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Excitation Control of the Synchronous Generator

In a world of change, new technologies replace old ones ever-more quickly. In the early years, change was slow as the evolutionary process transitioned from electromechanical voltage regulators with motor-driven rheostats to high-gain rotating exciters. These exciters included such systems as the Amplidyne, Regulex, and Rototrol, which improved performance to control the generator output. In the past 30 years, however, change has progressed from magnetic technology to analog control. Analog excitation represented the multiple component module assembly with interlooping wire interconnections (see Fig. 1).

Today, we see another major technology change, a movement away from analog control to digital control. An excitation system is now reduced to a single integrated assembly that includes the automatic voltage regulator (AVR), field current regulator (manual control), excitation limiters, and even protection [3]-[6]. Reliability is enhanced as multiple devices are implemented into the single component with multitasking microprocessors. Fig. 2 highlights a classic digital excitation system interconnected in a generator system.

A single component forms the primary element of the excitation system. Inputs include the instrument transformer for voltage sensing, current transformer signal from a line CT, and bus voltage transformer used for voltage matching. The output of the controller is an analog signal designed to work directly into a separate firing circuit that generates pulses for a three-phase, fullwave rectifier bridge to control the field (see Fig. 2).

In digital systems, the guidelines for selecting the power potential transformer and rectifier bridge are similar to methods utilized for analog systems. Input signals for raise/lower or start/stop can be controlled by a variety of methods. These include contact inputs, an RS485 serial communication port, or a PC using ASCII language connected into an RS232 serial communication port. Flexibility in digital systems offers more efficient methods to accomplish automation, which lowers installation cost.

Analog versus Digital Controller

In the past, shaping the generator response using an analog excitation system was a matter of adjusting potentiometers or adding or deleting capacitors and resistors in the control loops of the voltage regulator stability circuit. Adjustments could be very time consuming because changes would often involve turning the excitation system on and off

Fig. 1. A comparison of an analog-controlled excitation system (left) and an integrated, digitally controlled excitation system (right).

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many times to make modifications. Fig. 3(a) is a block diagram of a typical analog lead-lag controller utilized in the automatic voltage regulator control loop. The feedback gain (K_F) was adjusted by a potentiometer to achieve stable performance.

An optimally tuned excitation system offers benefits in overall operating performance during transient conditions caused by system faults, disturbances, or motor starting [5]. During motor starting, a fast excitation system will minimize the generator voltage dip and reduce the I^2R heating losses of the motor. After a fault, a fast excitation system will improve the transient stability by holding up the system and providing positive damping to system oscillations. Additionally, a well-tuned excitation system will minimize the voltage overshoot after a disturbance and avoid the nuisance tripping of generator protection relays.

Today, the digital excitation system provides the means to easily access the challenging parameters of the analog system. The heart of most digital controllers is the embedded microprocessors that perform various control functions for the excitation system. These control functions include the automatic voltage regulator, field current regulator (manual control) Var/power factor control, and a host of excitation limiters to regulate and maintain the generator within safe operating limits of the machine.

Fig. 3(b) is a block diagram of a PID block utilized in the AVR control loop. The P term represents the proportional gain, which affects the rate of voltage rise after a step change. The I term represents the integral gain, which affects the generator voltage settling time after the initial voltage overshoot. Lastly, the D term represents the derivative gain, which affects the percent of overshoot allowed after the system disturbances. The derivative term is used with those excitation systems that have a rotating exciter. For main field-excited systems, the D term is not required. Since the derivative term affects the amount of generator overvoltage, the lower the voltage overshoot, the faster the voltage recovers to nominal. The combined effect of the PID terms will shape the response of the generator excitation system to reach the desired performance. In addition to PID, K_G (loop gain) also provides an adjustable term to compensate for variations in system input voltage to drive the power converting bridge. Variations in K_G modify the PID terms by the same proportions to vary the overall performance.

Today, a wide range of the PID gains can be easily selected using PC menu screens as shown in Fig. 6 or a front-panel display.

The evaluation of system performance begins by performing voltage step responses to examine the behavior of the excitation system with the gen-

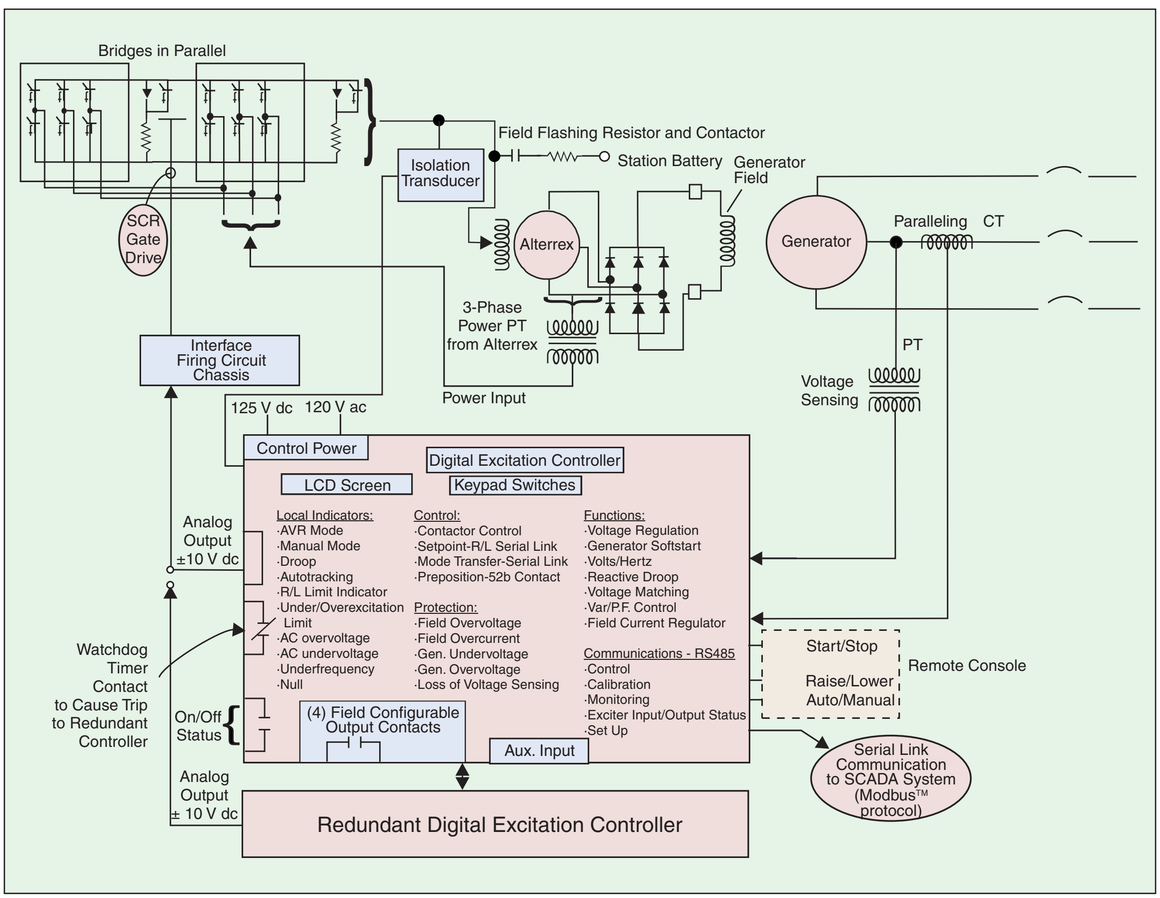

Fig. 2. A typical digital excitation control system.

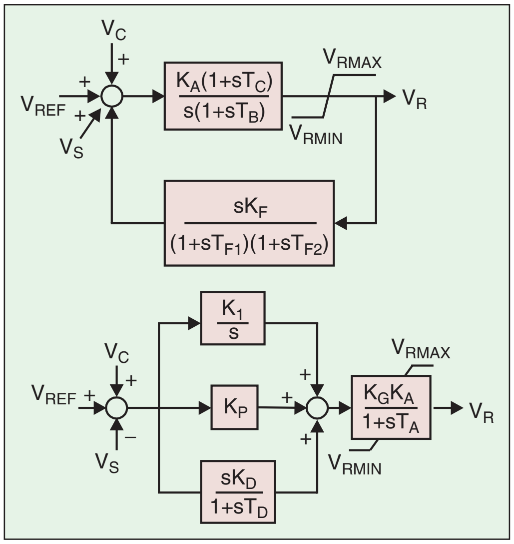

Fig. 3. Simplified block diagrams of automatic voltage regulators. (a) Analog AVR with lead-lag controller. (b) Digital AVR with PID controller.

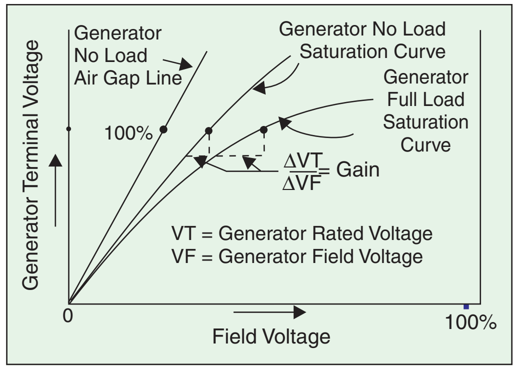

Fig. 4. Generator saturation curve illustrating generator gain.

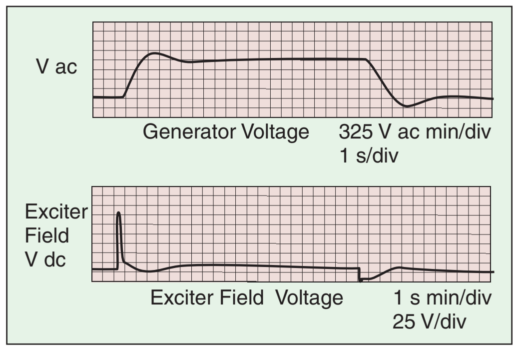

Fig. 5. Voltage step responses performed on a hydro turbine generator with analog voltage regulation.

erator. It is performed with the breakers open because the generator is in the least stable condition, i.e., the least saturation and the highest gain (see Fig. 4). Similar tests can be performed with the generator breaker closed, but with caution. Here, the voltage step change needs to be very small to avoid large changes in generator vars.

Comparing Analog to Digital Control System Performance

Performance comparison and tuning techniques are demonstrated by replacing the analog excitation system controlling the field of a rotating exciter with a digital system.

Analog system: The analog voltage regulator was installed on a hydroturbine generator in the late 1980s for a machine rated for 40 MVA, 13,800 V ac, at 0.85 pf. It has a 14-s main field time constant and a 2-s exciter field time constant.

One of the factors affecting machine performance is the generator field time constant. As the machine time constant increases, the speed of system response slows due to the inherent lag caused by the field inductance that will resist change. Additionally, since many systems have rotating exciters, the speed of response is further attenuated because of the additional phase lag introduced by the second field (see Fig. 2).

Fig. 5 and Table I represent step responses performed with the system described above. The original analog excitation system used a lead/lag stability network and a three-phase, single-quadrant, halfwave-controlled semiconductor- controlled rectifier (SCR) bridge for field control [7]. The excitation system was designed to provide 5 p.u. field forcing to speed the response of the generator.

IEEE 421.2 [8] provides the guidelines for performance analysis after a voltage step change. Here, a criterion is established for expected ranges of voltage overshoot, voltage rise times, and settling time. Depending upon the type of excitation provided and the type of control used, performance expectations will vary from acceptable to excellent.

For these tests, a voltage step change was introduced into the voltage regulator setpoint causing the generator voltage to move from 12.2 to 13.5 kV ac. During the test, generator voltage overshoot reached 303 V ac before recovering to nominal. The generator voltage reached the peak value in 3.5 s,

Table I. Initial Performance

Starting Generator V ac	*Final Generator Voltage*	*Generator Voltage Overshoot from Final Settling Value*	*Rise Time to Reach Peak*	*Voltage Recovery Time*
12.2 kV	13.5 kV	303	3.5 s	7.5 s
	Exciter field forcing	Field response		
	160 V dc	Optimum		

with total recovery in 7.5 s. Note the generator voltage swing prior to the generator voltage settling to the steady state value. During the initial tuning of the analog excitation system, different phase lead and lag compensation was implemented to determine best settings for performance. This was accomplished by adding external capacitors to optimize unit performance.

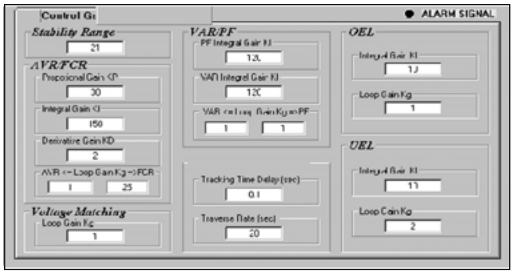

Fig. 6. Typical graphical user interface allows digital excitation controller setup.

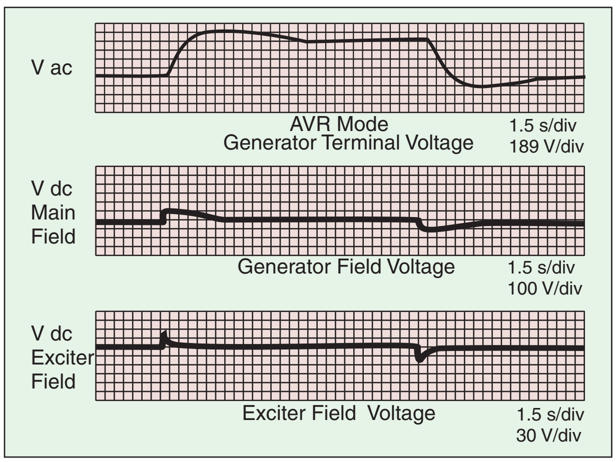

Fig. 7. Initial performance settings for PID controllers.

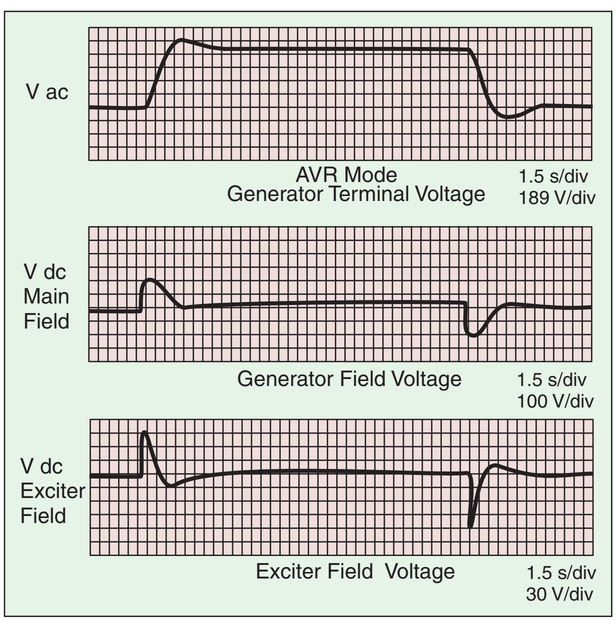

Fig. 8. Increased PID gains.

Digital system: After testing was completed using the analog system, the digital controller was installed. The new excitation system included a two-quadrant power SCR bridge that could provide both positive and negative field forcing, combined with a digital controller to hasten flux changes in the field winding and quicken system voltage recovery.

With the use of digital control, the ingredients for fast, but stable performance can be readily accommodated by adjusting the controller gains. To set the control gains, a graphical user interface, such as the one shown in Fig. 6, provides the user with an accessible method to modify the PID gains as well as loop gain (K_G) settings. The loop gain compensates for variations in system configuration that are associated with the power input voltage used to drive the SCRs in the field circuit. Variations in the magnitude of K_G loop gain affect the overall response.

To analyze the effect of the PID gains on generator performance, a number of tests were executed. The voltage step changes were performed open circuited in 5% voltage steps to increase and decrease generator voltage. Fig. 7 illustrates initial performance settings for the PID controllers prior to optimization. Initial readings indicate performance with voltage overshoot reaching 168 V ac from a 13.2-kV ac base value. The generator voltage takes 4.5 s to reach the peak voltage and more than 10 s to recover back to nominal after the step change.

Notice that the field voltage offers very little field forcing during the disturbance and the field voltage is very slow to decay back to the steady-state value (see Table II).

In the next test, the PID gains were modified to improve transient performance (see Fig. 8).

Here, the derivative gain (K_D) was increased from 100 to 120, the proportional gain (K_P) from 80 to 200, and the integral gain from 20 to 30. The voltage overshoot now reduces to 100 V ac as the increased derivative gain anticipates voltage recovery and improves damping. Note that the time it takes to reach the voltage maximum is down to 2 s, and the total recovery time is now only 4.5 s. As the gains were increased, the voltage regulator now reaches 110 V dc, and the field voltage becomes under damp momentarily and forces the field a negative 15 V dc (see Table III).

Fig. 9 further demonstrates the performance variation, as PID gain settings are further modified to improved system performance. An increase of the proportional gain from 200 to 300 reduces the time to reach the maximum voltage peak to 1.5 s. At the same time, increasing the derivative gain from 120 to 150 decreases the voltage overshoot to a level of 48 V ac. Notice how field behavior produces the cause and effect that improves performance, i.e., higher field forcing, faster response.

Table IV shows that the field forcing now reaches 140 V dc positive and becomes temporarily underdamp, forcing the field a −25 V dc before recovering to nominal. The total response improves to 3.2 s.

Fig. 10 highlights further improvements as gains settings determine the final performance of the generator. Increasing the derivative gain from 150 to 200 causes the generator voltage overshoot to be nearly zero, and the voltage recovery, since the voltage overshoot is nearly eliminated. Response time becomes 1.5 s (see Table V).

Step response tests can be performed using the graphical interface tools to enhance system performance and minimize commissioning time. The above study clearly demonstrates the performance tuning benefits of the digital system over the analog system.

Frequency Response Boosts Performance Analysis

A more complex method of determining generator voltage stability and unit performance is by performing a frequency response of the excitation system with the generator over a range of frequencies. This is known as a "closed-loop" analysis. The closed-loop frequency response provides information on the behavior of the excitation/generator system over a frequency range that represents the potential oscillating region of the generator system.

The test is performed by injecting a small sine wave at various frequencies (0.1 to 3.0 Hz) into the summing point of the excitation controller and measuring the response of the generator terminal voltage. Various methods are used to analyze system performance such as Root Locus, Nyquist, and Bode. In this study, Bode plots are utilized to compare phase versus frequency and gain versus frequency to evaluate system performance. The Bode plots show phase shift and relative gain of the overall generator system. For good performance, the gain should remain essentially flat at the low frequencies, then fall off as the signal frequency increases. It is important for the gain to remain high over a wide bandwidth for greater contribution to positive damping. The peak value of gain just before it rolls off is an indicator of the voltage overshoot during voltage step changes. Typically a 2-4 dB rise as referenced in IEEE 421.2 "Performance Guidelines to Testing and Evaluating Generator Performance" is favored for good system response. Peak values higher than 4 dB would imply potentially unstable systems [9].

Figs. 12 and 13 represent the closed-loop frequency response of the two excitation systems under study. They are used to demonstrate the difference in performance based upon the optimum settings established during the voltage step changes. Notice in Fig. 12, the maximum gain is zero at 0.1 Hz and quickly falls as the frequency is increased to 1.0 Hz. The phase shift follows similarly as it falls from −40 at 0.1 Hz to −160° at 1.0 Hz. The gain and phase shift exhibited illustrates a very sluggish responding system as noted in Fig. 4.

The range of 0.1 to 0.3 Hz represents the critical frequency of the generator. The critical frequency of the generator is derived from the 90° phase shift produced from the main field and the 90° phase lag caused by the exciter field. The two 90° phase shifts add directly to provide 180° phase

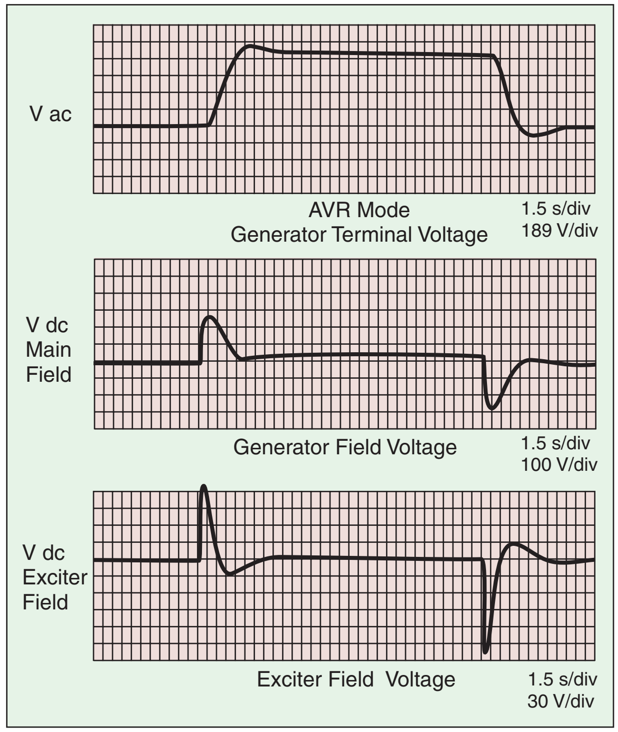

Fig. 9. Performance variation with modified P+D settings.

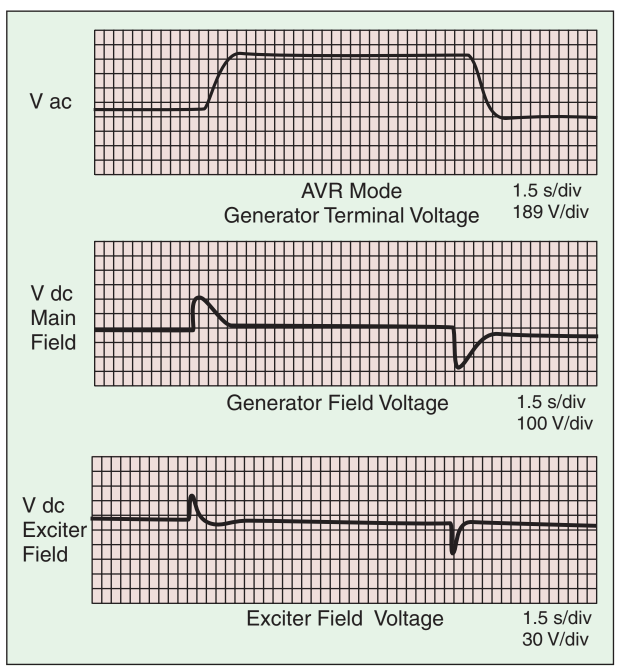

Fig. 10. Further improvements with gain settings increasing derivative (KD).

lag. The actual critical frequency depends upon the machine time constant; the larger the machine time constant, the lower the critical frequency. For this system, the range of 150 to 180° phase lag in the range of 0.1 to 0.3 Hz represents the potential oscillating area of the generator, which when combined with the overall loop gain of the generator, exciter, and voltage regulator can result in instability if the gain is equal to one. The excitation stability network minimizes the lagging phase shift to provide a stable and quickly responding system.

Fig. 13 illustrates the Bode plot of the digital excitation system utilizing optimized PID gains noted in Fig. 10 and Table V. Notice how the gain remains relatively flat from .05 to 0.2 Hz, then peaks (3 dB above nominal) and rolls off as the signal frequency increases. The slight gain rise at 0.2 Hz provides desirable positive damping and com-

Table II. Initial Performance Settings for PID Controllers

Starting Generator V ac	*Final Generator Voltage*	*Generator Voltage Overshoot from Final Settling Value*	*Rise Time to Reach Peak*	*Voltage Recovery Time*
12,552	13,180	168	4.5 s	14 s
KG – loop gain		KD – derivative gain	KP – proportional gain	KI – integral gain
10		100	80	20
	Excitation field forcing	Field response		
	90 V dc	Very sluggish		

Table III. Results of Increased PID Gains

Starting Generator V ac	*Final Generator Voltage*	*Generator Voltage Overshoot from Final Settling Value*	*Rise tTme to Reach Peak*	*Voltage Recovery Time*
12,483	13,107	120	2.0 s	4.5 s
KG – loop gain		KD – derivative gain	KP – proportional gain	KI – integral gain
10		120	200	30
	Exciter field forcing 110 V dc	Exciter field response under damp -15 V dc		
	110 V dc	Under damp -15 V dc		

Table IV. Results of Further Modification to PID Gains

Starting Generator V ac	*Final Generator Voltage*	*Generator Voltage Overshoot from Final Settling Value*	*Rise Time to Reach Peak*	*Voltage Recovery Time*
12,552	13,180	48	1.5 s	3.2 s
KG – loop gain		KD – derivative gain	KP – proportional gain	KI – integral gain
10		150	300	30
	Exciter field forcing	Exciter field response		
	140 V dc	Under damp -25 V dc		

Table V. Results of Further Improvements to Gain Settings

Starting Venerator V ac	*Final Generator Voltage*	*Generator Voltage Overshoot from Final Settling Value*	*Rise Time to Reach Peak*	*Voltage Recovery Time*
12,544.8	13,171	5 V ac	1.5 s	1.5 s
KG – loop gain		KD – derivative gain	KP – proportional gain	KI – integral gain
10		200	300	30
	Exciter field forcing	Exciter field response		
	150 V dc	-10 V dc		

pliments the performance observed during the voltage step responses in Fig. 10 as being optimal.

Tools for Easier Programming

To simply the process of custom tuning the excitation, tools are available in the excitation system to provide starting gains for the PID settings needed for commissioning. The often-provided graphical user interface screens are used to help select the PID numbers for the excitation controller stability. Here, the time constant of the generator fields is typed into a user screen and the PID numbers are automatically calculated. Step responses are then performed to verify system performance.

Although this article focuses primarily on PID settings of the voltage regulator controller, other control loops such as excitation limiters, var/PF controllers [10], and field-current regulators utilize similar gain-setting techniques for control system optimization. As before, step responses are again used to verify that the settings in the controllers will deliver stable operation when limits are reached or other modes enabled.

Conclusion

It has become increasingly important to have an optimally tuned excitation system to provide the highest degree of reliability possible for the system. The use of digital controllers helps dramatically improve the transient stability of the system with tools to easily achieve ideal performance [11]. Tuning of the overall system can be accomplished in a short period of time, even if the data supplied is incorrect. The changing of parameters can be quickly accomplished. This is not the case with the analog-type regulator used here. Certain startup functions can be easily accomplished, such as step changes and monitoring of operating levels, with the internal functions of the digital program. New technology provides a medium to achieve a higher standard of quality control in generation.

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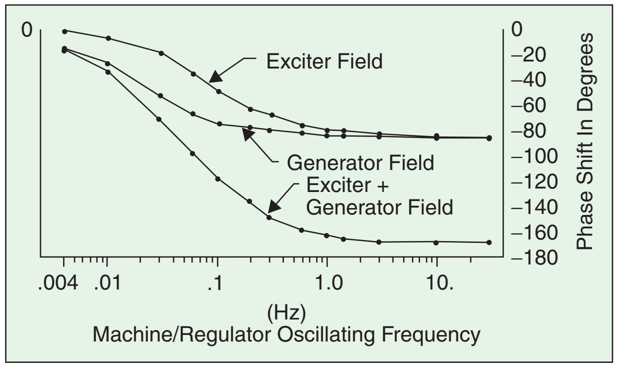


Fig. 11. Phase shift of the exciter field, the generator field, and the sum of the two.

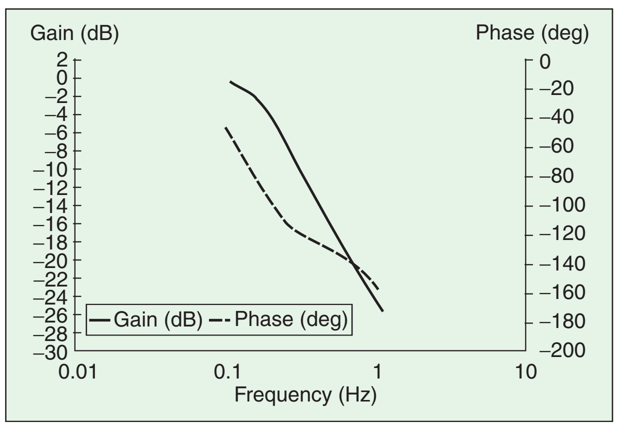
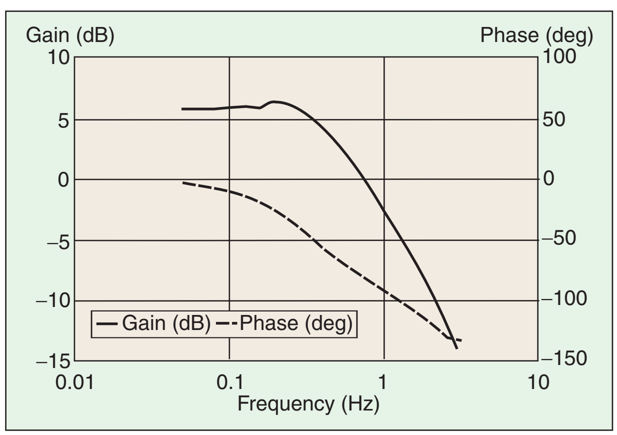


Fig. 12. Bode plot of off-line frequency response with analog voltage regulator.



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