Specifying Excitation Systems for Procurement

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Abstract: *With today's microprocessor technology, digital excitation systems have become very versatile compared to their analog voltage regulator predecessors. Full function digital excitation systems come equipped with various operating modes necessary to control terminal voltage on the synchronous machine. In addition, a full complement of excitation limiters is provided to ensure control of the synchronous machine over a wide range of operating conditions.*

When specifying new excitation systems, it is important to consider all of the various factors that can affect the successful purchase of the new equipment. These include but are not limited to environment, location of the excitation system, applicable specifications, agency requirements, performance, and ratings.

This paper discusses considerations involved in specifying the excitation system for a project.

I. Specifying the Excitation System Rating, Static Exciter Systems

The excitation system includes many components to provide control of the synchronous generator. These include the automatic voltage regulator, bridge rectifier, power potential transformer, and breakers. Figure 1 shows a static exciter system with revelant components. The digital controller integrates all of the individual functions, such as the automatic voltage regulator, manual control, and excitation limiters, into one controller.

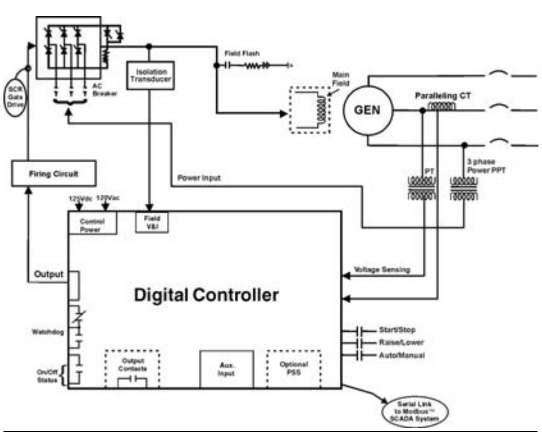

Figure 1. Static Exciter System

Perhaps the single most important concern in specifying the new voltage regulator is properly identifying the application. Is the new excitation system intended for the main field of the generator or the shunt field of the rotating exciter? Depending on the circumstances, sizing the excitation system can be derived from the generator nameplate as shown in Figure 2 or, looking at worse case and sizing the excitation system requirements for 115% the rated kVA at 105% rated voltage of the generator. Where the generator has been rewound or is anticipated to be rewound for a higher machine rating, it is important to consider the additional power requirements of the generator main field.

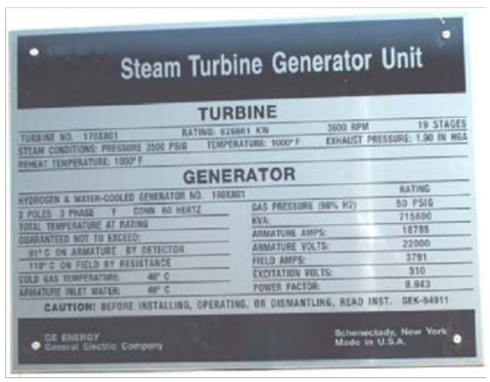

Figure 2. Typical Generator Nameplate

Field Forcing Concerns

For short time disturbance response, an overload rating is applied to the excitation system. Field forcing provides the ability to deliver higher than normal operating capacity to the field for short periods of time, typically a total of 30 seconds. Field forcing represents the percent of maximum ceiling voltage that can be applied to the field from rated full load field. Depending upon regional requirements, the magnitude can vary from 150% to 200% of full load, or even higher if there are special requirements to consider. Often, "field forcing" is expressed in terms of the Response Ratio, as referenced in IEEE 421.2. [1]

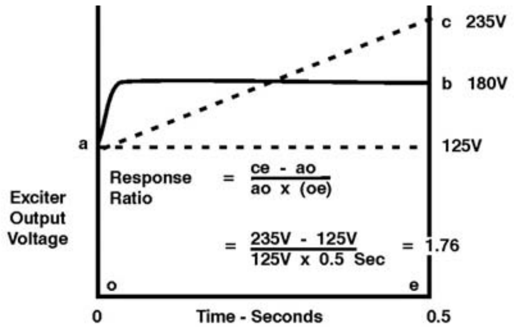

Figure 3. Excitation System Voltage Response Ratio

To determine the Response Ratio, the exciter is brought to its full rated voltage (Nominal 125V), and the generator terminal voltage suddenly is dropped by 20%. Then, the field ceiling voltage response is recorded over the first 0.5 seconds. The straight line, a-c, represents the area that is inside and outside the dotted line. The formula in Figure 3 is used to calculate the Response Ratio. In this instance, the answer is 1.76. As illustrated, by increasing the ceiling voltage, the response ratio becomes greater. [6]

The time duration required for maximum field forcing is a very short period, reaching the maximum value and holding for perhaps 3 seconds, then following an inverse time curve to approximately 110% of the full rated over a duration of approximately 30 seconds. ANSI C50.13 offers guidelines that show the permissible short time overload current plotted against time for cylindrical rotor machines. [7]

The Power Potential Transformer

Another element of the excitation system is the power potential transformer that provides the appropriate voltage for the rectifier bridge. See example shown in Figure 4. The manufacturer specifies the power potential transformer kVA once the field forcing requirements have been defined. Most power potential transformers are convection cooled, dry type and designed with anticipated harmonic content, but other considerations may include higher than normal BIL (Basic Impulse Level) ratings that may be above the normal manufacturer rating, special impregnation such as vacuum impregnation. Epoxy cast or resin core coils may be specified at times, depending upon the location of the power transformer. Each special requirement adds cost to the excitation system.

Figure 4. Excitation Power Potential Transformer

II. Bridge Rectifier Selection

The bridge rectifier used to convert ac to dc can be one of two types: half wave (3 SCR and 3 diode, see Figure 5A) or full wave bridge (6 SCR). Twenty years ago, the half wave bridge was very popular for main field applications, but today most new excitation systems require two (2) quadrant, 6 SCR bridges that provide for both positive and negative field forcing for optimum performance and faster generator voltage decay at shutdown. See Figure 5B. [8]

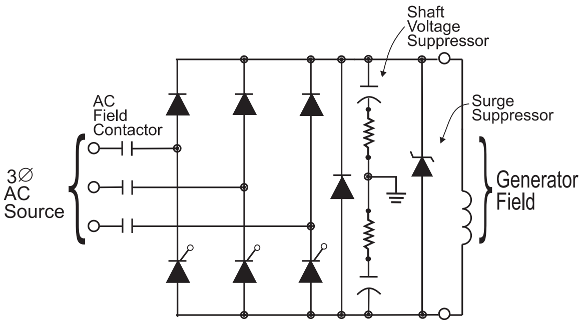

Figure 5A. 3 SCR Half Wave Bridge

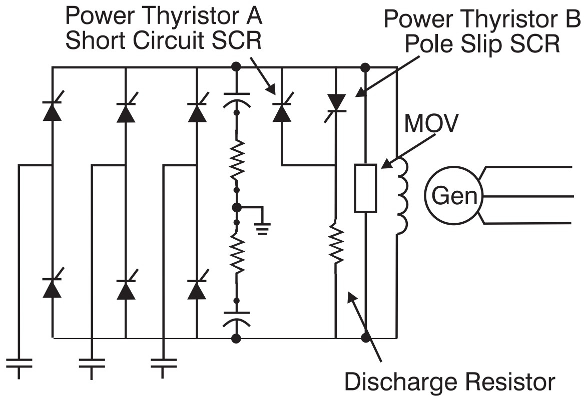

Figure 5B. 6 SCR Bridge with Crowbar Fast De-excitation Circuit

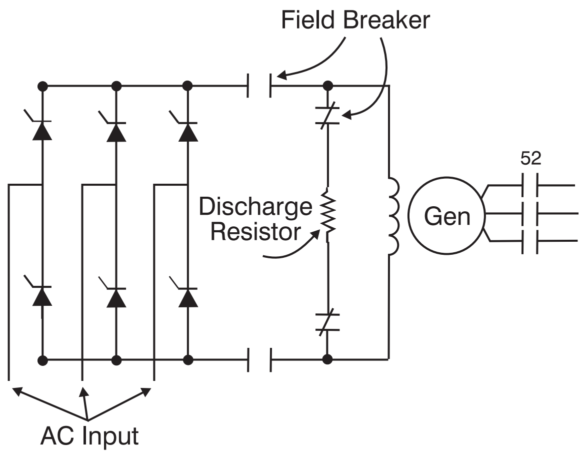

Figure 6. Full-Inverting Exciter System with Field Breaker

Where the dc field breaker (Figure 6) has been the standard for dc machines for years, due to age and cost and general mechanical concern, the dc breaker is being replaced for an ac field breaker at the ac input to the rectifier bridge. The discharge contacts are now replaced for a couple of SCRs connected in antiparallel; that is, connected in series with a discharge resistor to dissipate the field energy at shutdown. Figure 5B illustrates the crowbar circuit with SCRs for controlling the insertion of the field discharge resistor.

III. Rotating Exciter Voltage Regulator Applications

For rotating exciters, the excitation field requirements change quite dramatically. Instead of a current range of a few hundred to thousands of Amps for the main field, the voltage regulator field requirements range from 10 Amps to a couple hundred Amps for very large synchronous rotating exciter machines. See Figure 7. For these systems, the voltage regulator works directly into the exciter shunt field and eliminates various types of pilot exciters, including the Amplidyne and the multiple field Rototrol exciters. When sizing for the exciter field requirements, it is very important to obtain the exciter shunt field requirements for sizing the new excitation system. Unlike the generator nameplate provided on the main field excitation systems, the rotating exciter field information is not obvious. Often, measurements are necessary to obtain the operating field current of the exciter shunt field and voltage at full load to be sure of the rating required for the new excitation systems.

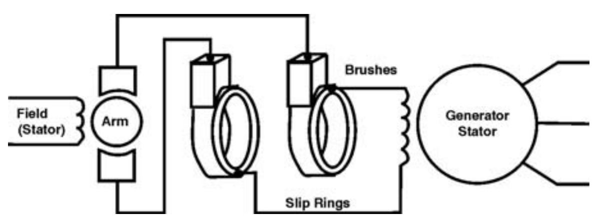

Figure 7. Rotary Excited, Brush-type Generator

Bridge Selection for the Voltage Regulator

Since the voltage regulator drives the exciter field, the type of bridge utilized is very important to achieve the best performance results. In this case, the 6 SCR bridge needs to be utilized. For exciter field applications, the magnetic flux needs to decay as quickly as possible in order that the generator flux can be drained quickly from the main field. This is particularly important on machines that have large machine exciter and main field time constants or that require power system stabilizers to optimize machine performance to improve transient stability recovery. See Figure 5B.

IV. Equipment Features

Today, the excitation system comes equipped with a full complement of features, whether it is a voltage regulator working into the exciter field or the generator main field. The features are integrated into a single controller with microprocessor architecture. Often, the operating software associated with the new excitation system allows for enabling and disabling of features important to the application. Table 1 identifies functions common to a new excitation system. In developing the technical specification, all features designed for the application should be specified to prevent mis-interpretations of the equipment needs.

Table 1. Voltage Regulator Features

Feature	Description
OPERATING MODES	
Voltage Regulation	Better than 0.20% accuracy 0-120% control range
Var/Power Factor Control	Maintains Constant Power Factor or Constant Vars
Automatic nulling	Between operating modes and/or redundant digital controllers for bumpless transfer
Voltage Softstart	Builds up terminal voltage slowly, based on programmed time intervals
Volts/Hertz Ratio Limiter	Maintains Volts/Hertz Ratio to prevent overfluxing of synchronous machine
Minimum Excitation Limiter	Flexible 5 point map on real/reactive power axis or internally-generated UEL curve
Maximum Excitation Limiter	Limits rotor heating due to excessively long periods of field overcurrent
Stator Current Limiting	Limits Stator Current after short time delay
Dual PID Setting Groups	Allows for programmed changes in PID gain settings for use with Power System Stabilizer to optimize voltage response with or without PSS
Autovoltage Matching	Automatically matches generator voltage to bus voltage
2 preposition set points	Programmable for AVR, Manual, Var/PF Controller
Reactive Droop or Line Drop Compensation	Provides Reactive Compensation
Transient Boost	Dynamically stabilizes the rotor after fault conditions
Loss of Voltage Sensing	Transfers to manual control automatically due to loss of voltage sensing at the voltage regulator
Oscillography	600 points, 6 programmable parameters, holds up to 6 records
Sequence of events	127 records
Real Time Monitoring	Chart Recorder for test analysis
Built-in Dynamic Analyzer	Measures frequency response of generator and excitation system
Protection	Field Over Voltage, Generator Over/Under Voltage, Field Overcurrent, Loss of Voltage Sensing, Loss of Field, Volts/Hertz Protection
Field Overvoltage, Generator Over/Under Voltage, Field Overcurrent, and Loss of Field Protection	Dual set points are selectable via programmable logic
HMI	Human Machine Interface that displays metering quantities, alarms, and provides control
IRIG-B Time Synchronization stamp	
Generator Field Temperature Monitoring	For use with brush-type or main field excited systems
2 Analog Transducer Outputs	4-20 ma Amp output
Built-in Power System Stabilizer	Optional - Type PSS 2A or selectable Frequency Type
Field Ground Detection	Detects field ground

V. Excitation Power for Rotating Exciters

For many steam or combustion turbine generators with brushless exciters, the voltage regulator system often is powered from a permanent magnet generator. The PMG (see Figure 8) is a self-excited generator that provides reliable three phase power (or sometimes single phase power) at some frequency, typically in the range of 120 to 500 Hertz, depending on the manufacturer. [5] The benefit of the permanent magnet generator is that the output is always constant regardless of degradation in terminal voltage due to fault or machine overload. As an alternative, some excitation systems use station power for the voltage regulator. Here, a 480Vac is commonly used to supply power into the rectifier bridges.

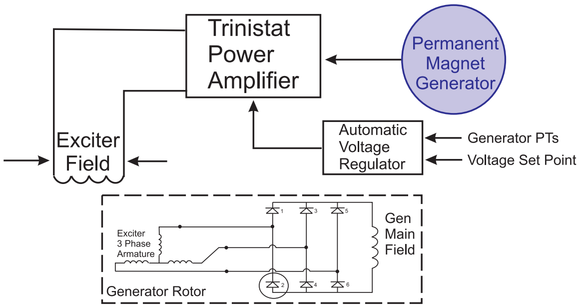

Figure 8. Permanent Magnet Generator for Brushless Rotating Exciter System

VI. Special Feature Considerations

Power System Stabilizer

Depending on the importance and size of the machine to the system, other features may be included to enhance the uptime reliability of the machine. Since the blackouts that occurred in the Eastern and the Western United States, the use of power system stabilizers has become increasing popular. In the Western United States, the WECC (Western Electric Coordinating Council) requires power system stabilizers on all machines 35 MVA and higher and on all groups of machines in a plant totaling 75 MVA. The power system stabilizer provides damping to power system oscillations that occur after a fault. [9]

Redundant Digital Controllers

For base loaded machines, redundancy usually is specified. The cost of a machine trip caused by an excitation failure can be costly. In the unlikely event it should occur, backup digital controllers will transfer and provide the means for the machine to remain on line. The end user may specify either a redundant full function controller and/or a redundant rectifier bridge for the system. See Figure 9.

The redundant digital controllers are set up for transfer to the backup controller in the event of a malfunction in the primary controller. Transfer can be based on an internal watchdog processor monitor that detects failure in the digital controller, accompanied by internal field overcurrent monitoring as well as independent external field overcurrent monitoring.

The redundant controller is equipped with duplicate features such as voltage regulation, manual control, var/Power Factor control, excitation limiters, and power system stabilizers. Each digital controller automatically tracks the other for a bumpless transfer. Depending on the manufacturer, the digital controller can be either drawout construction for easy on-line replacement or fix mounted.

Figure 9. Cabinet with Redundant Digital Excitation Control Systems

Backup Instrument Transformers

In the past, excitation systems offered an independent manual control as backup to the voltage regulator and a fault transfer in the event of the AVR failure. Now, the manual control is integrated into the digital controller and used only for commissioning and transfer in the event of loss of voltage sensing.

To avoid transfer to manual control in the event of loss of voltage sensing, it is not uncommon to specify a second set of instrument transformers to be supplied to the voltage regulator which is monitored by a 60 Balance relay. In the event of an instrument PT fuse failure, the 60 Balance relay permits automatic transfer to the second set of instrument transformers, allowing the excitation system to remain in voltage regulator mode. See Figure 10.

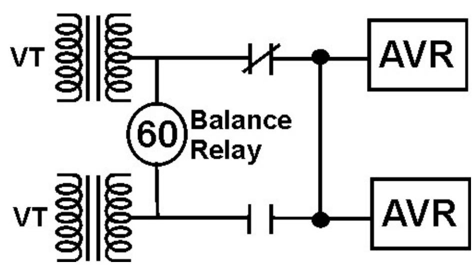

Figure 10. Dual Channel AVR with Dual Instrument Transformers

Redundant Bridge

Redundant rectifier bridges for base loaded machines also are common to avoid possible machine trip due to a failed SCR bridge. Depending upon field requirements, the bridges can be sized for 100% redundancy so each bridge is designed to carry the continuous rating of the field or N+1 redundancy where current is divided between multiple bridges and, if one bridge fails, the two remaining bridges will be able to meet the full load requirements. See Figures 11 and 12. Depending upon the manufacturer, the bridges can be either drawout or fixed rack design.

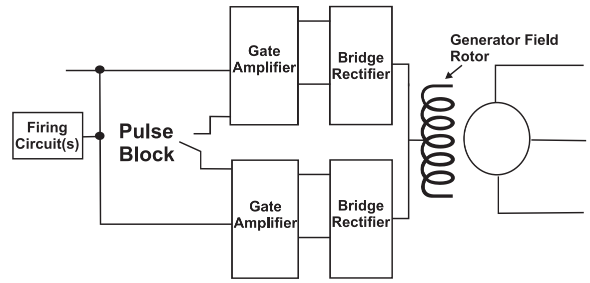

Figure 11. 100% Converter Redundancy

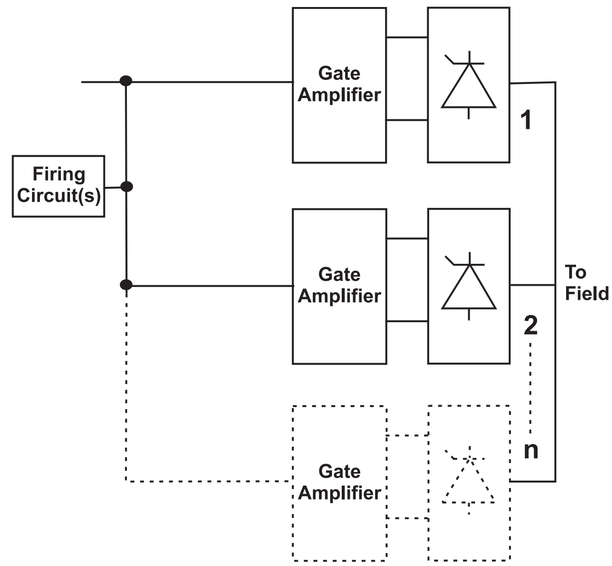

Figure 12. N+1 Converter Redundancy

Field Ground Protection

It is not uncommon to have field ground protection provided with new excitation systems. In some areas of the United States, insurance companies may require that a field ground relay be added to reduce the risk of a major failure due to multiple grounds on the field of the synchronous machine. There are various types of field ground relays available. A common type is one that has two levels of monitoring, a high level and a low level. The high level generally is set for 30,000 ohms and a low level generally is set for 5,000 ohms. Should the first field ground be detected, the higher ohm setting will provide adequate time to schedule a shutdown for investigation. Field ground relays are typical on all brush type exciter systems to monitor the main field. For brushless excited systems where the main field is not always accessible, radio frequency based transmitters are used at times to monitor the main field for ground.

VII. Environment

It is important to know the issues involved in equipment location. If there is possible dripping water, the cabinet needs to be specified with an overhead extended roof to keep moisture and water from dripping into the cabinet. If water splashing is possible, the cabinet should be equipped with louvers instead of punched holes and the louvers need to be located above the splash area.

Temperature can be a concern, as some power plants will become particularly warm. Although new equipment is fairly tolerant of high temperatures, if the temperature rises above 50°C ambient, long-term life can be affected. Steps can be taken by adding an air conditioner and/or locating the equipment in a controlled environment.

If the equipment is located outdoors near the seacoast, salted air spray can cause rusting and metal decay. The specification needs to call for the equipment to be located in an environmentally controlled room.

Space can become an issue if not considered in the project. The size of the exciter and transformer cabinet must be addressed to make sure there is space for each item, where the termination will be made, and how the conduit will be dropped into the cabinets. Consider how the exciter cabinet doors open. If the exciter cabinet has two doors, having them open from the center can be useful. Specifying lighting and outlets in the cabinet help insure a comfortable working area when commissioning begins or for followup maintenance.

Where drawings are available, provide layout drawings as well as an interconnect drawing of the existing system. Note the available power supply voltage control power; e.g. 120 Vac and 125 Vdc are important.

VIII. Exciter Models

Transfer function of the voltage regulator system is important information in order that transmission planners can properly analyze data against real time performance of the generator and excitation system. It is important to specify model requirements at the time of equipment specification as well as the type, AC8B for rotating exciters and ST4B for Static Exciters. See Figure 13. [3, 12]

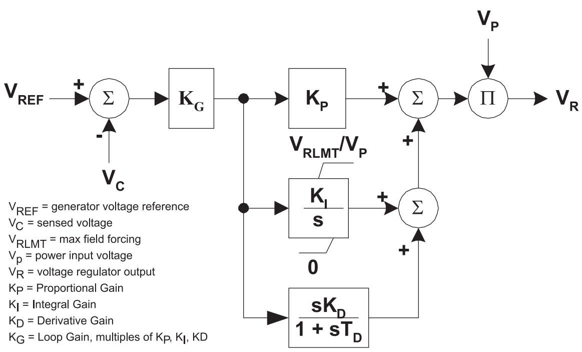

Figure 13. Typical Model of AVR with PID Control

IX. Turnkey

Today, power plant personnel can be in short supply with changes in personnel structure. Where plant personnel often would have performed the design detail and installed the new excitation system, today's shortage of manpower may prevent this in many cases and outside contractors are used to accomplish the task. The level of involvement may include total turnkey or technical direction. [10]

Defining the Project

To have a successful project, communication between the end user and the vendor is necessary. The following outlines a summary needed by the vendor:

1. Defined schedules.
2. Drawings (system elementaries, connections, and interconnections) of the existing system.
3. Generator design data and curves.
4. Cable and conduit availability
5. Review how the interface is to be developed, from contacts inputs or digitally input from a RS-485 serial communication.
6. Documentation format for the final drawings.

7. Technical training schedule.
8. Technical specification.

<u>Customer Expectations from the Turnkey Contractor</u>

1. System Interconnection Drawings.
2. Electrical Construction Details.
3. Specification of all Installation Materials.
4. Bill of Material to include installation materials, additional interface relays, control switches, indicating lights, meters, etc.
5. Demolition details.
6. Installation details.
7. Interface details.
8. Electrical layout.
9. Grounding details.
10. Cable and conduit schedule.
11. Wire schedule for all modification work.
12. Equipment Interconnection Diagram.

<u>Final Documentation</u>

1. All instruction manuals that apply to all of the equipment.
2. New recommended operational procedures.
3. Elementary and Construction Drawing Package.
4. Software settings for the new excitation system.
5. Operating software for the new excitation system.
6. Spare and Renewal Parts information.

X. Startup and Commissioning

Outage schedules continuously are being reduced to maximize power production, while commissioning time for the new equipment is often pushed to a minimum to meet market power demands.Time spent in commissioning represents lost revenue. Hence, the emphasis on testing makes it important to have tools built into the operating software of the new excitation system to speed the effort. See Figure 14. [4]

These commissioning tests will minimally include:

1. Startup and Sequence Logic Checkout
2. Off-line and On-line generator voltage step responses (See Figure 15)
3. Under Excitation (See Figure 16) and Over Excitation Limiter testing
4. Volt/Hertz Limiter
5. Autotracking verification between operating modes and Digital Controllers
6. Frequency Response Testing
7. Power System Stabilizer Testing

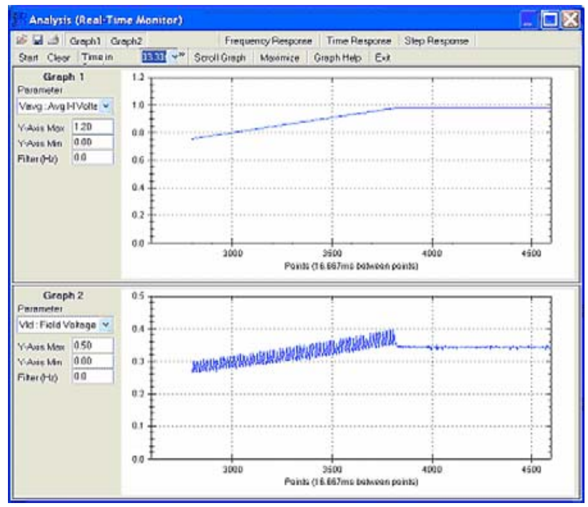

Figure 14. Voltage Buildup in Voltage Regulator Mode at Startup Commissioning

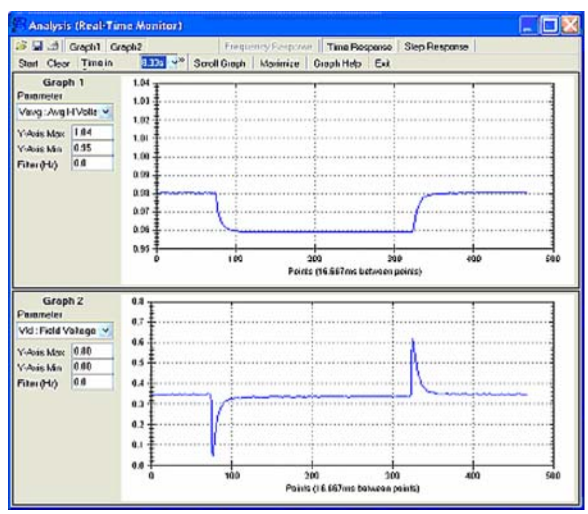

Figure 15. Open circuit 5% Generator Voltage Step Change, Voltage Regulator Mode

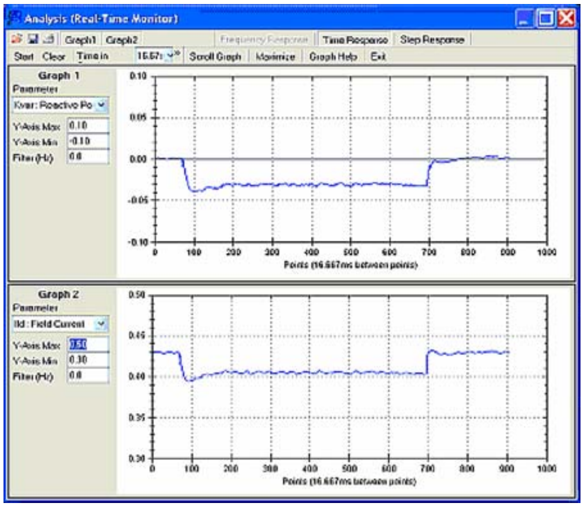

Figure 16. Under Excitation Limiter Dynamic Step Test

Figure 14 shows results of the generator voltage buildup during initial commissioning. The top graph illustrates the generator voltage, while the lower graph denotes the accompanied field voltage.

Off-line voltage step responses (illustrated in Fig. 15) are introduced for a 5% generator voltage step change from the initial set point.

Figure 16 illustrates Underexcitation Limiter stable operation when a large voltage step change has been initiated.

A final report of all of the performed tests should be expected at time of completion of the equipment testing, including oscillography record fields, setting files, and calibration data. Where a power system stabilizer is involved, often a third party may provide recommended settings for the power system stabilizer and may create a report that is provided to the customer that represents the regional needs to comply with NERC. [9]

XI. Guide Specifications for Reference

Over the years, IEEE has created a number of technical specifications to help the end user to prepare the purchasing document needed to define the excitation system. These reference specifications include IEEE 421.4 "Guide for the Preparation of Excitation System Specifications" and IEEE 421.2 "Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control System". [1, 2] Where NERC is involved, the WECC requires these tests to be documented and submitted in a report, along with other pertinent data. [11] When a specification is intended to be applied to some portion of the specifying document, it should be referenced at the sentence it is being applied.

Conclusion

When specifying the excitation system, it is important to share all the information that is pertinent to proper selection. Definitions of performance, location, features, and drawing documentation are necessary. The Appendix highlights the questions that should be addressed to help ensure the specification accurately defines the equipment needs.

References

[1] IEEE Std. 421.2-1990, IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems

[2] IEEE Std. 421.4-1990, IEEE Guide for Specification for Excitation Systems

[3] IEEE Std. 421.5-1992, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.

[4] Brimsek, M., Kim, K., Rao, P., and Schaefer, R.C., "Feature Enhancements in New Digital Excitation Systems Speeds Performance Testing", Presented at Doble Client Conference, April 2006.

[5] Demcko, J., Vachon, T., Stendin, A., Schaefer, R.C., and Ross G., "New Solutions for Brushless Exciter Rectifying Modules Reduce Down Time During Overhaul", Presented at EPRI Workshop, August 2005.

[6] Schaefer, R., "Why Static Excitation?", Presented at Basler Electric Power Control and Protection Conference, October 2007.

[7] ANSI C50.13-1989, Requirements for Cylindrical Rotor Synchronous Generators.

[8] R. Schaefer, "Application of Static Excitation Systems for Pilot and Rotating Exciter Replacement," Presented at Basler Electric Power Control and Protection Conference, October 2007.

[9] Kral, D., and R. Schaefer, "Easing NERC Testing with New Digital Excitation Systems," Presented at EPRI General Meeting, January 2008.

[10] Estes, J., and R. Schaefer, "Retrofitting SCT/PPT Excitation Systems with Digital Control", Presented at IEEE/IAS Pulp & Paper Conference, June 2002.

[11] NERC Standards web site - http://www.nerc.com NERC/WECC Publication doc. http://www.wecc.biz.

[12] Kim, K., and R. Schaefer, "Tuning a PID Controller for a Digital Excitation Control System", Presented at Basler Electric Power Control and Protection Conference, October 2007.

[13] Schaefer, R., "Discussion: Excitation System Redundancy", IEEE PES Equipment Working Group of the Excitation System Subcommittee, Presented July 22, 2008.

SPECIFYING EXCITATION DATA

Project # ____

MACHINE DATA

Turbine-Generator Size & Mfg: ______MW ________________________Manufacturer
Turbine Drive Type: ____Steam ____Gas ____Hydro ____Diesel
Is this a *Voltage Regulator* System Retrofit project? _____yes _____no
Is this a *Static Excitation* System Retrofit project? _____yes _____no

What is the environment at the Exciter Cubicle (dry, wet, dirty, etc.)? ______________________
Describe Conditions ____
What is the Ambient Temperature of the equipment location? ______________________
Does system have a *Main Rotating Exciter*? _____yes _____no
What is the existing *System Control* Power? _____125VDC _____250VDC
Is 120VAC *Control* Power available in the exciter cubicle? _____yes _____no

What is the Excitation Power Source?

Static Exciter:
Generator Output _____yes _____no
Station Power _____yes _____no

Rotating Exciter Voltage Regulator Applications
Generator Output _____yes _____no
PMG (Permanent Magnet Generator) _____yes _____no
Station Power _____yes _____no

Specify Station Power Voltage: ________
Where Station Power is used, is backup ac Station with power transfer switch required? _____yes _____no

GENERATOR DATA

Manufacturer: ____
Voltage: ____
MW: _______________ MVA: _______________
Power Factor: _______________ Frequency: _______________
RPM: _______________ Stator Amps: _______________
Coolant Type: _______________

FIELD DATA

Rated Full Load Field Voltage: ___________ Amps: _______________
115% MVA @ 105% Generator Voltage Field Voltage: _________ Field Amps: _______________
(See Technical Paper page 1)

MAIN ROTATING EXCITER DATA

Armature Voltage: _______________ Armature Amps: _______________
KW: _______________
Exciter Shunt Field Ohms: _______________ Rated Exciter Shunt Field Voltage: _______________
Full Load Exciter Shunt Field Amps: _______________
Is this a *Brush Type* Exciter? _____yes _____no
Is this a *Brushless* Exciter? _____yes _____no
What are the ratings of the Permanent Magnet Generator? ____Volts ____Amps ____Hz ____# of phases

ADDITIONAL FEATURE CONSIDERATIONS BEYOND THOSE SPECIFIED IN TABLE 1

Is *black start* required? _____yes _____no
Is a redundant *digital controller* needed? _____yes _____no
Are redundant *SCR Bridges* required? _____yes _____no
Will a *Power System Stabilizer* be required? _____yes _____no
Is a redundant digital controller needed?
Will a *PSS Tune-up* be required as part of this project? _____yes _____no
Is automatic transfer to redundant instrument PTs required? _____yes _____no
Is 60 balance relay transfer to second instrument PTs required? _____yes _____no
Is turnkey install required? _____yes _____no
Is commissioning required by manufacturer? _____yes _____no
Special Field Forcing Requirements? _____yes _____no
Define: ____
Special Power Potential Transformer Consideration? _____yes _____no
Define: ____
Is Excitation Model Information required? _____yes _____no
Field Ground Relay? _____yes _____no
Automatic Synchronization? _____yes _____no

DRAWING DOCUMENTATION

Schematic Interconnect Drawing
Outline Drawings
Other Special Drawing Considerations

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