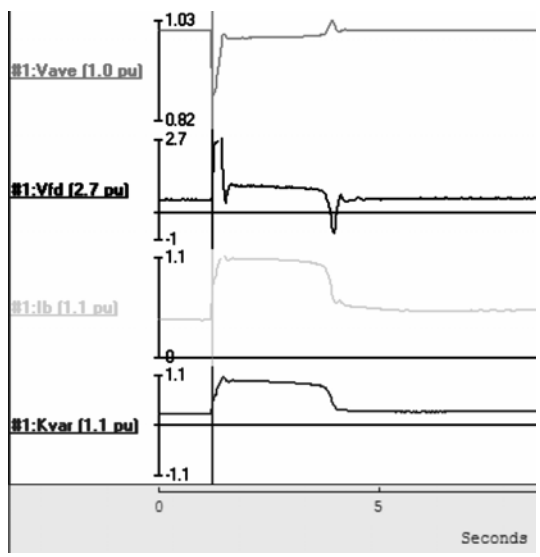


Figure 17 Thresholds during Motor Starting

DECS-400 SEQUENCE OF EVENTS REPORT (New Events)   Qty = 37
REPORT DATE : 05/24/05
REPORT TIME : 02:10P20
STATION ID   : BREESE
DEVICE ID   : DECS 400
USER1 ID   : LP #1
USER2 ID   :

--DATE-- ----TIME----	--------POINT DESCRIPTION------------------------	STATUS--------
05/24/05 05:10P00.972	SOFT START MODE	STARTUP
05/24/05 05:10P00.871	ON/OFF RELAY	DISABLED
05/24/05 05:10P00.771	STOP/START	STOP
05/24/05 05:09P30.542	RELAY 4	DISABLED
05/24/05 05:09P27.539	RELAY 4	ENABLED
05/24/05 05:09P04.316	OPERATING MODE	OFF
05/24/05 05:07P53.647	RELAY 1	DISABLED
	CONTROL MODE	AVR
05/24/05 05:07P47.441	RELAY 1	ENABLED
	CONTROL MODE	FCR
05/24/05 05:07P39.934	SOFT START MODE	OFF
05/24/05 05:07P34.328	OPERATING MODE	VAr CTL
05/24/05 05:07P24.719	ON/OFF RELAY	ENABLED
05/24/05 05:07P24.669	BUILDUP RELAY	DISABLED
05/24/05 05:07P24.619	BUILDUP RELAY	ENABLED
	STOP/START	START
05/24/05 12:06A29.090	OPERATING MODE	OFF
05/24/05 12:06A16.678	OPERATING MODE	VAr CTL
	LOAD COMP MODE	DROOP
05/24/05 12:06A16.577	ONLINE (52 L/M) CONTACT	ENABLED
	var/PF ENABLE (52 J/K) CONTACT	ENABLED
05/24/05 12:06A11.072	SOFT START MODE	STARTUP
05/24/05 12:06A10.972	ON/OFF RELAY	DISABLED
05/24/05 12:06A10.872	STOP/START	STOP
05/24/05 12:05A49.951	OPERATING MODE	OFF
	LOAD COMP MODE	OFF
05/24/05 12:05A49.851	var/PF ENABLE (52 J/K) CONTACT	DISABLED

Figure 18 Sample of Partial Sequence of Events Download

VI. CONCLUSION

Today, where uptime is essential and manpower is limited, technology is playing an increasingly important role in easing the burden of the operating and maintenance engineer. Technology can provide the tools to perform diagnostics and speed commissioning.

Simultaneously, the software tools provide the system engineer the means to evaluate data promptly. Speed and efficiency are important and the operating software must be intuitive and user friendly to aid the engineer in problem solving and promptly collect system data.

With the new tools, the need for repeat test very five years can be handled as routine maintenance, rather than requiring specialized services.

The power demand on the transmission system continues to spiral as load demands peak daily. The blackouts in the Northwest and Northeast highlight the vulnerability of the transmission system and the need for more equipment intelligence. Increasingly important are the tools provided by the manufacturer to aid the system engineer to diagnose problems and find solutions quickly to keep the power system reliable.

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