Auto Tuning Speeds up Commissioning of the Generator Excitation System

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Abstract - This paper discusses PID tuning capabilities of a digital excitation system and a new feature called automatic tuning which can accelerate the process involve of commissioning the generator with the new excitation system. Based on given excitation system parameters, several PID tuning approaches are reported. Since in general, these parameters are not available during commissioning, specifically the machine time constants, this lack of information causes a considerable time delay and cost of fuel usage for commissioning the automatic voltage regulator (AVR). In the automatic tuning method, the excitation system parameters are identified and the PID gains are calculated using well-developed algorithms. With self-tuned PID gains, commissioning is accomplished very quickly with excellent performance results. Also discussed are the new software tools that can ease the burden of testing and aid in achieving compliance with the latest North American Electric Reliability Corporation (NERC) Mods 026 and PRC 19 standards.

Introduction

An optimally-tuned excitation system offers benefits in overall operating performance during transient conditions caused by the following: 1) system faults; 2) disturbances; or 3) motor starting. 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 transient stability by holding up the system and providing positive damping to system oscillations. Additional advantages include the following: 1) improved relay coordination; and 2) first swing transient stability. A well tuned excitation system will minimize voltage overshoot after a disturbance and avoid the nuisance tripping of the generator protection relays.

Digital excitation systems have come a long way since they were introduced in the late 1980s and early 1990s. Past challenges have been overcome to ease the programming required for commissioning as well as new testing tools being added to the operating software to minimize the time required to perform excitation tests to validate gains and limiter performance for generator modeling.

Traditionally, one of the main challenges of commissioning a generator excitation system has been deriving the proper proportional-integral-derivative (PID) gains required in the voltage regulator to achieve a good response for transient and steady state stability after a system disturbance and during motor starting.

Additionally, mathematical models of excitation control system are very important for transmission personnel to understand the mechanics of the excitation as it is interfaced with the generator.

NERC Requirements

The interconnection requirements have changed dramatically since the Energy Act was passed in 2005 [10]. This Act gave the North American Electric Reliability Corporation (NERC) the ability to mandate the required testing of an excitation system to produce various models and verify them for accuracy. Required tests included a coordinated performance test of the excitation limiters and the generator protection to ensure there is no overlapping of settings which could otherwise result in untimely trips of the generator. Recently, NERC's PRC 019 [1] was revised to require these tests be performed within a certain time frame. Similarly, Mod 026 [2] for generator/excitation modeling is required within a certain time frame for the generating plants as follows:

- Individual generating unit greater than 20 MVA directly connected to the bulk electric system.
- Generating plant or facility consisting of one or more units connected to the bulk electric system at a common bus with total generation greater than 75 MVA (gross aggregate nameplate rating)
- Any generator, regardless of size, that is a blackstart unit material to and designated as part of a transmission operator's restoration plan.

Additionally, these tests are to be conducted at least every five calendar years. The time line specified is that 40% of the machines shall be tested within the first two calendar years of regulatory approval. Within three calendar years, 60% of machines are to be tested and verified. Lastly, after five years from the calendar date, 100% of testing must be verified at applicable facilities of regulatory approval.

The mandates are intense and demanding upon personnel involved in the performance testing at applicable plants. Depending upon the age of the excitation system, substantial costs can be involved in performing these tests for either new or existing installations. For paper mill generating plants, the application may vary with the geographical area. From a practical view, it is a good industry practice to make certain coordination between the relay and excitation limiters at the facility.

The technological evolution of digital excitation systems and operating software continues to provide a means to help reduce the time needed to accomplish these tests.

PID Tuning

During initial testing, open circuit voltage step tests are performed to determine PID gains for the voltage regulator. The PID gain shapes the generator voltage response after a system disturbance and optimizes the voltage recovery time during motor starting. Depending upon the needs of the system and the MVA rating of the generator, voltage response times will vary. For smaller MVA generators, voltage response is less critical and less aggressive gains can be realized. However, for larger units, more aggressive gains are desired to achieve good transient stability and maximum synchronizing torques needed for voltage fault support and optimum relay co-ordination. **Figure 1** illustrates a typical voltage regulator system driving the exciter shunt field.

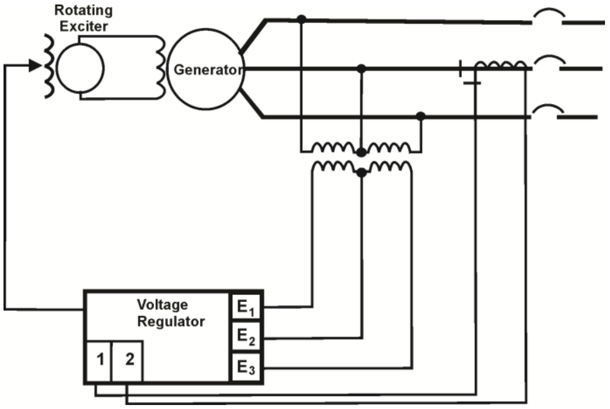
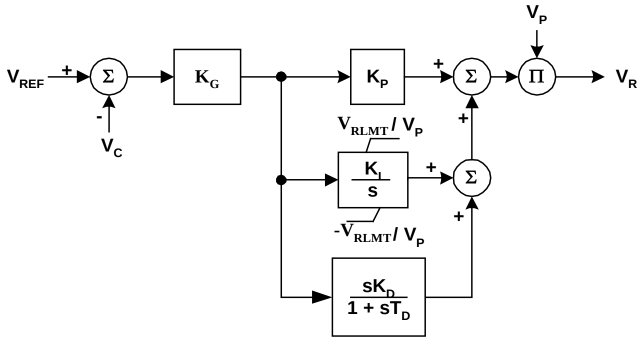


Figure 1. Typical voltage regulator system

Figure 2 illustrates a model of a typical voltage regulator. The adjustable gains in the controller are described as proportional (K_P), integral (K_I) and derivative (K_D) gain.



V_{REF} is generator voltage Reference
V_C is sensed voltage
V_{RLMT} is max field forcing
V_p is power input voltage
V_R is voltage regulator output
K_P is Proportional Gain
K_I is Integral Gain
K_D is Derivative Gain
K_G is Loop Gain, multiples of K_P, K_I, K_D

Figure 2. Simplified block diagrams of digital voltage regulator

For each of the gains noted, each has a special function that affects the generator excitation performance.

- Proportional gain (K_P) - The proportional term makes a change to the output that is proportional to the current error value. The proportional response is adjusted by multiplying the error by a constant K_P, called the proportional gain. A larger K_P typically means a faster rise time response.
- Integral gain (K_I) - The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. Integral gain is required in order for the system to achieve zero steady state error and steady state stability. The integral term, when added to the proportional term, accelerates the change of the process towards the set point and eliminates the residual steady-state error that occurs with a proportional only controller.
- Derivative gain (K_D) - The derivative term applies to the rotating exciter application that slows the rate of change of the controller output and is used to reduce the magnitude of the overshoot produced by the proportional and integral component. Too large of K_D will decrease the voltage overshoot and slows down the transient response. An adjustable derivative time constant (T_D) is added to help filter out the noise from the derivative gain.

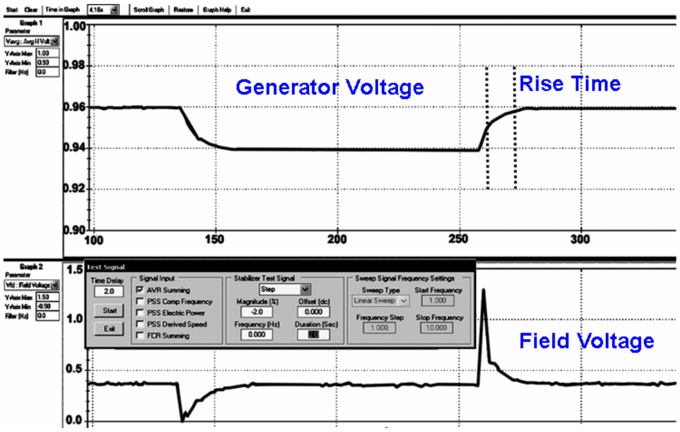
The K_P, K_I, K_D gains are multiplied in a block defined by K_G which can be increased or decreased depending upon the desired overall response. The output of the summing block is directed into the firing circuit.

The method of selecting the proper PID gains has varied over the years, but the most common method used is pole-zero cancellation. In this method, a ratio between the proportional gain and the integral gain is at least 4:1. This allows for a fast rise time and results in essentially no voltage overshoot. The larger the proportional gain, with respect to the Integral gain, the more aggressive the generator's digital controller voltage response will be [3] [4].

Generator voltage response needs to be performed on all generators. In particular, those machines where generator modeling is required. For these machines, voltage step responses are performed and the results are compared with generator simulations. These simulations include machine reactance and time constants combined with the excitation model to verify that agreement exists between the actual test performed and the model validation. Modeling is required for units falling into the category of NERC compliance of 20 MVA and above.

Testing

Performance evaluation can be time consuming and costly if equipment needs to be connected that would require the shutdown of machines in order to interface with PT and CT circuits. Time required for testing is reduced by implementing the tools found in the operating software. An on-board real time chart recorder eliminates the need for external equipment hookup. The use of specially designed menu screens can allow voltage steps to be quickly implemented regardless of how they are related to off-line or on-line performance testing. See **Figure 3**.



Time in Graph 4.16s

Graph 1
Parameter Vavg : Avg H Volt
Y-Axis Max 1.00
Y-Axis Min 0.90
Filter (Hz) 0.0

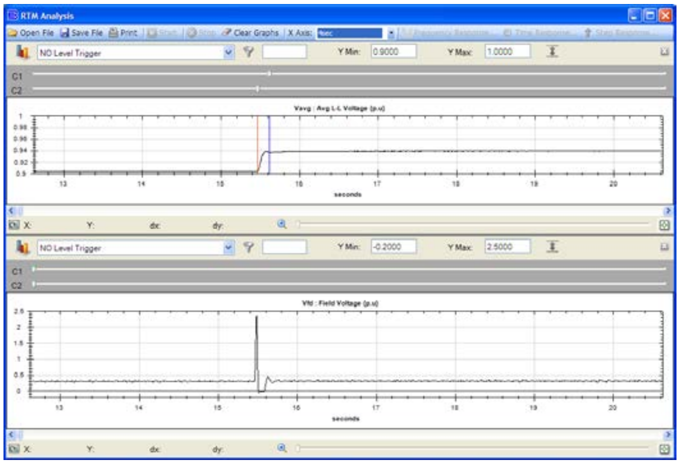
Graph 2
Parameter Vfd : Field Voltage
Y-Axis Max 1.50
Y-Axis Min -0.50
Filter (Hz) 0.0

Test Signal
Time Delay 2.0
Signal Input
☑ AVR Summing
☐ PSS Comp Frequency
☐ PSS Electric Power
☐ PSS Derived Speed
☐ FCR Summing
Stabilizer Test Signal Step
Magnitude (%) -2.0
Offset (dc) 0.000
Frequency (Hz) 0.000
Duration (Sec) [illegible]
Sweep Signal Frequency Settings
Sweep Type Linear Sweep
Start Frequency 1.000
Frequency Step 1.000
Stop Frequency 10.000

Figure 3. Voltage step response using software tools

Figure 4 illustrates a voltage response using the using Pole Zero Cancellation method. The desired gains are entered into the operating software and voltage step responses are performed to evaluate the gains utilized.

Figure 4 demonstrates a 4% voltage step being performed on a brushless excited rotating generator with a 1MVA rating and a terminal voltage of 4160 Vac. The use of the Pole Zero Cancellation approach resulted in very aggressive voltage rise time of less than .16 seconds. The voltage rise time is determined based upon a voltage step measured at the moment of its introduction (10% of the step) until the settling time (90%) when there is no voltage overshoot observed. During the voltage step, notice the sharp rise of the field voltage upon initiation of the voltage step. The aggressive response is symptomatic of the gains selected. Aggressive response can aid in motor starting for large motors and to help minimize the voltage dip to speed generator voltage recovery.



X Axis: Sec

NO Level Trigger
Y Min: 0.9000
Y Max: 1.0000

NO Level Trigger
Y Min: -0.2000
Y Max: 2.5000

Figure 4. Manual Tuning using KP 80, KI 20, KD 20
+4% generator voltage response

Auto tuning Solution

Manually tuning a digital voltage regulator requires expertise and years of experience to quickly determine the best starting gains for a voltage regulator to be tuned to a generator. The cost of a downed machine can be very expensive. Combined with the cost of testing and fuel used, the overall cost can be very high. Today, a new feature described called auto tuning is offered as a method to help reduce the time required for commissioning. Auto tuning involves the process of automatically determining a set of PID gains for the generator to obtain a good voltage response. Indirect method for self tuning the PID controller is proposed [8]. It consists of three steps:

A. Estimation of the System Gain

Figure 5 illustrated the basic block diagram of a self-exciting excitation control system with PID block utilized in the automatic voltage regulator control loop. As shown in **Figure 5**, the PID controller output is multiplied by the power voltage (V_P). For the external power input case, V_P becomes a constant. Thus, linear theory can be applied for the small signal stability. If the power input is derived from the generator voltage for the self-excitation application, i.e., $V_P = K_T V_T$ where K_T is a gain that represents a power transformer, the exciter field voltage is the PID control output multiplied by a factor of the generator terminal voltage, and the excitation control system becomes a bilinear system.

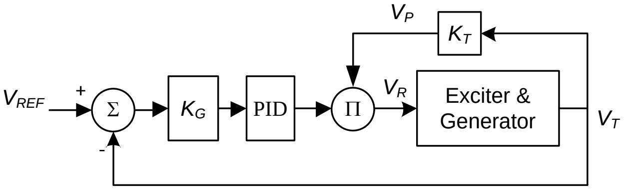


Figure 5. Simplified excitation control system with the PID controller

The gain K_G in **Figure 5** is used for compensating variations in system configuration dependent gains such as power input voltage (V_P) and saturation effects. The gain K_G is estimated based on steady state condition near rated generator voltage. This is accomplished with a robust controller with soft start feature. The soft start feature is designed to avoid a large voltage overshoot during voltage buildup. The PI controller is utilized to measure the regulator output and terminal voltage, which are measured at steady state condition of the closed loop with the PI controller. The regulator output and generator voltage are utilized to determine the system gain K_G.

B. Estimation of the Time Constants

For the excitation control system with power input supplied from the generator output, a simple feedback linearization loop is implemented to make it a linear system as shown in **Figure 6**.

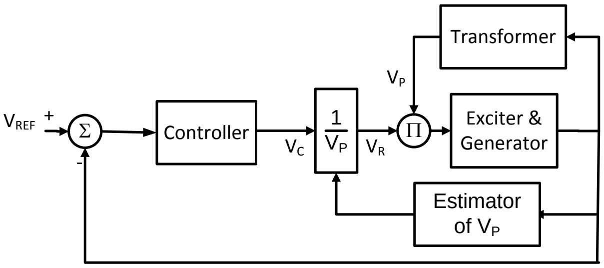


Figure 6. Feedback linearization of self-excitation control system

With inner loop control implemented, a linear estimation algorithm can be utilized. Thus, the plant transfer function *G(s)* is approximated as

$$G(s) = K_S\left(\frac{1}{1+sT_E}\right)\left(\frac{1}{1+sT_{do}^{'}}\right) \tag{1}$$

Where K_S, T_E, and T'_{do} are the system gain, the exciter and generator time constants, respectively.

The generator and exciter time constants are identified using well developed algorithms, Recursive Least Square (RLS) as well as Particle Swarm Optimization (PSO) techniques. The functional block diagram of the RLS estimator is illustrated in **Figure 7**. For Recursive Least Square (RLS) with linearization via feedback, the closed loop control system with proportional gain is used, which makes the system stable as well as operates continuously in a linear region, i.e., not in the saturation region. The white noise disturbance is added to the P-controller output (V_C). The resultant regulator output and generator terminal voltage are utilized for estimating the time constants.

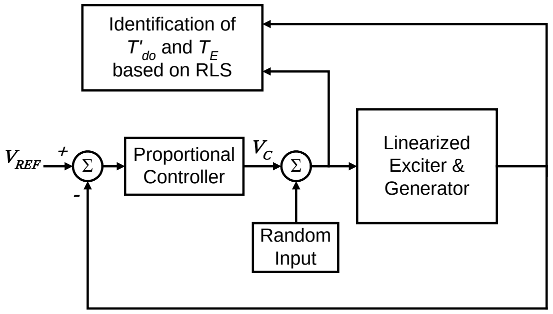


Figure 7. Identification of time constants using RLS

Figure 8 shows the functional block diagram of Particle Swarm Optimization (PSO) technique, which is also applied to estimate the time constants. Based on the estimated value K_S in the previous step, the system parameters are normalized in per unit. A simple feedback linearization loop is constructed to eliminate the bilinear system characteristics as shown in **Figure 6**. A step response is performed at the generator voltage of 0.9 p.u. and the generator voltage is recorded every 4 msec. This set of data is used as actual system step response for identification of time constants using the PSO technique.

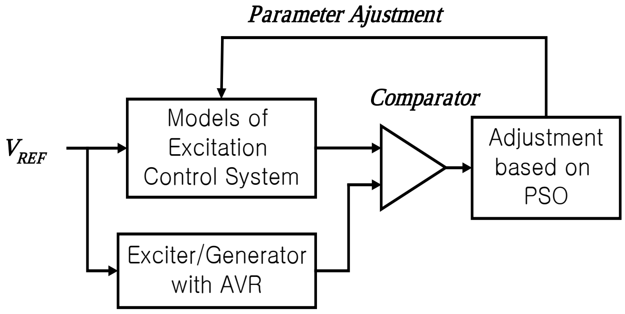


Figure 8. Identification of time constants using PSO

PSO technique searches through the best time constants to minimize the fitness function, the sum of the square of the differences between measured value (z_k) and simulated value (y_k), $k=1,\ldots,N$ as follows:

$$J = \sum_{k=1}^{N} \left(z_k - y_k\right)^2 \tag{2}$$

C. Calculation of PID Gains

Based on the identified system parameters, the PID gains are calculated using either the pole-placement design or the inexact pole-zero cancellation method [3].

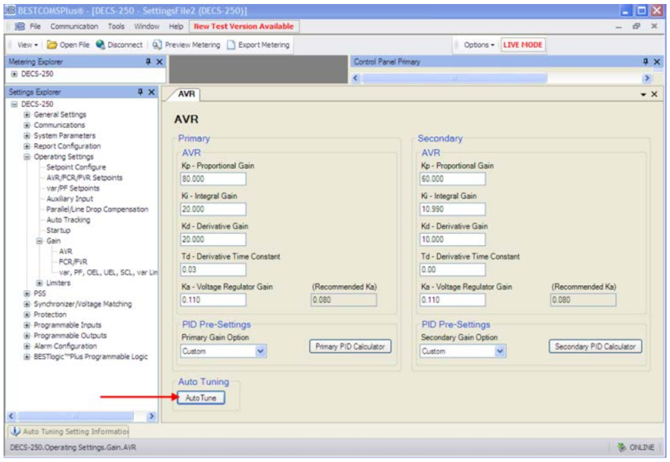
In this paper we will explore its use as a practical solution to commissioning. **Figure 9** shows a software tool to set the PID gains which also includes an option to access the auto tuning function. By clicking the *Auto Tune* button in **Figure 9**, the auto tuning window (**Figure 10**) is provided with options for choosing the PID Design methods, pole-zero cancellation method or pole-placement method, and the power input mode, permanent magnet generator (PMG) powered or shunt powered from either the generator output or station power.

When the desired settings are selected, the *Auto Tune* button enables a special software program that takes control of the generator during initial commissioning and analyzes the generator system to determine what voltage regulator gains are required for suitable generator voltage response.

This method involves performing a number of voltage steps in the auto tuning mode. The operating software takes control of the generator output when the turbine is spinning to build generator voltage while the circuit breaker is open. A generator voltage step is then executed through the operating software causing the generator voltage to rise or fall in 5% steps which determine the exciter and generator time constants. Once the time constants are determined, the pole and zeros in the digital controller are arranged via the automatic selection of PID gains to provide the optimum generator voltage response.

The PID controller contains one pole and two zero terms with the low-pass filter in the derivative block ignored. The selection and the location of poles and zeros in relation to the exciter and generator field poles determine the performance of the excitation control system.

It takes approximately 60 seconds for the operating software performing the auto tuning test to determine the selection of the gains.



BESTCOMSPlus® - [DECS-250 - SettingsFile2 (DECS-250)]

AVR

Primary

AVR

Kp - Proportional Gain: 80.000

Ki - Integral Gain: 20.000

Kd - Derivative Gain: 20.000

Td - Derivative Time Constant: 0.03

Ka - Voltage Regulator Gain: 0.110

(Recommended Ka): 0.080

PID Pre-Settings

Primary Gain Option: Custom

Secondary

AVR

Kp - Proportional Gain: 60.000

Ki - Integral Gain: 10.990

Kd - Derivative Gain: 10.000

Td - Derivative Time Constant: 0.00

Ka - Voltage Regulator Gain: 0.110

(Recommended Ka): 0.080

PID Pre-Settings

Secondary Gain Option: Custom

Auto Tuning

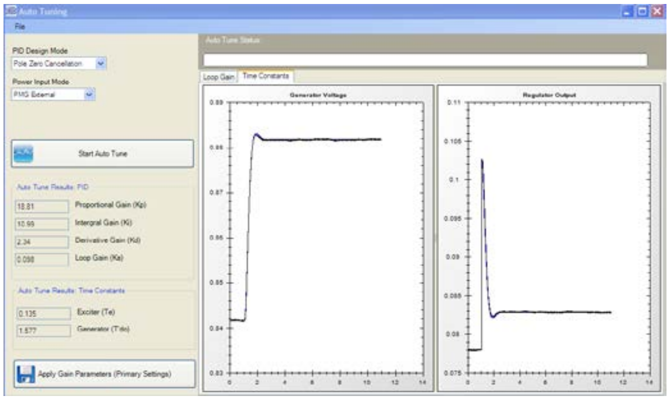
DECS-250.Operating Settings.Gain.AVR

Figure 9. Auto tune Initiate

Tests were conducted on a 1 MW, 4160 Vac generator located in Quay County, New Mexico. The generator was used to provide blackstart capability for a 25 MVA generator utilized to start oil pumps and fan motors in the event that the tie line to the city lost utility connection. Generator voltage step tests were performed to evaluate the performance using both the auto tune and the manual tuning method of pole zero cancellation solution utilizing the K_P 80, K_I 20, K_D 20 rule discussed earlier. See **Figure 4**.

Figure 10 highlights the auto tuning test completion with the recommended gains for the digital voltage regulator derived by the program. The generator voltages and regulator outputs are shown, measured responses (black) and simulated responses (blue), which are practically identical. Also, the derived machine time constants are displayed. The gains of K_P 19, K_I 11, K_D 2.3 were determined along with a calculated main field time constant of 1.58 seconds (T'_{do}) and an exciter time constant of 0.135 (T_E) seconds.

Once gains are determined, an open circuit step test is performed to determine voltage regulator performance. **Figure 11** illustrates the voltage regulator and generator performance using the auto tuning solution gains. Here, a generator voltage step of 4% was introduced and the generator voltage responded in 0.6 seconds. The gains derived from the auto tuning solution are shown. The response represents a stable generator system with no voltage overshoot and an appropriate rise time for the generator system.



PID Design Mode: Pole Zero Cancellation

Power Input Mode: PMG External

Auto Tune Results: PID

18.81 Proportional Gain (Kp)

10.99 Intergral Gain (Ki)

2.34 Derivative Gain (Kd)

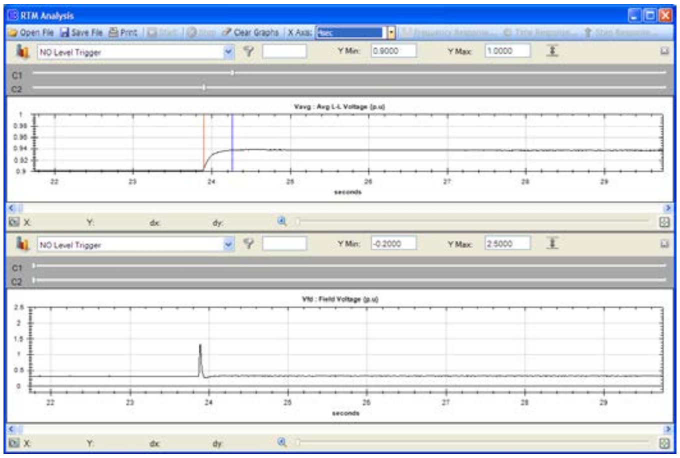
0.098 Loop Gain (Ka)

Auto Tune Results: Time Constants

0.135 Exciter (Te)

1.577 Generator (T'do)

Figure 10. Auto tune derived gains of KP=19, KI=11, KD=2.3, and machine time constants of T'do=1.58 sec and TE=0.135 sec.



X Axis: sec

NO Level Trigger Y Min: 0.9000 Y Max: 1.0000

NO Level Trigger Y Min: -0.2000 Y Max: 2.5000

Figure 11. Generator voltage response using auto tuned gains, +4% generator voltage step, 0.6 second generator voltage response time, no voltage overshoot

Acceptable Performance Evaluation

Auto tuning provides a means to quickly determine gains as a starting point to begin commissioning. The final product of generator voltage response is a function of the system needs. For example, a motor starting would require more aggressive gains than a system that has no motors. Depending upon the interconnection of the generator to the system intertie, a fast voltage response can lead to power system instability when paralleled to the utility. This may happen when the generator is connected to a radial line on a voltage weak system [5] [6]. Here, the voltage response may be excellent, but negative damping caused by a fast excitation system may cause MW oscillations for a number of cycles after a voltage step is introduced into the voltage regulator summing point. **Figure 12** illustrates fast excitation gains and its affect on a voltage weak system which causes the MW oscillations after a voltage step. Notice how the MW oscillations are very unstable despite the voltage regulator response being very stable.

A voltage regulator which is too fast will cause this power system response for high impedance interconnections. In these cases, where performance is needed, a power system stabilizer control loop is added to supplement the voltage regulator with additional feedback based upon changes in the generator shaft rotor combined with the change in power being measured.

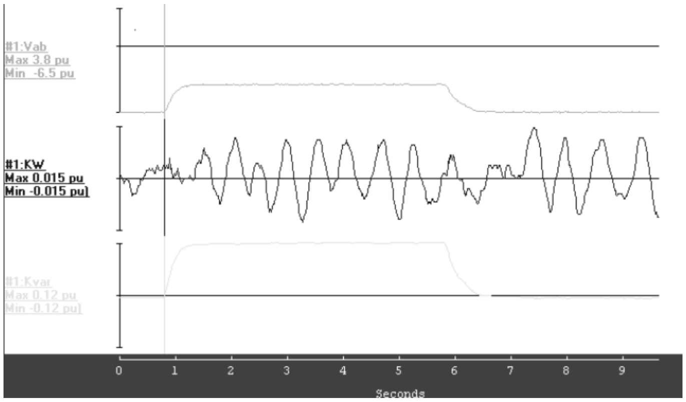


Figure 12. AVR 2% voltage step response with fast gain, stimulates MW oscillation on a voltage weak system

Figure 13 and **Figure 14** illustrate two different voltage regulator gains, one set being very slow and sluggish and the other being very aggressive which demonstrates how the selection of gains can impact motor starting. Notice in **Figure 13** how the generator voltage dips to 47% during motor start for a large boiler feed pump with little voltage regulator gain [9]. The generator voltage recovery is longer than 15 seconds. **Figure 14** illustrates significant improvements when the voltage regulator PID gains are increased. Here, the generator voltage recovers within 0.2 seconds after the starting the same large motor and the voltage dips only 12%. A fast response reduces the I^2R heating of the motor and improves the relay coordination necessary for better motor protection.

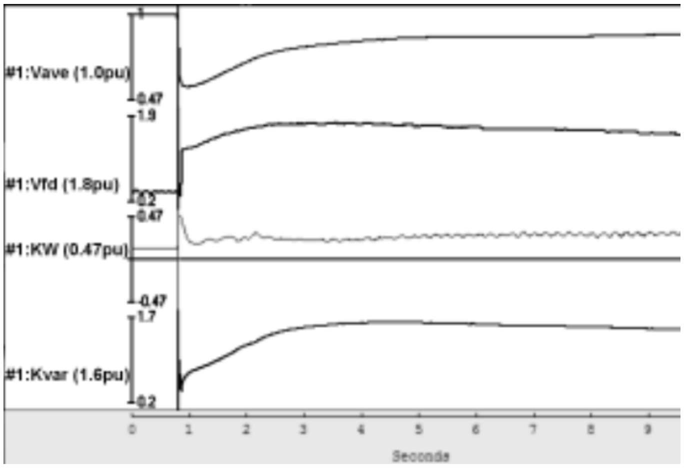


Figure 13. Motor starting with static exciter with low gain, results in 47% generator voltage dip & 15 second recovery

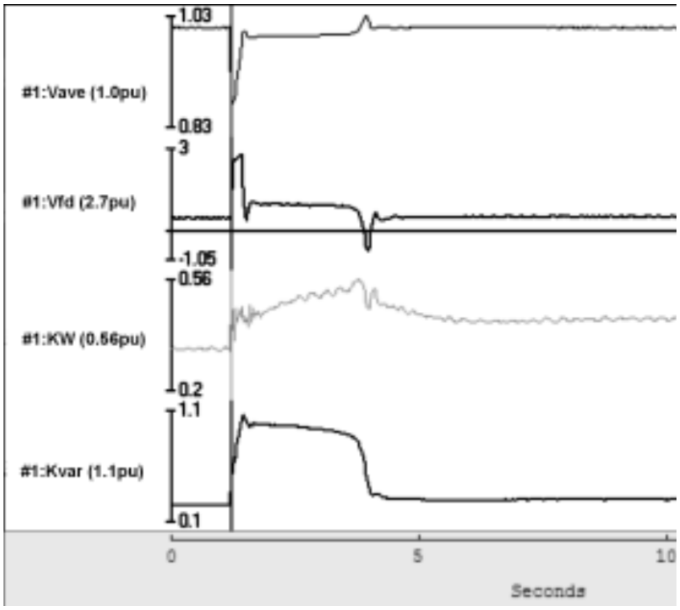


Figure 14. 12% voltage dip, 0.2 second voltage recovery with high gain and high field forcing

There is no guideline that recommends how the excitation system is to be tuned for performance. Generally, it is up to the experience of the commissioning engineer to understand the plant and adjust the performance accordingly. The IEEE 421.2 Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems [6] is a performance guide specification explaining criteria of performance. It is not application specific so knowledge of the system is important to determine the best voltage performance for the plant.

Conclusion

Today's technology continues to offer new tools to satisfy the industry needs. NERC requirements demand higher expectations from the power producers connected to the transmission system to ensure the power system is protected against issues that may occur. Modeling plays a significant role in system performance. The ability of the manufacturer to provide the tools to accomplish easier testing and to speed up commissioning can offer significant savings to the plant as NERC reliability expectations continue to increase and accountability for all facets of the operation is required. Auto tuning of the voltage regulator to define performance offers one more benefit to ease the increasing burden at the power plant and to take less time for commissioning.

References

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