

# Tuning a PID Controller for a Digital Excitation Control System

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Some of the modern voltage regulator systems are utilizing the Proportional, Integral, and Derivative (PID) control for stabilization. Two PID tuning approaches, pole placement and pole-zero cancellation, are commonly utilized for commissioning a digital excitation system. Each approach is discussed including its performance with three excitation parameter variations [1]. The parameters considered include system loop gain, uncertain exciter time constants, and forcing limits. This paper is intended for various engineers and technicians to provide a better understanding of how the digital controller is tuned with pros and cons for each method.

## Introduction

Today's digital excitation systems offer numerous benefits for performance improvements and tuning over its analog voltage regulator predecessor. The analog voltage regulators commonly used a rate feedback control to provide voltage regulation stability. Potentiometers, screwdrivers, and voltmeters were the common tools used to calibrate the operating system, but today, digital excitation systems are tuned very precisely with the aid of a laptop computer and data is recorded into a file for future performance comparison in the form of an oscillography record.

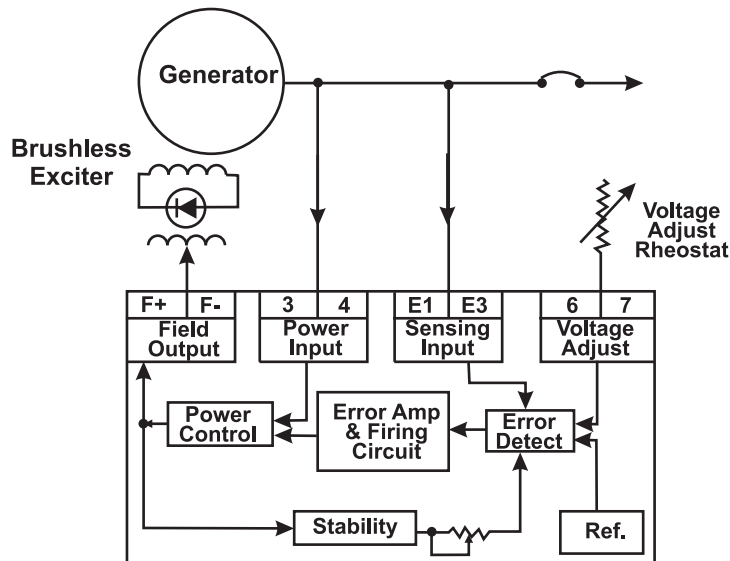


Figure 1. Typical VR with Rate Feedback

## PID Control

The present day digital regulator utilizes a PID controller in the forward path to adjust the response of the system. For main field excited systems, the derivative term is not utilized. The proportional action produces a control action proportional to the error signal. The proportional gain affects the rate of rise after a change has been initiated into the control loop. The integral action produces an output that depends on the integral of the error. The integral response of a continuous control system is one that continuously changes in the direction to reduce the error until the error is restored to zero. The derivative action produces an output that depends on the

rate of change of error. For rotating exciters, the derivative gain is used which measures the speed of the change in the measured parameter and causes an exponentially decaying output in the direction to reduce the error to zero. The derivative term is associated with the voltage overshoot experienced after a voltage step change or a disturbance. The basic block diagram of a PID block utilized in the automatic voltage regulator control loop is shown in Figure 3. In addition to PID block, the system loop gain ( $K_G$ ) provides an adjustable term to compensate for variations in system input voltage to the power converting bridge. When performance is measured, the voltage rise time is noted at the 10% and 90% level of the voltage change. The faster the rise time, the faster the voltage response [5].

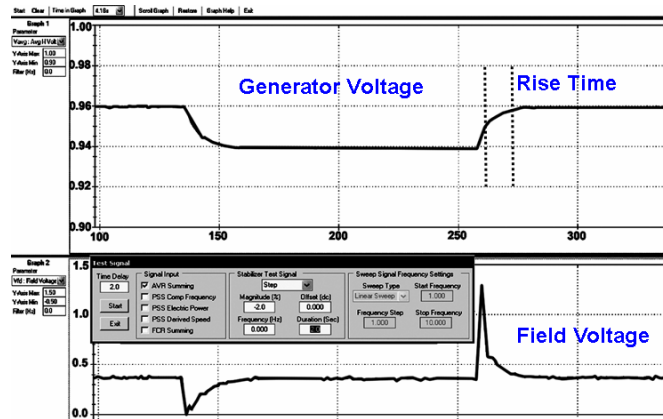


Figure 2. Voltage Rise Time

The benefits of a fast excitation controller can improve the transient stability of the generator connected to the system or, stated another way, maximize the synchronizing torque to restore the rotor back to its steady state position after a fault. A fast excitation system will also improve relay tripping coordination due to the excitation systems' ability to restore terminal voltage quickly, and providing more fault current to protective relays for optimum tripping time.

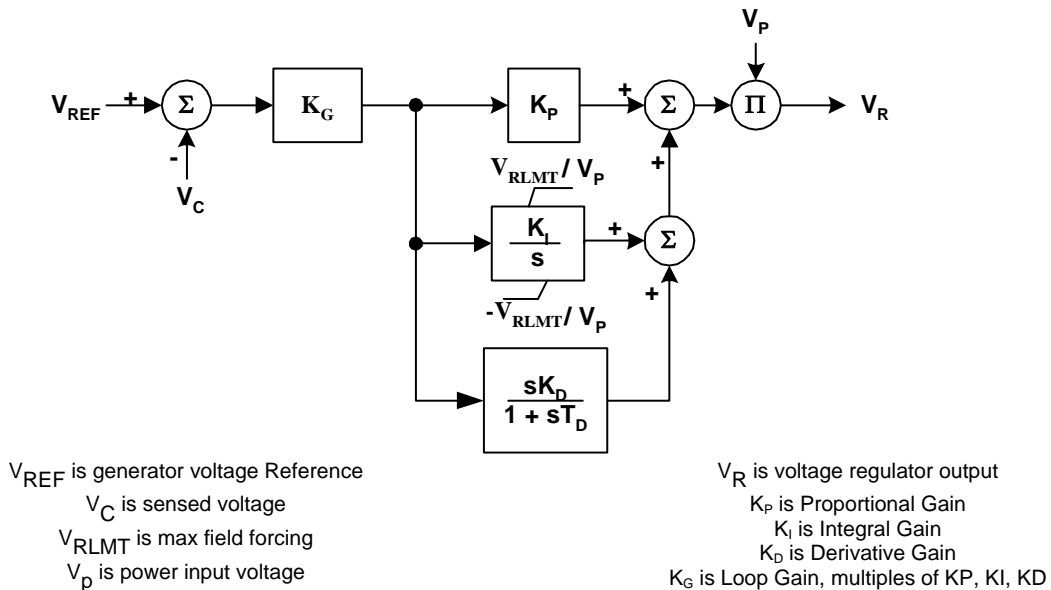


Figure 3. Simplified Block Diagrams of Automatic Voltage Regulators

## Characteristic of Excitation Control Systems

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.

A fast excitation system offers numerous advantages, improved relay coordination and first swing transient stability, however an excitation system tuned too fast can potentially cause MW instability if the machine is connected to a voltage weak transmission system. For these systems a power system stabilizer may be required to supplement machine damping.

The evaluation of system performance begins by performing voltage step responses to examine the behavior of the excitation system with the generator. It is performed with the generator breaker open, since the open circuited generator represents the least stable condition, i.e. the highest gain and the least saturation (See Figure 4). Figure 5 represents a block diagram of an exciter-generator and Figure 6 represents the phase shift of the generator and exciter field for a sweep frequency from 0-12 Hertz. The frequency plot represents the potential voltage oscillation frequency after a disturbance. The time constant of the generator field and the exciter field is plotted and illustrated to show that as the frequency increases, the phase angle becomes more lagging. The phase angle of the generator field adds directly with the phase angle of the exciter field. As the phase angles add to 180 degrees, the system will most likely become unstable because of the combined gain of the generator and the excitation system. Unless compensated properly through the PID controller, the synchronous machine may become oscillatory after a fault [8].

A control system that exhibits a phase lag of 180 degrees at a frequency where the open loop gain is equal to or greater than one will result in an unstable system when the control loop is closed. The combination of a rotary excited generator and a high gain AVR will contain more than two poles, making it possible to have a phase shift of 180 degrees with a gain greater than one. This is the reason that a high gain automatic voltage regulator requires a well-designed stability circuit to achieve stable operation.

Besides the open circuit voltage step test, another test performed is the voltage step test with the generator breaker closed. When voltage step tests are performed with the generator breaker closed, very small percentage voltage steps are introduced to avoid large changes in generator vars. In this case, a 1-2% voltage step change is typical [7].

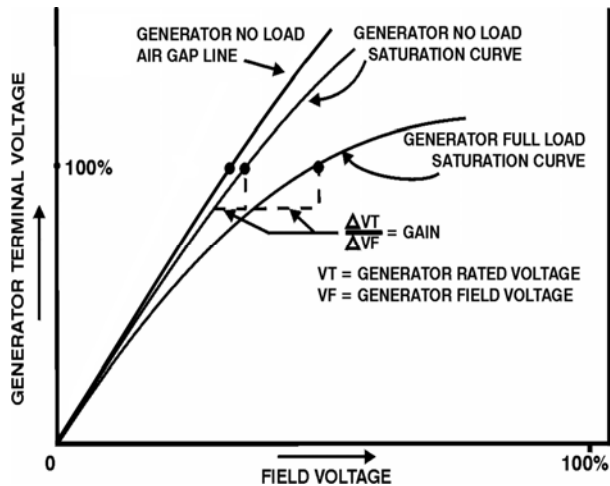


Figure 4. Generator Saturation Curve Illustrating Generator Gain

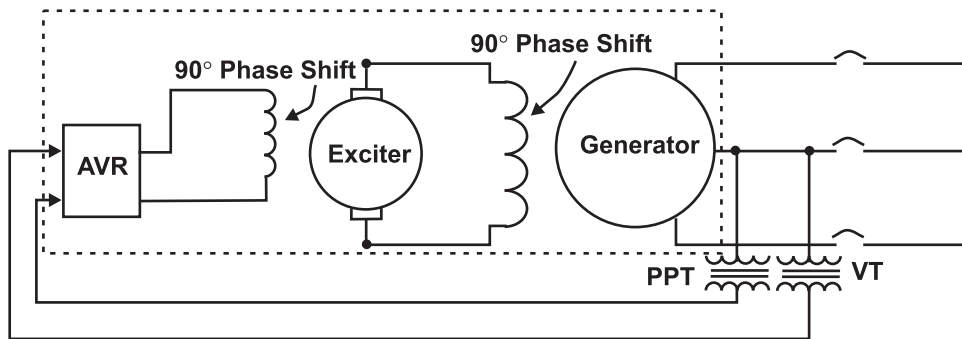


Figure 5. Ingredients for Poor Stability Compensation  
Unity Gain + 180° Phase Shift = Voltage Instability

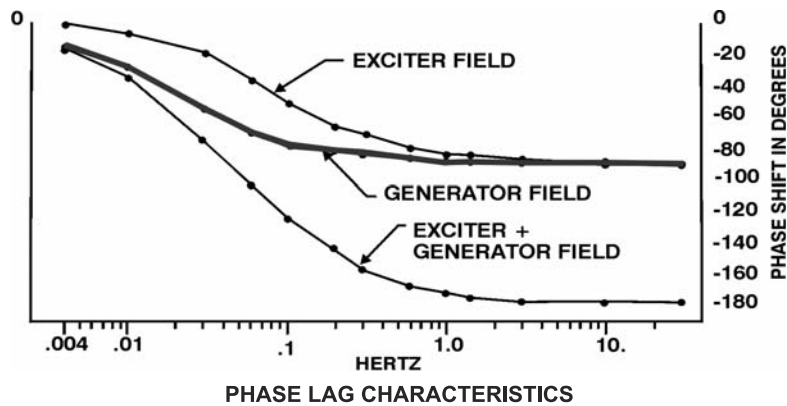


Figure 6. Phase Shift of the Exciter Field, the Generator Field, and the Sum of the Two

## Tuning of PID Controller

The controller parameters are determined with several excitation system parameters, such as voltage loop gain and open circuit time constants [1]. These parameters vary with not only the system loading condition but also gains dependent on the system configuration, such as the input power voltage via PPT to the bridge rectifier as shown in Figure 7. Commissioning a new AVR can be a challenging task of checking excitation system data in a short time, without any test data, and with no other link to the actual equipment, except for an incomplete manufacturer's data sheet, or some typical data set.

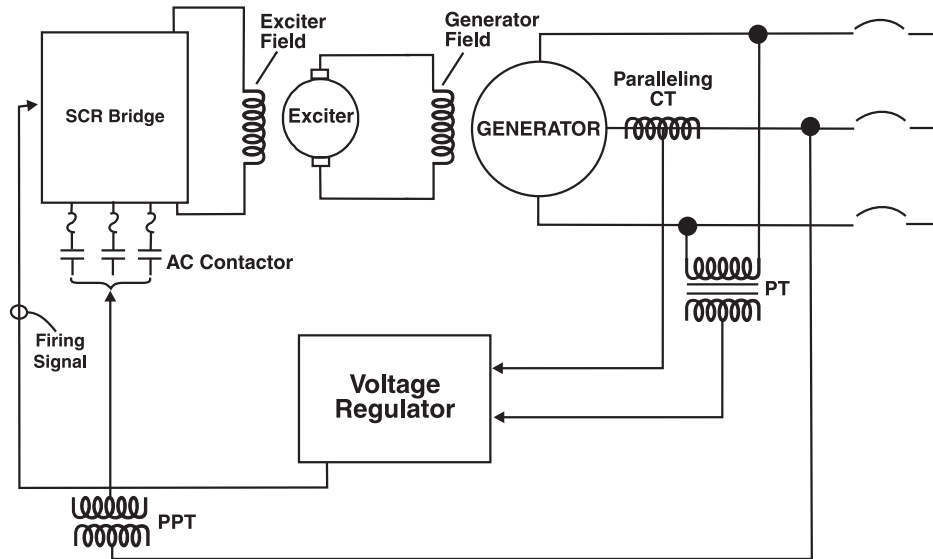


Figure 7. One-line Diagram

To tune the digital controller, two methods are predominantly used, one being the pole placement method and the other being the pole zero cancellation approach [1, 2]. To simplify the design of the PID controller, we assume  $T_D=0$  in Figure 3.

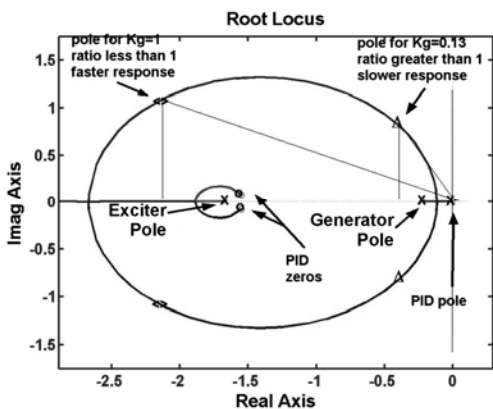
Every PID controller contains one pole and two zero terms with low-pass filter in the derivative block ignored. For generators containing rotating exciters, the machine contains two open loop poles, one derived from the main field and the other derived from the exciter field. A pole represents a phase lag in the system while the zero tends to provide a phase lead component. The location of poles and zeros with relation to the exciter and generator field poles determines the performance of the excitation control system.

Root locus is used to describe how the system responds based upon gain in the system. Using the pole placement method and referencing Figure 8a, the poles of the generator main field and exciter field are located on the real axis. The generator main field pole is located close to the origin while the exciter field pole is typically tens times the distance, the distance depending upon the time constant of the exciter field versus the main field. The smaller the exciter field time constant, the greater the distance. The PID controller consists of one pole and two zeros.

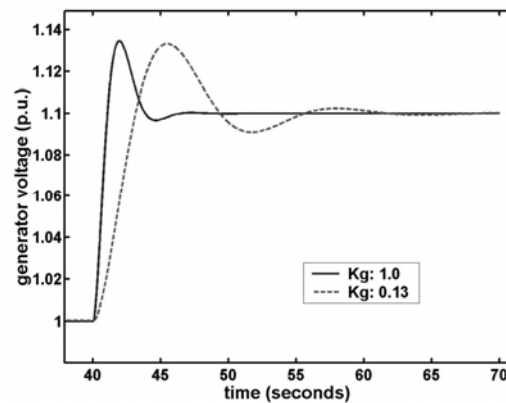
Figure 8a shows how the closed loop poles move as the loop gain increases. The loop gain,  $K_G$ , represents the totalized gain that includes the generator, field forcing of the excitation system

and PID controller. The open loop zeros becomes the closed loop zeros and do not depend on the loop gain. On the other hand, the poles of the closed loop system (exciter, generator, and controller) are moving toward zeros in a certain path as the loop gain increases. The path of the closed loop poles depends on the relative location of poles and zeros based upon its time constants. With fixed PID gains, a certain system gain ( $K_G$ ) determines the closed loop poles. Two cases of the closed poles are shown in Fig 8a, one for system gain 1.0 and the other for system gain 0.13.

In general, the poles nearest to the origin determine the system responses. When the poles become a conjugate pair, the system response will be oscillatory. The conjugate pair represents the ratio of the imaginary to real value of poles to determine the voltage overshoot. Absolute value of pole determines the frequency of voltage oscillation. The faster voltage response can be achieved by moving the poles from the origin and the less oscillatory response with the smaller ratio. See Figure 8b.



(a) Root Locus of Different Loop Gains  
Gains:  $K_P=90$ ;  $K_I=70$ ;  $K_D=25$



(b) Step Responses Performance  
Gains:  $K_P=90$ ;  $K_I=70$ ;  $K_D=25$

Figure 8. Root Locus and Voltage Response with Two Different System Gains ( $K_G$ )

**Pole Placement:** In the pole placement method, the desired closed-loop pole locations are decided on the basis of meeting a transient response specification. The design forces the overall closed-loop system to be a dominantly second-order system. Specifically we force the two dominant closed-loop poles (generator and controller) to be complex conjugate pair resulting in an underdamped response. The third pole (exciter) is chosen to be a real pole and is placed so that it does not affect the natural mode of the voltage response. The effect of zeros to the transient response is reduced by a certain amount of trial and error and engineering judgment involved in the design.

The pole placement method generally requires specific information of the exciter field and main generator field time constants to determine the gains needed for the digital controller for adequate response. Voltage overshoot of at least 10-15% is anticipated with the pole placement method with a 2 to 3 second total voltage recovery time; although its voltage rise time can be less than one second.

Figure 9 illustrates the generator terminal voltage performance of a 100 MW steam turbine generator when a +5% open circuit voltage step change has been introduced. Generator voltage overshoot is 20% with a total voltage recovery time of 2.5 seconds. The PID gains are as follows:  $K_p=90$ ,  $K_i=70$ , and  $K_d=29$ .

The excitation system bandwidth is used to characterize the response of the generator with the voltage regulator. The wider the voltage regulator bandwidth, the faster is the excitation system.

To derive the voltage regulator bandwidth, the gain and phase shift is plotted over a range of frequencies typically 0-10 Hertz by applying a signal oscillator into the voltage regulator summing point. The input signal is compared to the generator output signal by measuring the phase and gain of the frequency range of 0-10 Hertz, which represents the potential oscillating frequency of the generator interconnected to the system. For these bode plots, information of the generator and exciter time constant along with the excitation system gains are used to determine the bandwidth of the generator excitation system.

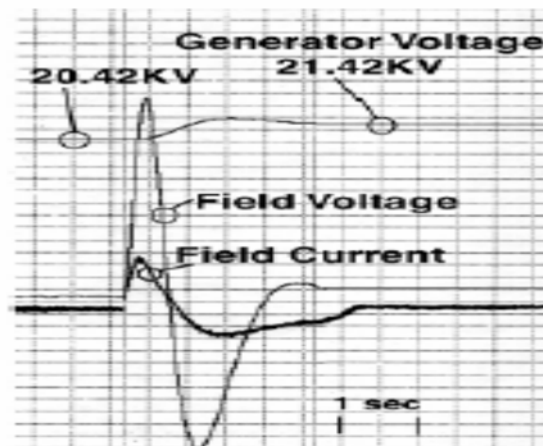


Figure 9. 5% Voltage Step Response Using Pole Placement Method

A typical root locus with pole placement method is shown in Figure 10. Notice how the close loop poles move along the circle with increasing gain. Figure 11 shows the phase lag, -59.1 degrees at -3 db. The db rise prior to roll off confirms the voltage overshoot noted during the voltage step response in Figure 9.

The ideal excitation system will maintain high gain with minimum phase lag. The point of interest is the degree of phase lag and gain at -3 db, the bandwidth of the excitation system. The less phase lag with higher gain gives the better performance of the excitation system. Figure 12 highlights the open loop response of the excitation system. It shows the phase lag of -105 degrees at 0db, crossover frequency.

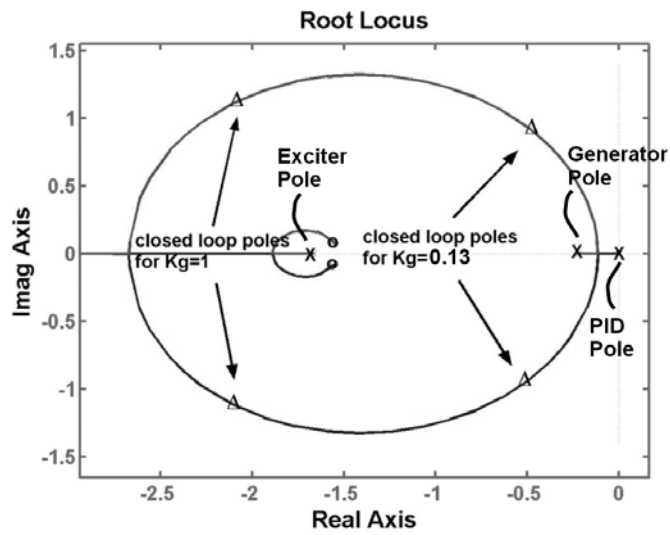


Figure 10. Root Locus for 100MW Generator Using Pole Placement Method  
Gains:  $K_p=90$ ;  $K_i=70$ ;  $K_D=29$ ;  $K_G=15$

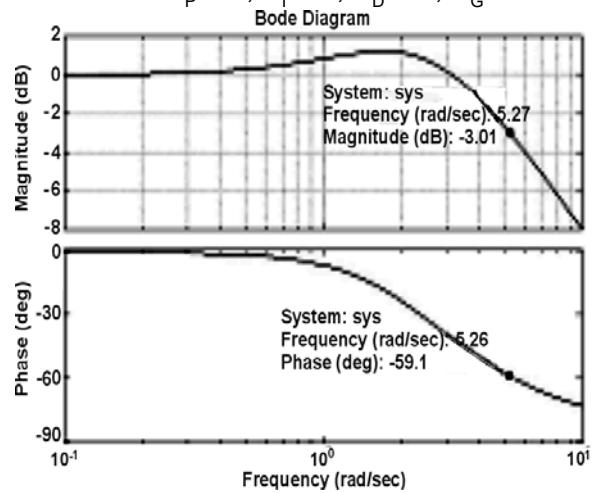


Figure 11. Closed Loop Bode Diagram of Pole Placement Method

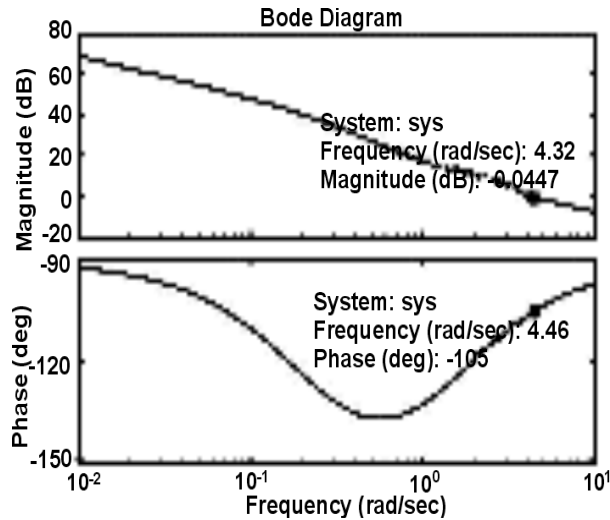


Figure 12. Open Loop Bode Diagram of Pole Placement Method

**Pole Zero Cancellation:** The pole zero cancellation method offers the benefit of performance with minimum voltage overshoot. This method uses the fact that the dynamic behavior of the pole is cancelled if zero is located close to the pole. The PID controller designed using pole-zero cancellation method forces the two zeros resulting from the PID controller to cancel the two poles of the system. The placement of zeros is achieved via appropriate choice of the PID controller gains. Since exciter and generator poles are on the real axis, controller has zeros lying on the real axis. Unlike the pole placement method that uses high integral gain, a proportional gain is set to be at least four times greater than the integral term.

A typical root locus with inexact cancellation is shown in Figure 13. The zeros are selected to cancel the poles corresponding to exciter and generator time constants. Thus the closed loop system will be dominantly first-order.

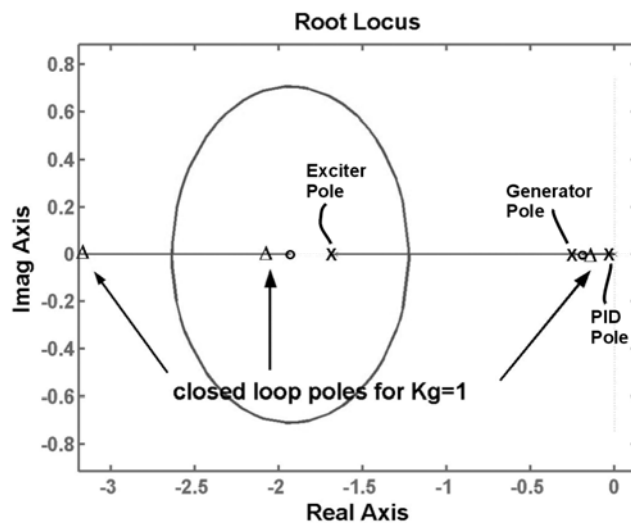


Figure 13. Root Locus for 100MW Generator Using Pole-Zero Cancellation Method  
 Gains:  $K_p=80$ ;  $K_i=20$ ;  $K_D=40$ ;  $K_G=15$

The exciter and generator time-constants vary with the system condition. The exact pole-zero cancellation is not practical. However, the exciter time constant is much smaller than generator time constant in rotary excitation control systems. As the loop gain increases, the poles move toward the corresponding zeros. Since the two time-constants are well separated, the effect of non-exact pole-zero cancellation is not detrimental.

The pole zero cancellation method provides for an extremely stable system with very minimum voltage overshoot and the field voltage remains very stable even with high  $K_g$  loop gains ( $K_p=85$ ,  $K_i=20$ ,  $K_D=40$ ,  $T_D=0.01$ ). Figure 14 shows the voltage response of a 100 MW steam turbine generator using pole-zero cancellation gains.

The closed and open loop bode plots are respectively illustrated in Figures 15 and 16 when the pole-zero cancellation method is used. The gain remains high and the phase lag is compensated for a wide frequency. Again using the -3 db point that represents the bandwidth of the excitation system, the phase lag is -46.3 degrees - a very fast excitation system. Notice the gain remains very flat before it begins to roll-off. The flat response illustrates a very stable system with little to no voltage overshoot. Figure 13 shows the phase lag of -91 degrees at crossover frequency of zero db.

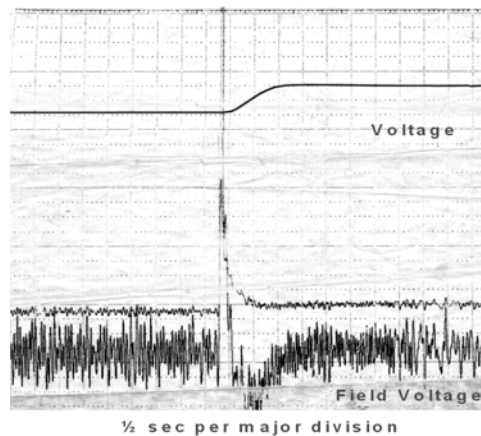


Figure 14: Voltage Response Using Pole-Zero Method

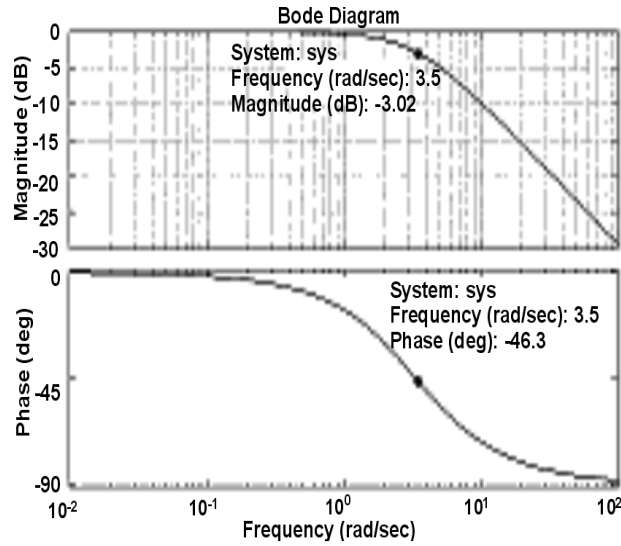


Figure 15: Closed Loop Bode Diagram of Pole Zero Cancellation Method

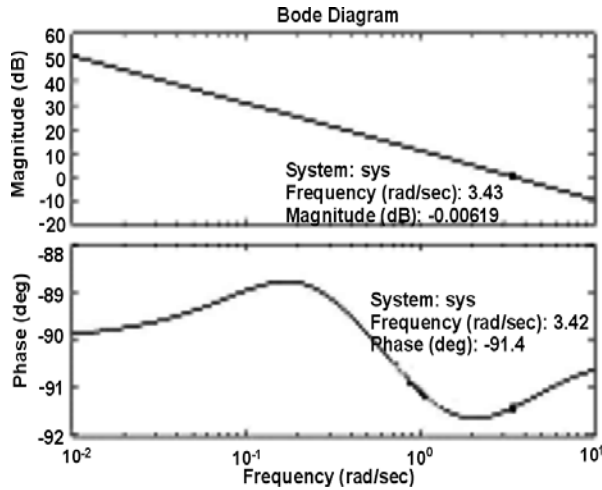


Figure 16: Open Loop Bode Diagram of Pole Zero Cancellation

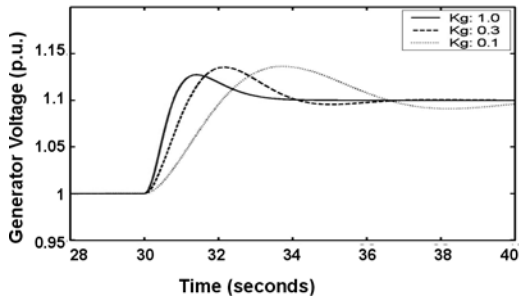
### Effect of Parameter Variations

The performance of two methods is conducted using computer simulation in the presence of parameter variations. The parameters considered include system loop gain and uncertain exciter time constant.

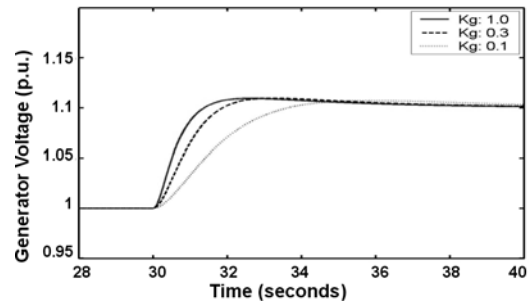
Since in general, the calculation of loop gain requires several excitation system parameters that are generally not available during commissioning, specifically the machine time constant, this lack of information can make the use of the pole placement approach more time consuming for setup than pole zero cancellation approach.

**Variation due to uncertainty in the loop gain** is considered by variations in  $K_G$  from the value of 0.1, 0.3, and 1.0. All the other parameters remain unchanged. Figure 17 illustrates the responses of the two methods described, pole-placement and pole-zero cancellation, while changing the loop gain ( $K_g$ ) of the digital controller. Note that both Figure 17a and 17c display similar rise time but voltage overshoot only occurs using the pole-placement method in this

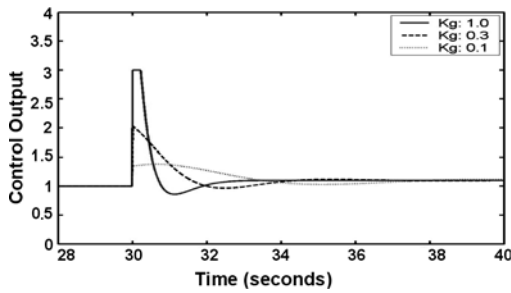
example. The pole-zero cancellation method provides a means to quickly and accurately tune the generator excitation system. Faster voltage response can be achieved by simply increasing the loop gain.



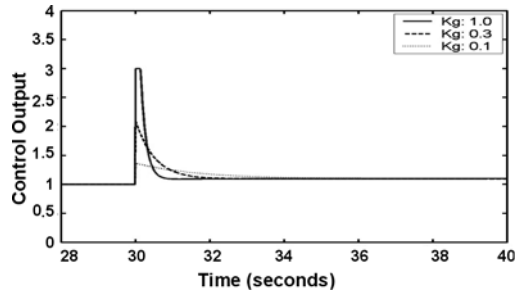
(a) Generator voltages for pole placement



(c) Generator voltages for pole zero cancellation



(b) Control outputs for pole placement



(d) Control outputs for pole zero cancellation

Figure 17: Step Responses with Loop Gains

**Uncertainty in the knowledge of the exciter time constant** is considered from the value of 0.2 sec, 0.6 sec, and 1.0 sec (See Figure 18). All other parameters remain unchanged. The comparison from Figure 18a and 18c indicates the superiority of the performance resulting from pole-zero cancellation design over the pole placement design. The root locus of each method is respectively shown in Fig 19a and 19b. For the pole placement design, the exciter pole at  $s=1$  pushes the root locus to the right with small loop gain ( $K_G$ ). On the other hand, the root locus is moved to the left for the pole-zero cancellation design, providing a more stable system.

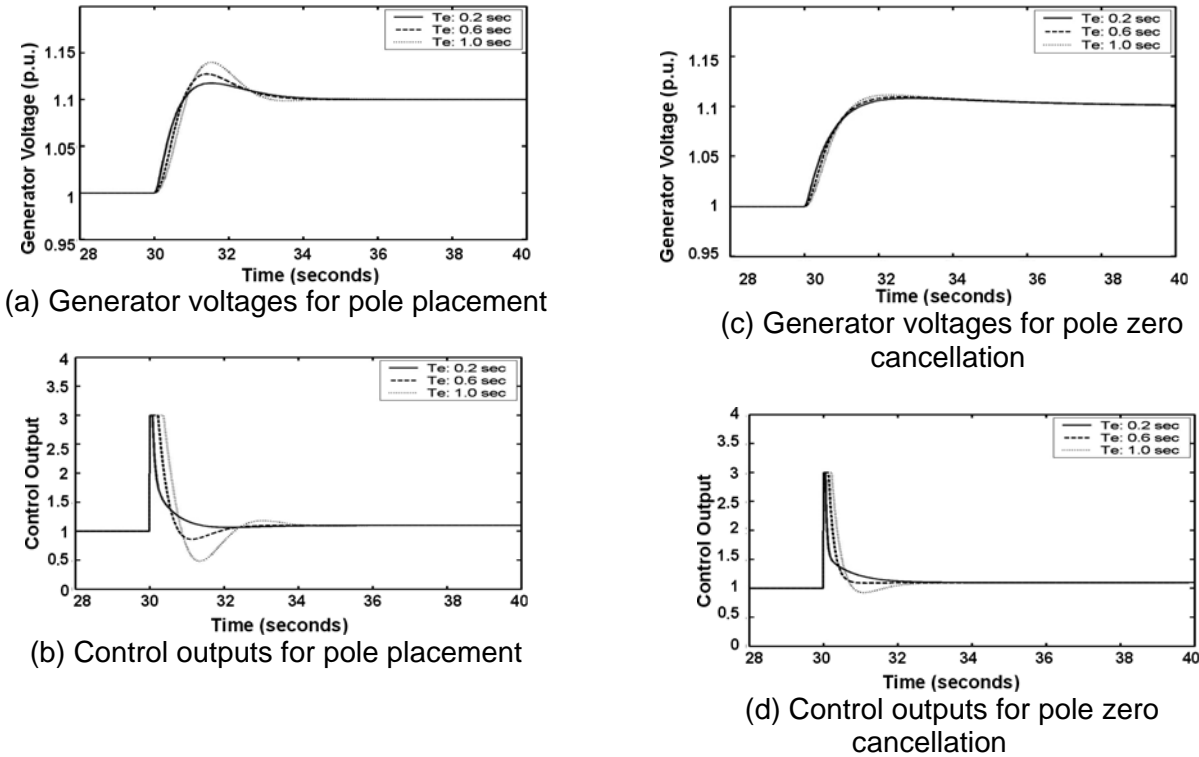


Figure 18. Step Responses with Exciter Time Constants

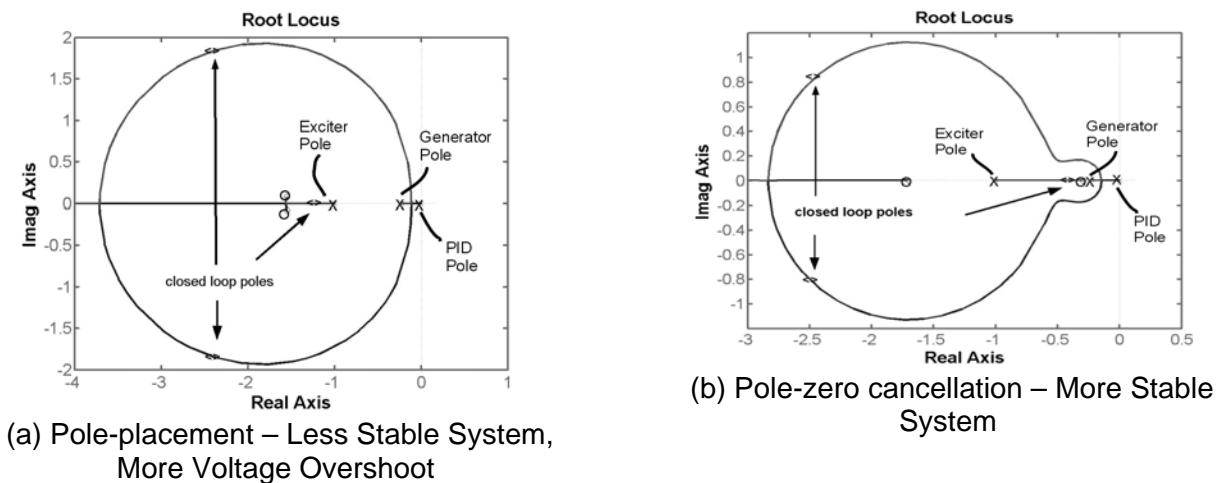


Figure 19. Root Locus with Exciter Time Constant 1 sec.

## Some Tips for Tuning the PID Controller

**Main Field Excited Excitation Systems:** For main field excited systems, since only one field exists, the derivative term is not used. The same gains ratio between the proportional term and the integral term is used with no derivative term applicable [3].

**Applying Suitable Gains:** The ratio between the integral term and the proportional term must be a minimum of four for good performance. Hence, with an Integral gain of 20, the Proportional gain will be 80. It has been found that it works best to have an Integral gain of not more than 20 in most cases to obtain satisfactory performance [8, 9]. The derivative term will affect the voltage overshoot, and here, a value of 20 will generally be adequate. For faster voltage rise time, the proportional term is increased. On slow speed hydro machines where the generator and exciter time constant tend to be quite large due the slow speed of the turbine. Often the  $K_p$  term is increased to 150 to help overcome the large inductive lag of the machine's field which will normally slow the voltage reaction time of the machine's response. Figure 20 illustrates the performance of a 70 MW hydro machine that has a 9 second main field time constant and a 2 second exciter field time constant. Notice the voltage overshoot and settling time [6]. Figure 20 utilizes a  $K_p=150$ ,  $K_i=20$ , and  $K_d=20$ .

Where the generator such as a hydro, have large field time constant as mentioned above, and the exciter field ratio to main field becomes less, an additional damping factor may be required to make the field voltage more damped or stable, known as  $T_D$ . It is an additional filter that affects the derivative term used with rotating exciter applications to reduce the effect of noise. For these systems where the field voltage may require additional damping, the  $T_D$  gain value should be applied. Values of 0.01 to 0.08 can be used to reduce the noise content of the field voltage.

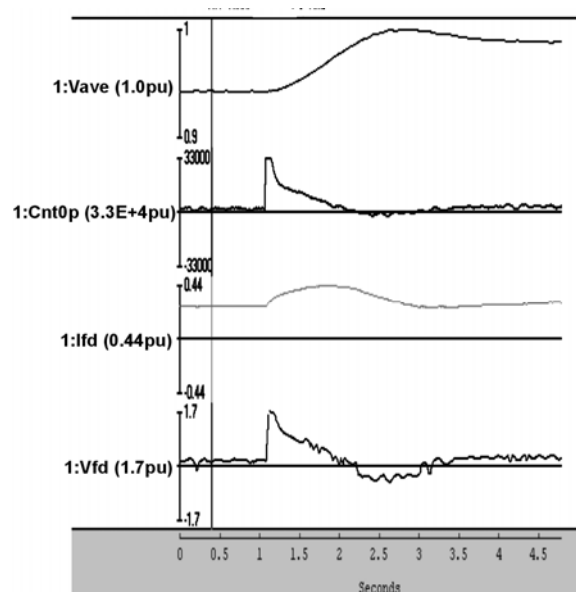


Figure 20. 5% voltage Step Response, .976 Seconds Voltage Recovery, and .8% Voltage Overshoot

**Excitation Limiters - Gains:** Establishing the gains for excitation limiters that provide a supplementary control for the voltage regulator to rotating exciter applications can be challenging at times. Different machine ratings and RPM all affect the gain selected for optimum response. For voltage regulator applications where two fields (main field, exciter shunt field) are involved, the tuning process for the under and over excitation limiter can become quite involved. Figure 21 shows a typical interconnect for the field current input for the over excitation limiter for a larger brush type machine. Here the shunt is placed on the main field where for brushless machines its' field current input would be derived from the exciter shunt field.

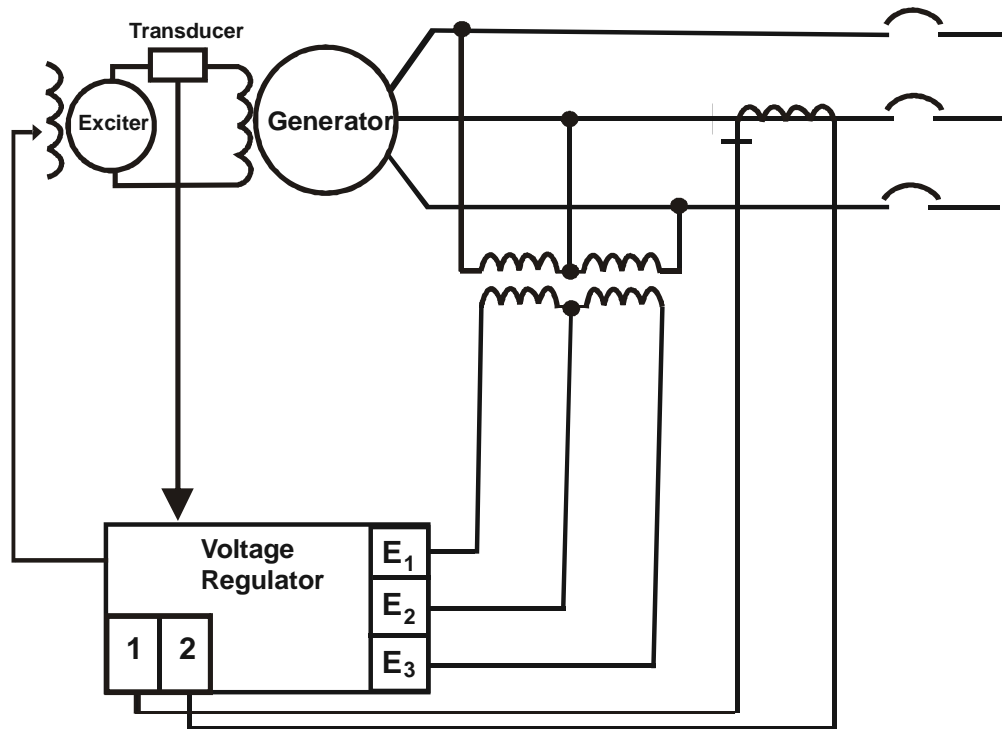


Figure 21. Block Diagram of Over & Under Excitation Limiter Inputs

Figure 22 illustrates a maximum excitation limiter using typical gains,  $K_I=7$ ,  $K_G=8$ . Notice the overall sluggish response and the over shoot observed for both the terminal voltage and field current. The field current limiter receives a signal from a field shunt that represents the dc current of the machine. Its location determines whether the field current is acting upon the main field or the exciter shunt field even though the voltage regulator may be driving the exciter shunt field.

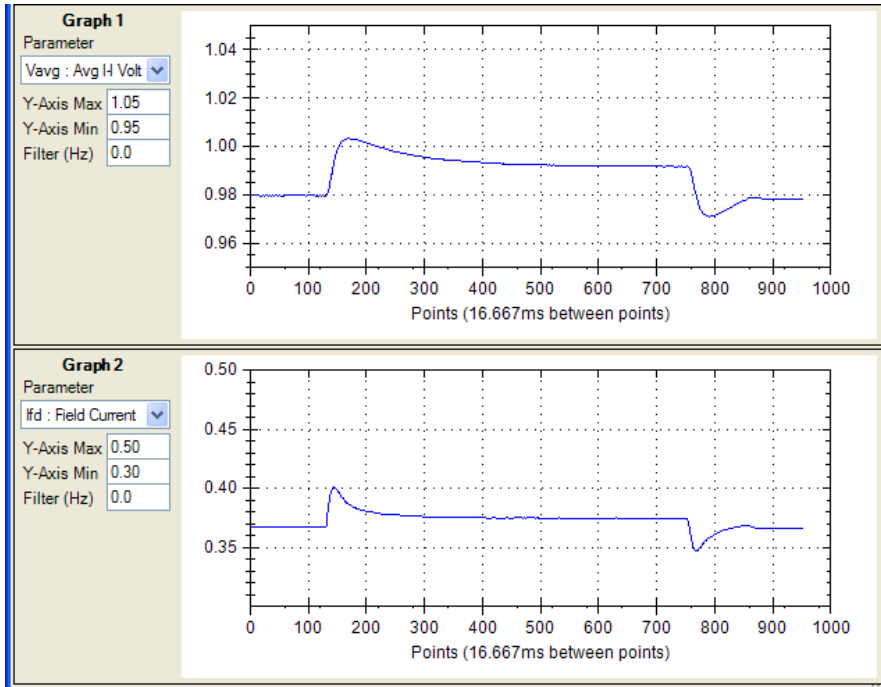


Figure 22. Over Excitation Limiter with Gains, KI7, KG8 - Sluggish Response with Overshoot

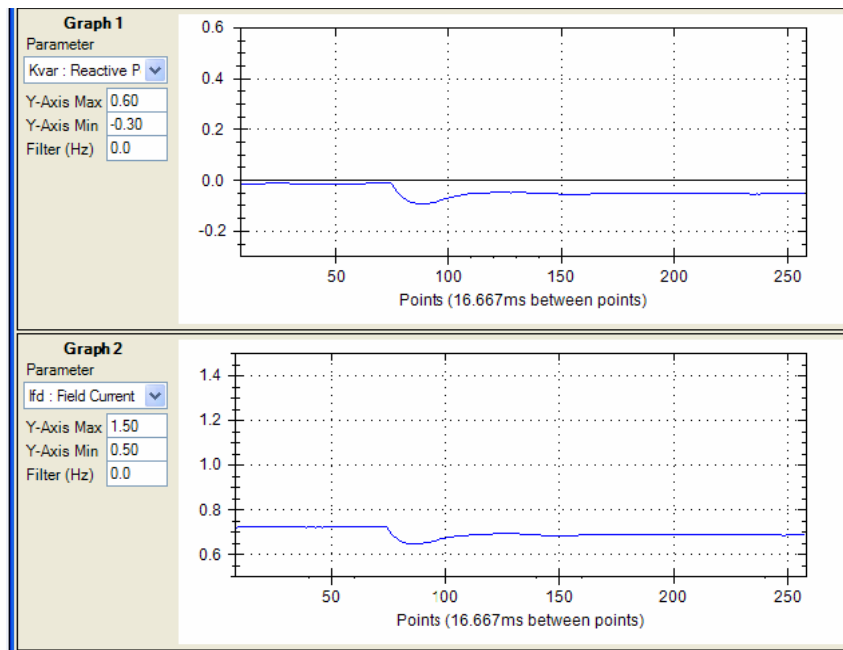


Figure 23. Underexcitation Limiter with Gains of KI=7 and KG=8 - Sluggish Response

Figure 23 illustrates similar gains with the underexcitation limiter active. The underexcitation limiter receives input from the generator output via the instrument PTs and a current transformer signal from the generator output, See Figure 21, In Figure 23 notice the under damp, and over

damp response before stabilizing the reactive power. The performance illustrated for either for the under or over excitation limiter could be much improved.

Today, a different set of rules can be applied to the excitation limiters to ensure fast accurate performance. In Figure 24 the over excitation limiter, changing the gain for  $K_I=1$  and raising the  $K_G$  to the range of 25-50 changes immediately the strategy of performance. No overshoot can be observed and the performance of the over excitation limiter is very fast. For large, slow speed hydros, the  $K_G$  value may need to be as high as 100, i.e. 120 RPM 100 MW.

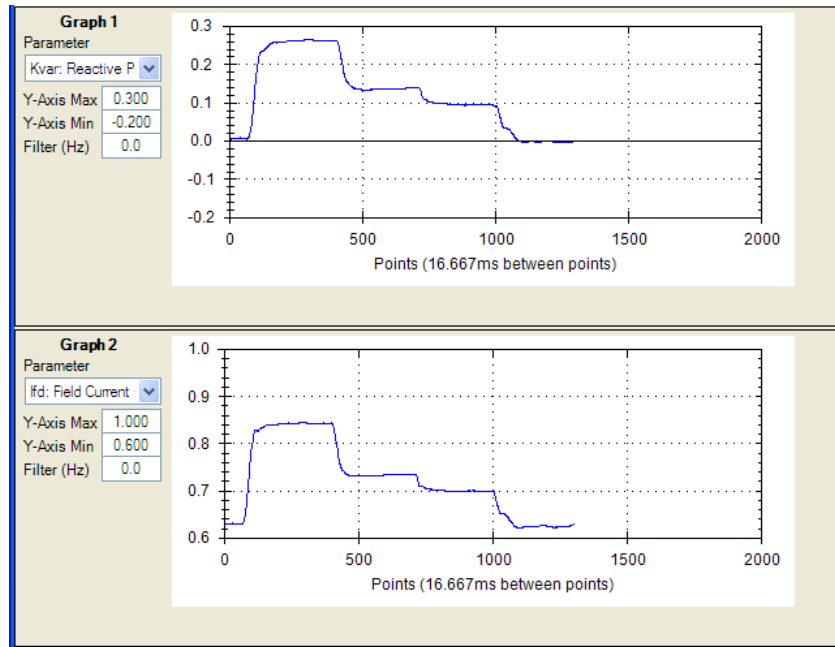


Figure 24. Overexcitation Limiter with  $K_I=1$  and  $K_G=50$  - Fast Response with No Overshoot.

Equally important is the under excitation limiter performance, its response is critical to avoid machine pole slip and needs to be fast. Figure 25 shows the new performance for the underexcitation limiter with a different gain group implemented. Here,  $K_I=1$  and the  $K_G=50$  is utilized, a slightly underdamped response of reactive power is indicated initially, but it recovers with a flat line characteristics and the response is less than a second!

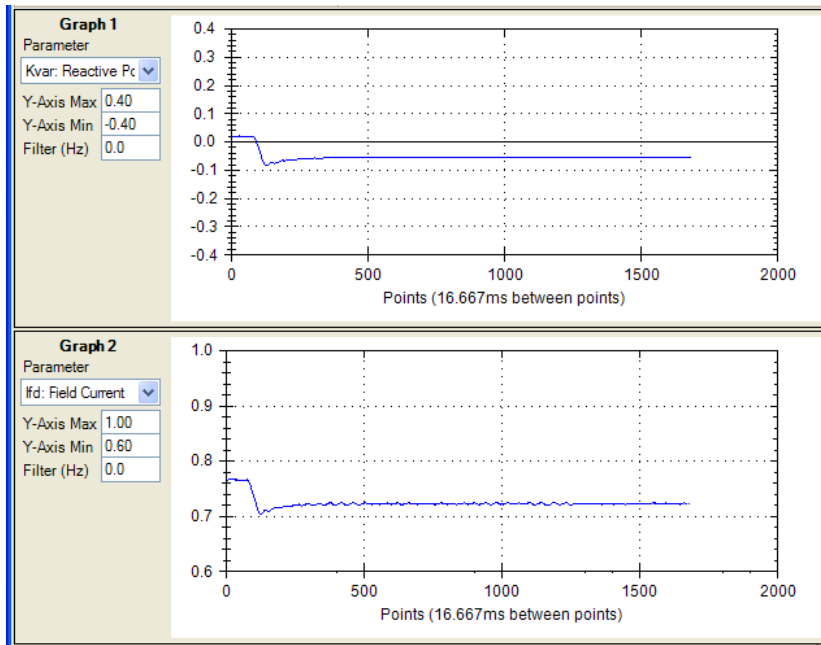


Figure 25. Underexcitation Limiter using  $KI = 1$  and  $KG = 50$  - Fast and Flat Line Response.

For main field excited systems, similar gains can be utilized.

### Directional versus Bi-Directional Excitation Systems with Power System Stabilizers

For a power system stabilizer to be fully beneficial for generators having rotating exciters, the voltage regulator must have fast response and a wide frequency bandwidth, ideally in the range of 135 degrees phase lag at 1 Hertz. Where many excitation system used on turbine generators in the 30MVA range have only positive field forcing to drive the exciter shunt, field performance is limited. See Figure 26.

Adding negative field forcing into the excitation systems with exciter shunt field restores the linearity and optimizes the unit response.

Figure 26 is a simulation of an external fault. The first half of the record is for a full-controlled bidirectional bridge; at time equals 3 seconds, a single directional bridge is implemented. The single directional bridge produces a generator terminal voltage increase of over 10%. See Figure 22c. The settings for PSS on these systems must consider this effect. Notice how the power swings dampen much faster when the bi-directional field control is utilized. See Figure 26d.

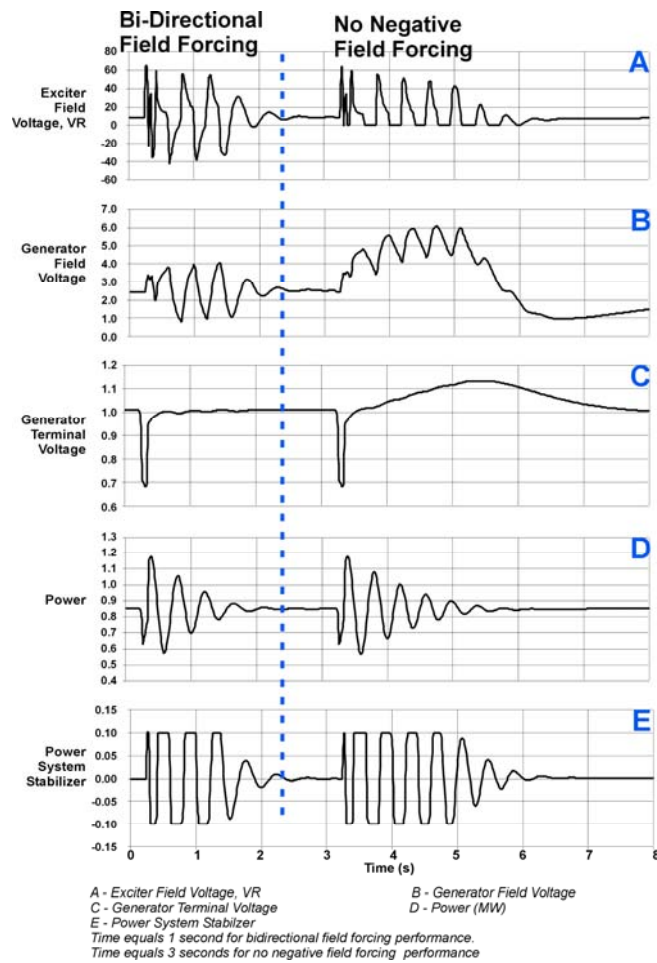


Figure 26: Performance Benefits with Negative Field Forcing Excitation Systems Requiring Power System Stabilizers

## Conclusion

The pole placement and the pole-zero cancellation methods for designing PID controllers for excitation systems are presented. The sensitivity of the two designs to various uncertainties and parameter variations are presented. Using the pole zero cancellation method of tuning PID gains, commissioning can be accomplished very quickly with excellent performance results.

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