Modern Digital Controllers Provide Additional Features to Improve Hydro Generators Reliability

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Abstract

Modern digital automatic voltage regulators (AVR) provide many more features than the analog AVRs or early digital AVRs. This paper will discuss several of these features in detail and the benefit of these features in today's hydro power generation system.

In modern digital AVR systems, it is common to have multiple modes of operation including automatic voltage regulation, manual regulation, var control, and power factor control. One of the most important items with an AVR system is that it is tuned properly so it can handle transient conditions with the ability to rapidly return to steady state voltage without oscillation. With an auto-tuning feature, this is easily done. This paper will explore the auto-tuning feature compared to manual tuning.

It is common to have excitation limiters integrated in the digital AVR. These include overexcitation limiters, underexcitation limiters, V/HZ or underfrequency limiters, and stator current limiters. This paper will also discuss all of these features of newer digital regulators.

The integrated power system stabilizer (PSS) that meets the IEEE PSS2A integral of accelerating power, and how and when it should be applied in different applications will also be discussed. The focus will be on the available software tools that allow the user to commission a Digital AVR system and the PPS more easily and accurately.

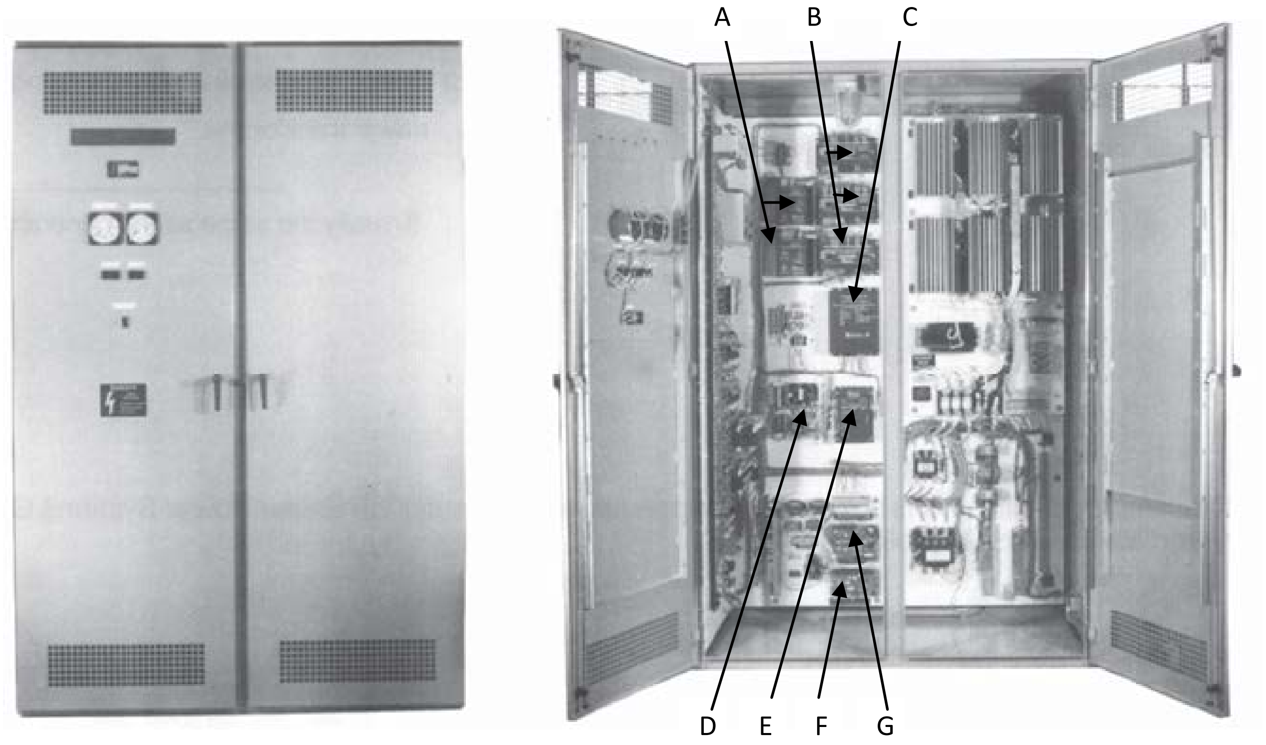
Other topics to be discussed are protection, data log and trending, synchronizing/voltage matching, permissive for synchronizing (sync check), and redundancy. Programmable logic and how it is used to program the logic for protection schemes, inputs, outputs, and alarms will also be discussed.

The modern digital AVR is much more than previous AVRs. It is a digital excitation control system equipped with numerous tools that will save the customer time and money.

Introduction

The digital AVR was first introduced in the late 1980s and early 1990s. The attraction to these types of digital controllers was the integrated functionality. These digital controllers combined many functions in one package. The analog version of the AVR system had a separate module for most of the function. See Figure 1. All mode of operation was done by separate modules or boards. This included the AVR, manual mode of operation and the var/Power Factor (PF) mode of operation. The limiters, mainly the overexcitation and underexcitation, were all separate modules. Any protection was accomplished by discreet relays and the PSS was provided done by a separate module. All of these components were tied together through a complex wiring scheme that made troubleshooting a very tedious process.

Figure 1 shows a simple analog static exciter with all the separate components identified. The modern digital AVR controller has incorporated the function of these analog components internal in the controller. The functions are now more precise and easier to set up.



A	Protective Relays
B	Motor Operated Potienometers
C	Limiter Module
D	Over Flash Module
E	VAR-Power Factor Controller
F	Automatic Voltage Regulator
G	Manual Controller and Firing Control

Figure 1: Typical Analog Static Exciter

While the early version of the digital AVR combined many of these features into one module, the biggest drawback was the inability of the interface software packages to tune the AVR system. Since then, the software programs have become more user friendly due to graphical user interface and the ability to tune the system has became less challenging because of the advancement of software tools available with modern controllers that will automatically tune your system.

Mode of Operation

In the analog era, the AVR and manual controller were two independent modules. The controllers had independent rheostats to adjust the set point (AVR Mode) or to adjust the excitation directly (manual mode). These rheostats have always been a common point of failures due to the environment of the plant or general wear. It was common practice to have the manual mode back up the AVR mode incase of failure in the AVR channel.

When the digital controllers were first introduced, the AVR and manual controller (also referred to as Field Current Regulator or FCR mode) where integrated with the var/ PF controller. This was quite an improvement over the analog systems. The set point inputs to the digital controllers no longer needed a rheostat input as they were replaced by dry contact inputs.

The modern digital controller’s mode of operation has expanded the features and functions of the earlier versions of digital controllers. The following are some of the new features commonly found in a modern digital controller:

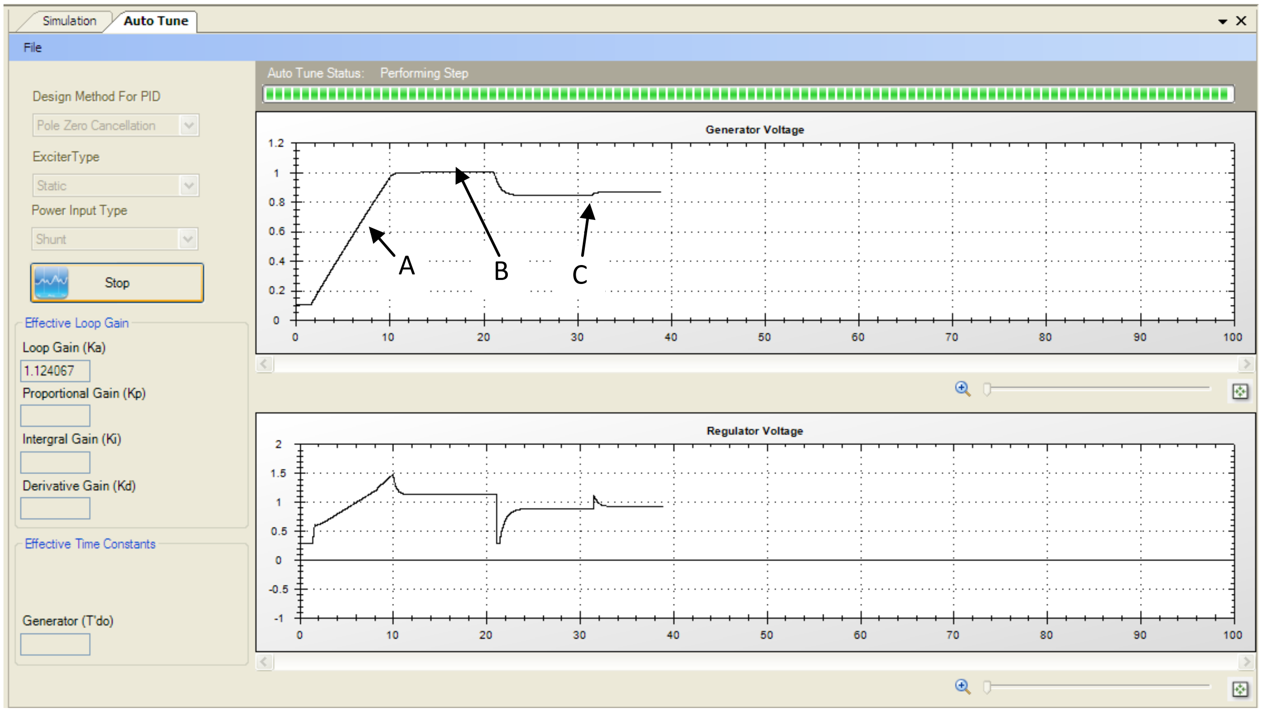
- Better regulation accuracy, up to .10% from no load to full load.
- Ability to regulate on the high side of the generator step-up transformer (generator synchronized).
- Multiple preposition set points for each mode of operation (AVR initiated by user defined logic.
- Reactive Differential Compensation (cross current) via a communication link.
- Field Voltage Regulation (FVR) mode of operation. This is a manual control designed to perform specific modeling tests. It is used to validate models for load rejection test and capture the generator reactances.

In 2005, because of previous blackouts in the Northwestern and Northeastern United States, the U.S. Congress passed the Energy Act. This act included numerous new regulations and mandates and was overseen by the North American Electric Reliability Council (NERC). One such regulation stated that an “excitation system must be operated in automatic voltage regulation mode to help provide voltage support to the system in the event of the disturbance” [1].

All machines, based on the machine size and the region they were in, had to stay in AVR mode. If they transferred to manual mode, the owner must immediately report it to the systems operator. Running in manual mode could result in penalties and fines being assessed to the owner.

With the requirement to run the generator in AVR control, it is important to have an optimally-tuned AVR system. Since most modern digital controller are utilizing the proportional, integral and derivative control for stabilization, knowing all the machine parameters (field time constants) is critical to tune the excitation system properly. The lack of this information causes a considerable time delay and cost of fuel usage for commissioning the AVR system [2].

Some modern AVR controllers are equipped with a new feature called Auto-Tuning or Self-Tuning. This feature can be beneficial in the older hydro generation plants where the time constants of the main field and exciter field are not known. The auto-tuning test is performed at rated speed and the generator breaker is open (no load). Figure 2 shows a graphical display illustrating a soft start ramp up and several steps to calculate the time constants and gain values for the AVR system.


Auto Tune Status: Performing Step

Design Method For PID: Pole Zero Cancellation

ExciterType: Static

Power Input Type: Shunt

Effective Loop Gain

Loop Gain (Ka): 1.124067

Proportional Gain (Kp):

Intergral Gain (Ki):

Derivative Gain (Kd):

Effective Time Constants

Generator (T'do):

A	Soft Start Test
B	Calculating the Gain
C	Calculating the Time Constants

Figure 2: Auto-Tuning Testing

After the test is complete, the AVR system will be a tuned and any fine tuning can be performed during the required step test. As noted above, this tool saves valuable time when commissioning the excitation system.

Limiters

Limiters have been a part of the excitation system for a very long time. In analog excitation system the limiter function was performed by a separate module that biased the AVR auxiliary input to influence the excitation. The most common types of limiters in the analog era were the overexcitation limiter, also referred to as the maximum excitation limiter, and the underexcitation limiter, also referred to as the minimum excitation limiter. The analog AVR also had an underfrequency compensation circuit or a Volts/Hertz (V/Hz) limiter. These limiters used adjustable resistance and, at times, added resistors to the board to adjust the level of set points for the limiters.

Modern digital AVR systems have the limiter functions in the software of the controller. With the limiters discussed above, the digital AVR controller also includes other types of limiters such has generator overvoltage, generator undervoltage and stator current.

Modern limiter functions can be set up as a summing type or a takeover type of limiter. Figure 3 shows a simple model of a static exciter with the summing type limiter. Figure 4 shows a static exciter with a takeover type limiter. [3]

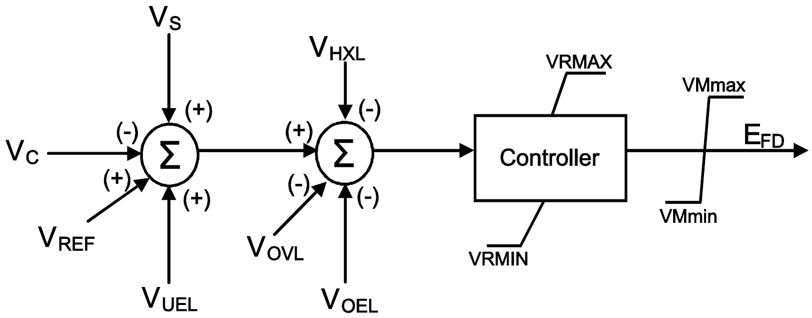


Figure 3: Summing Type Limiter.

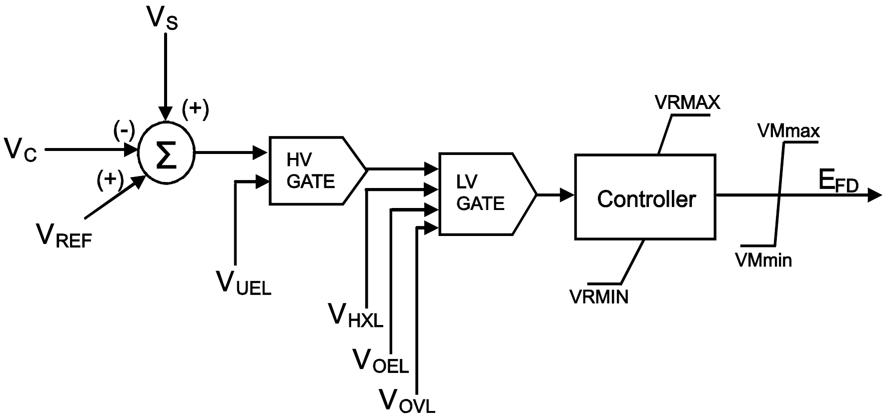


Figure 4: Takeover Type Limiter.

Limiters are a vital function of an excitation system. The limiter must be coordinated with the related protection elements to prevent false transfer to the redundant controller (if applicable) or nuisance trips. A coordination study of the protection and limiters is a new regulation mandated by MOD-019. In certain NERC regions, tests to validate the overexcitation limiter and underexcitation limiters are required. With modern controllers and interface software, the ability to coordinate the limiters is a much easier task than it was with their analog counterparts. This is especially true for the underexcitation limiter whose function is to limit the reduction of excitation when the generator is operating underexcited to prevent heating in the stator end region and prevent a loss of synchronism event [4]. Figure 5 illustrates the programmable feature in establishing the underexcitation curve with a modern digital system and how it can coordinate the protection curve. A common practice is to use five real power points and five reactive power points to establish the underexcitation limiter curve.

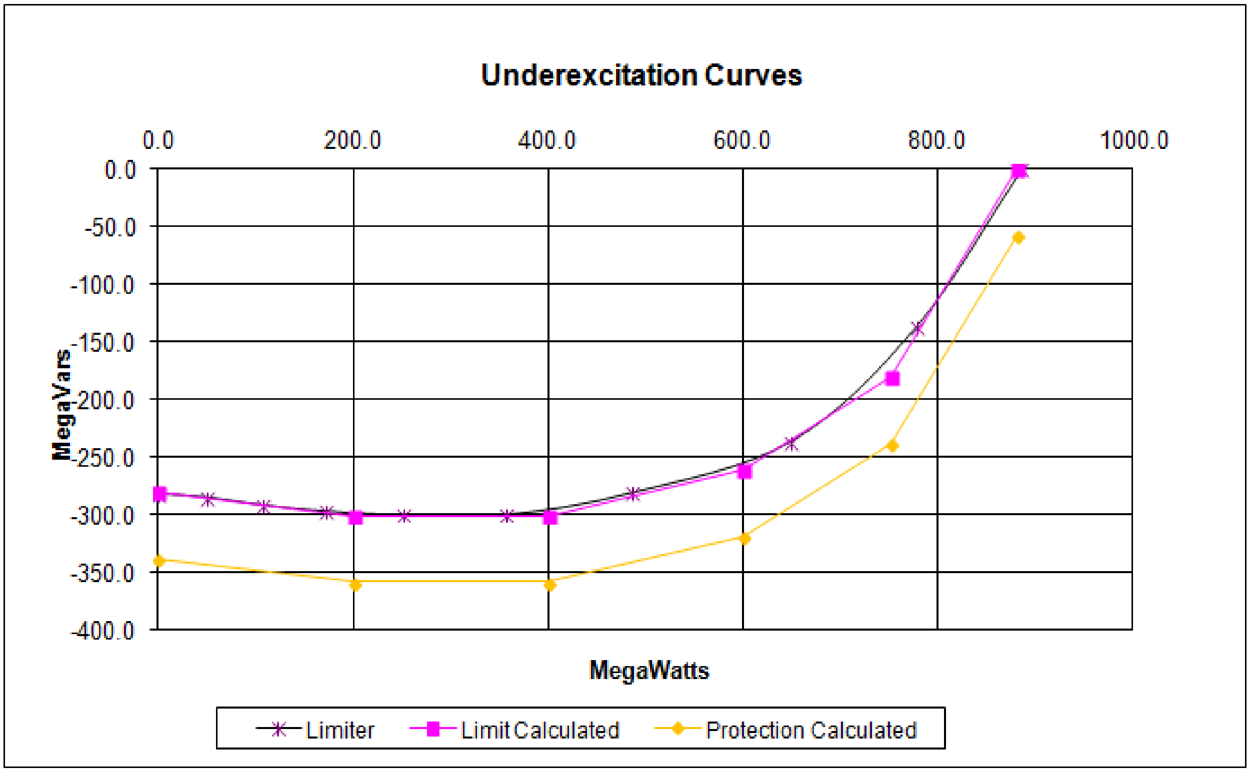


Figure 5: Underexcitation Limiter Programmable Feature

Overexcitation limiters limit the field current to prevent field overheating. It can be used as a takeover type limiter or a summing type limiter as illustrated in Figures 3 and 4. The limiting action comes with a programmed time delay; either a definite time delay or an inverse time delay. The time delay allows the exciter system to run in the overload condition for a specified time and then return the excitation system to a safe region. Modern digital AVR systems commonly have an off-line overexcitation limiter (breaker open) in addition to an on-line overexcitation limiter. Figure 6 shows a graph of some typical settings and definite time delays of the on-line summing type over excitation limiters.

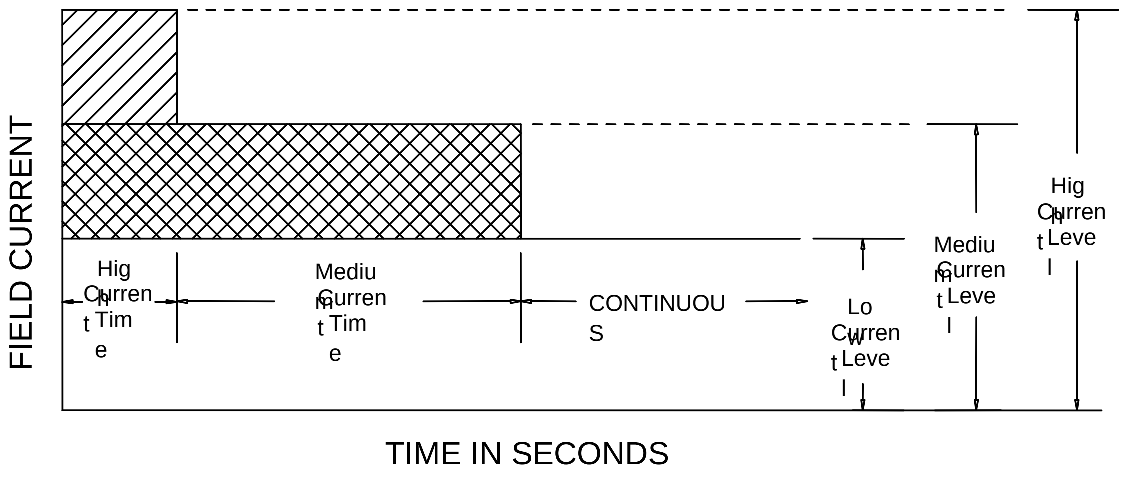


Figure 6: On-Line Overexcitation Limiter, Definite Time delay

The V/Hz limiters prevent the machine from going beyond a predetermined per unit setting of the ratio between volts and frequency. This is to control the overflexing of the generator and transformers on the system due to an overvoltage or underfrequency condition. This will be coordinated with the protective relay 24 element to ensure that nuisance tripping will not occur. Figure 7 is a graphical representation of the settings for the V/Hz limiter.

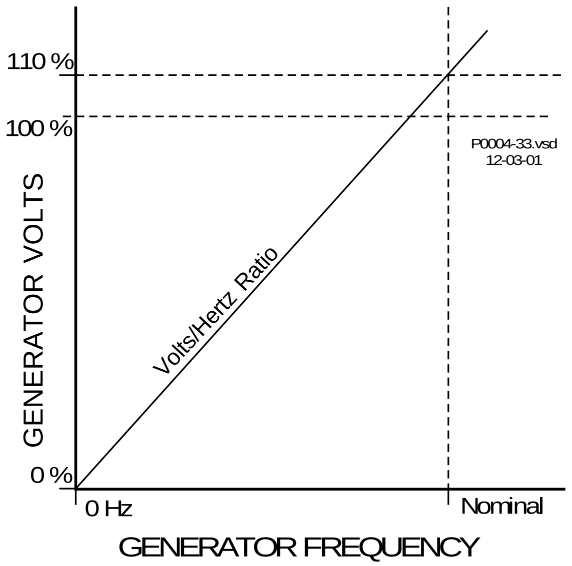


Figure 7: 1.1 PU Volts/Hertz Limiter

Power System Stabilizers (PSS)

For the past six (6) decades, AVR systems have become faster reacting which gives the system more synchronizing torque and faster transient response. At the same time, it affects the positive damping of the generator. The effect on the power system is a low frequency oscillation that could limit the amount of power on the power system. The PSS is used to modulate the excitation and provide positive damping to reduce or eliminate the power oscillations [5].

There have been many PSS types and they are classified as the following:

- Type PSS1A – Single Input PSS
- Type PSS2B – Dual Input PSS
- Type PSS3B – Dual Input PSS
- Type PSS4B – Multiband PSS

The PSS2B integral of accelerating power is the most common used in North America for any generators being upgraded with a PSS. As illustrated in Figure 8, the PSS senses power and frequency to produce the integral of accelerating power and creates the speed signal.

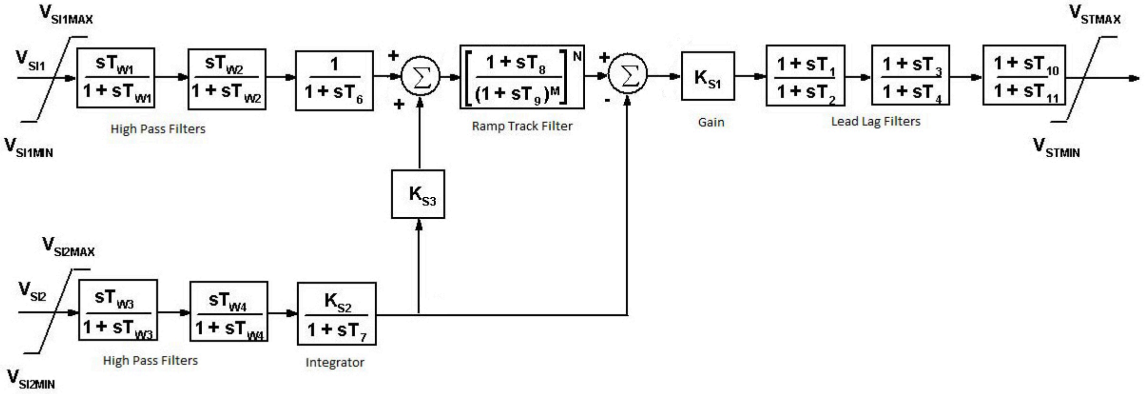
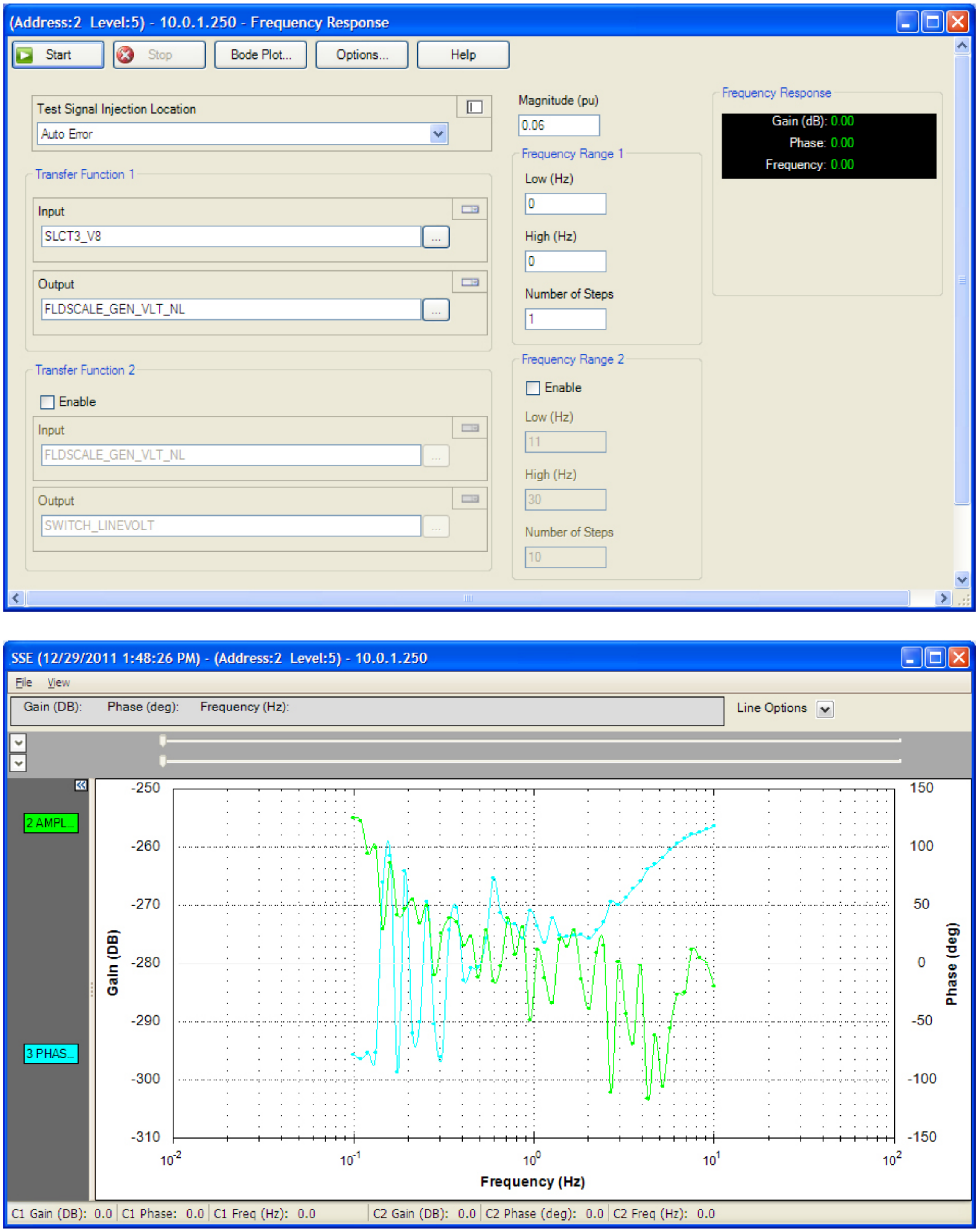


Figure 8: Type PSS2B – Dual Input PSS

The modern digital AVR has new features that improve the performance of the PSS in different applications and will improve the time needed to commission a system with a PSS.

One improvement in the digital controller concerning the PSS is the ability to have secondary settings groups. This is highly beneficial when a plant has parallel transmission lines. If one transmission line happens to trip, the impedance of the system changes and the original settings of the PSS may not give you the best performance. The modern digital controller will allow you to switch to the secondary settings group when a transmission line is lost and maintain top performance. Another application would be within hydro generating units. Previously, it was common practice to disable the PSS function until 30% load was reached due to penstock oscillation. With the use of the secondary settings group, a less aggressive PSS will be employed up to 30% load and then switched to the primary settings group with a more aggressive response.

Another feature of the modern digital controller is the availability of software tools that will assist in commissioning the PSS. The real time monitoring illustrated in Figure 14 allows the user to see immediate results of the step test. Another PSS commissioning tool commonly incorporated in the software program is the frequency response test. This test was performed by a dynamic signal analyzer in older units at an added expense to the customer and increased commissioning time. Figure 9 illustrates the frequency response test setup along with immediate bode plot results.



(Address:2 Level:5) - 10.0.1.250 - Frequency Response

Test Signal Injection Location: Auto Error

Transfer Function 1
Input: SLCT3_V8
Output: FLDSCALE_GEN_VLT_NL

Transfer Function 2
☐ Enable
Input: FLDSCALE_GEN_VLT_NL
Output: SWITCH_LINEVOLT

Magnitude (pu): 0.06

Frequency Range 1
Low (Hz): 0
High (Hz): 0
Number of Steps: 1

Frequency Range 2
☐ Enable
Low (Hz): 11
High (Hz): 30
Number of Steps: 10

Frequency Response
Gain (dB): 0.00
Phase: 0.00
Frequency: 0.00

SSE (12/29/2011 1:48:26 PM) - (Address:2 Level:5) - 10.0.1.250

Gain (DB): Phase (deg): Frequency (Hz):

C1 Gain (DB): 0.0 | C1 Phase: 0.0 | C1 Freq (Hz): 0.0 | C2 Gain (DB): 0.0 | C2 Phase (deg): 0.0 | C2 Freq (Hz): 0.0

Figure 9: Frequency Response Test Set Up with Bode Plot Results

Protection

A modern digital AVR controller has many types of protection integrated in the controller without using external protection relays. The protection elements most common in digital AVR controllers are:

- Field Overcurrent
- Field Overvoltage
- Field Ground Protection
- Field Temperature Protection
- Generator Overvoltage
- Generator Undervoltage
- Loss of Excitation
- Volts Per Hertz Protection
- Exciter Diode Protection (Brushless Exciter Applications)

Some controllers also include other generator protection features like underfrequency, overfrequency and reverse power protection. These element will can have multiple pick-up points and inverse and/or definite time characteristics.

The protection elements can be displayed as an alarm or enable an output. The output arrangement is set by a programmable logic program; this feature is explained later in this paper.

While all of the protection elements can be crucial depending on the application, the new NERC regulations pertaining to running in the automatic regulation mode make the loss of sensing protection crucial to a modern digital controller.

There are many types of loss of sensing techniques. The following are three types that can be set up as a hierarchy detection scheme.

The first order in the sequence uses a primary set of potential transformer (PTs) for regulation and a secondary set of PTs with the main function of sensing voltage for protection relays and metering. The PTs should be arranged in a configuration so that if a loss of sensing is detected in the voltage regulator PTs, then a transfer is initiated to the secondary set of PTs. It is very common to use a voltage balance relay (60 device) to initiate the transfer. This will allow the AVR system to remain in AVR mode. A simple one line diagram of this technique is illustrated in Figure 10. In modern digital excitation controllers, the initiation of the transfer is an integral part of the controller and no longer requires the use of an external relay.

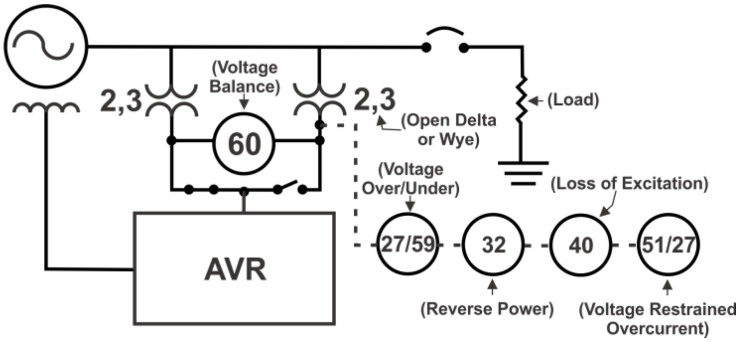


Figure 10: Voltage Balance - Loss of Sensing

If a loss of sensing is detected on the protective relay/metering PTs, necessary action is required. One such action would be to block the transfer so the AVR sensing will not be transferred to a set of compromised PTs. At the same time, the protective elements that require voltage sensing (i.e. 32R-reverse power, 40-loss of excitation, 81- frequency, 27/59 under- and overvoltage) must be blocked to prevent misoperation [6].

The second order in the sequence will use a three-phase PT and three-phase current transformers (CTs). It mimics the 60 fuse loss function that is found in many numeric multifunction relays. Figure 11 is a simple one line diagram of a 60 fuse loss connection. By monitoring the positive sequence and negative sequence voltage and currents, the modern digital AVR controller can determine if the event is a true loss of sensing condition or a transient on the system. This feature will allow a transfer to manual mode only when there is a true loss of sensing on the voltage sensing circuit and prevent nuisance transfer.

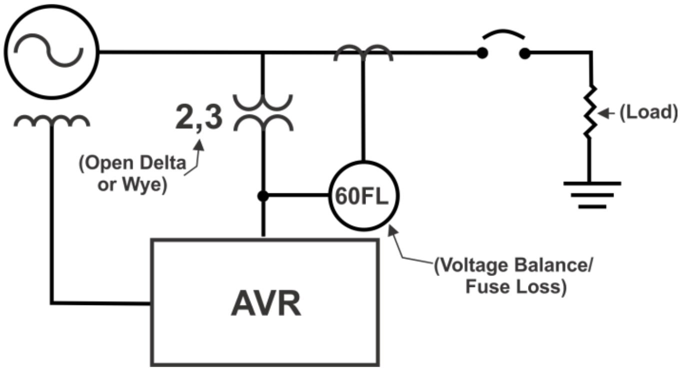


Figure 11: Voltage Balance - Fuse Loss (60FL)

The third order in the sequence is a straight voltage sensing circuit that will monitor the balance voltage and unbalance voltage (three-phase sensing). If an unbalance condition or a balance undervoltage condition exists for a certain time period, the digital AVR controller will transfer from AVR mode to manual mode of operation. Although this event will require notification to the system operator, and a penalty may be enforced, this action is better than having the generator trip off-line.

Fault Recording and Sequence of Events

Diagnostic tools have been around for many years in digital AVR systems. These tools included event recording data, sequence of event reports and, in some cases, a trending report that provides an extended look at how the generating unit is performing. Years ago, this information was stored in volatile memory which meant losing the control power to the AVR system would clear this data. Today this information is stored in nonvolatile memory to avoid this issue.

These diagnostic tools are valuable during commissioning to perform the required step test illustrated in Figure 12.

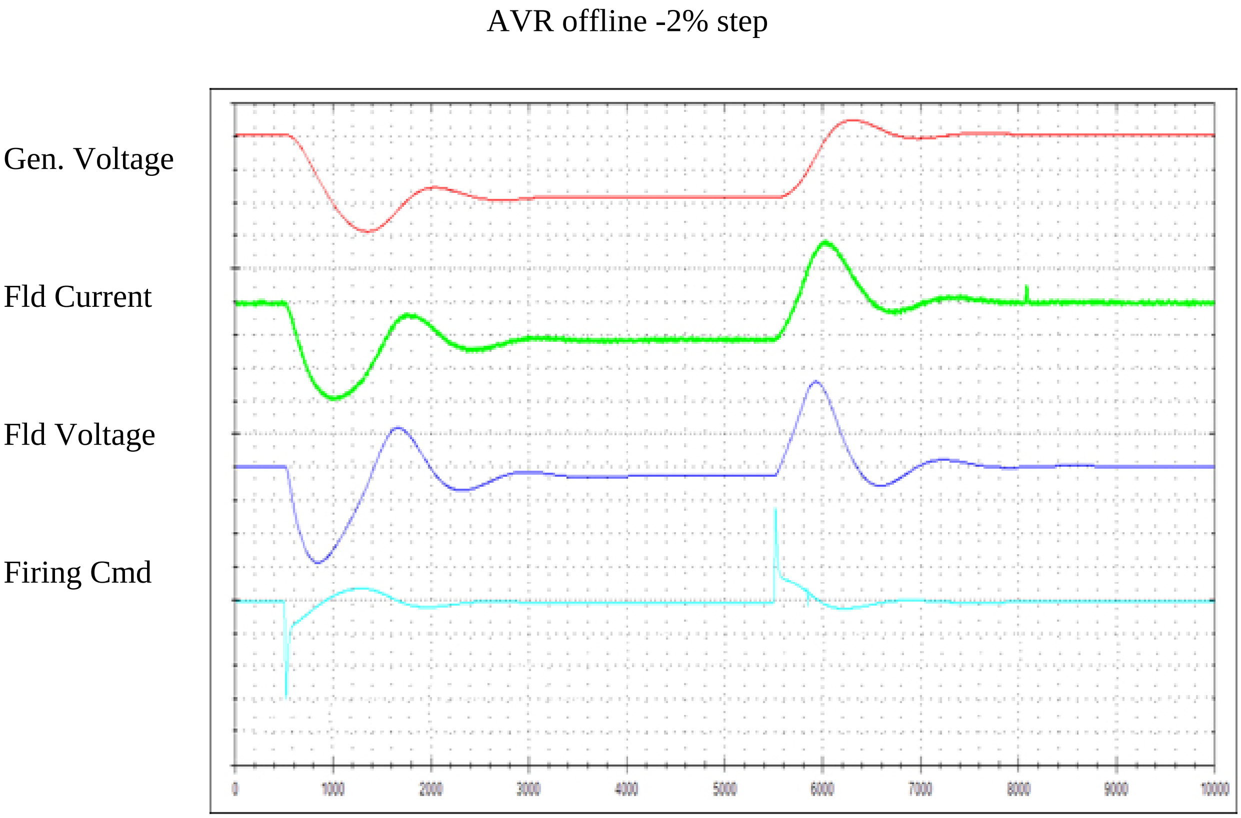
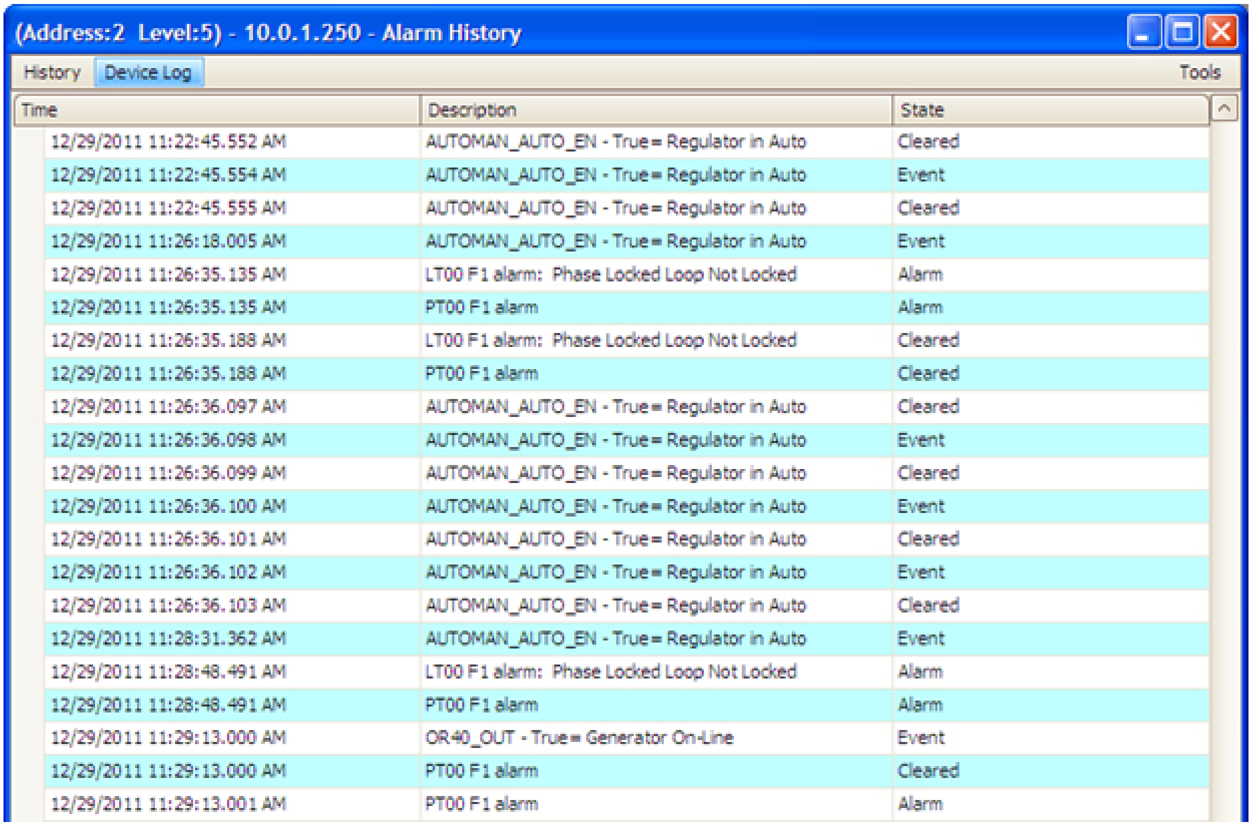


Figure 12: Single Event Recording of a 2% Step

Based on the capture data, the gain setting would be adjusted to get a better response. The diagnostic tools are also used as a valuable troubleshooting tool. If properly set up, an event will trigger an oscillograhy report that can be viewed by the operator, technician and engineer.

Sequence of event data is a tabular list of data as to what occurred within the AVR system. In modern digital AVR systems, a time sync (IRIG-B) input is used to ensure an accurate time and date for every event of the report. An example of a modern sequence of event report is illustrated in Figure 13.



Time	Description	State
12/29/2011 11:22:45.552 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Cleared
12/29/2011 11:22:45.554 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Event
12/29/2011 11:22:45.555 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Cleared
12/29/2011 11:26:18.005 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Event
12/29/2011 11:26:35.135 AM	LT00 F1 alarm: Phase Locked Loop Not Locked	Alarm
12/29/2011 11:26:35.135 AM	PT00 F1 alarm	Alarm
12/29/2011 11:26:35.188 AM	LT00 F1 alarm: Phase Locked Loop Not Locked	Cleared
12/29/2011 11:26:35.188 AM	PT00 F1 alarm	Cleared
12/29/2011 11:26:36.097 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Cleared
12/29/2011 11:26:36.098 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Event
12/29/2011 11:26:36.099 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Cleared
12/29/2011 11:26:36.100 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Event
12/29/2011 11:26:36.101 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Cleared
12/29/2011 11:26:36.102 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Event
12/29/2011 11:26:36.103 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Cleared
12/29/2011 11:28:31.362 AM	AUTOMAN_AUTO_EN - True= Regulator in Auto	Event
12/29/2011 11:28:48.491 AM	LT00 F1 alarm: Phase Locked Loop Not Locked	Alarm
12/29/2011 11:28:48.491 AM	PT00 F1 alarm	Alarm
12/29/2011 11:29:13.000 AM	OR40_OUT - True= Generator On-Line	Event
12/29/2011 11:29:13.000 AM	PT00 F1 alarm	Cleared
12/29/2011 11:29:13.001 AM	PT00 F1 alarm	Alarm

Figure 13: Sequence of Event Data

More advanced digital AVR controllers are also equipped with real time monitoring. This gives the user the ability, during commissioning or NERC compliance testing, to view the results of the step test immediately. See Figure 14. The channels to view can range from two (2) to six (6).

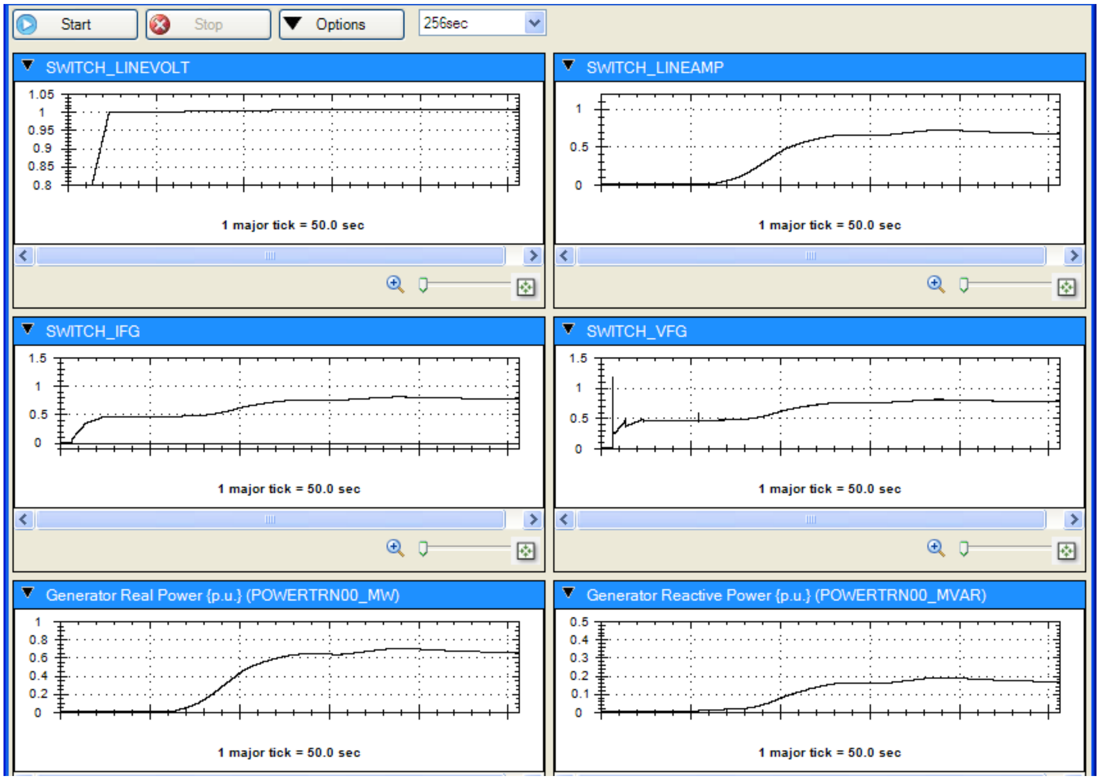


Figure 14: Six Channel Real Time Monitoring

Synchronizing

Automatic synchronizing has been around for several decades and was typically a standalone module. See Figure 15. It provided signals to the AVR and governor to match the voltage, frequency and the phase angle between the oncoming generator and the bus the generator is syncing to.

Figure 15: Anticipatory Type – Automatic Synchronizer (25A)

Over the years, the voltage matching functions have been incorporated in to the digital AVR. The modern AVR controller may have the full functionality of an automatic synchronizer as an integral part of the controller. It would have the capability to supply contacts to the governor to match the frequency and the phase angle. The AVR controller can also enable a requirement that the generator frequency and voltage can be greater than the bus frequency and voltage, but must meet the parameters set forth by the synchronizer. Figure 16 illustrates a simple one line diagram of the digital AVR connections during synchronizing. It should be noted that the sync check function should be performed by a separate device.

The synchronizing feature of the modern digital AVR has the ability to synchronize in phase lock type mode or anticipatory mode.

The phase lock type of synchronizing sets up a target for the frequency, voltage and phase angle between the oncoming generator and the bus. Corrective signals are given to the governor and AVR (internally) until the targets are met and the sync check is satisfied. The digital AVR controller will then generate an output that will close the breaker.

The anticipatory type of synchronizing is a more accurate way of synchronizing, but takes longer compared to the phase lock type. This type of synchronizing will send corrective signals via contacts and calculates the advance angle closing time based on the slip frequency of the oncoming generator, base and breaker closing time. This advance closing time provides the optimum breaker closing with minimal phase difference [7].

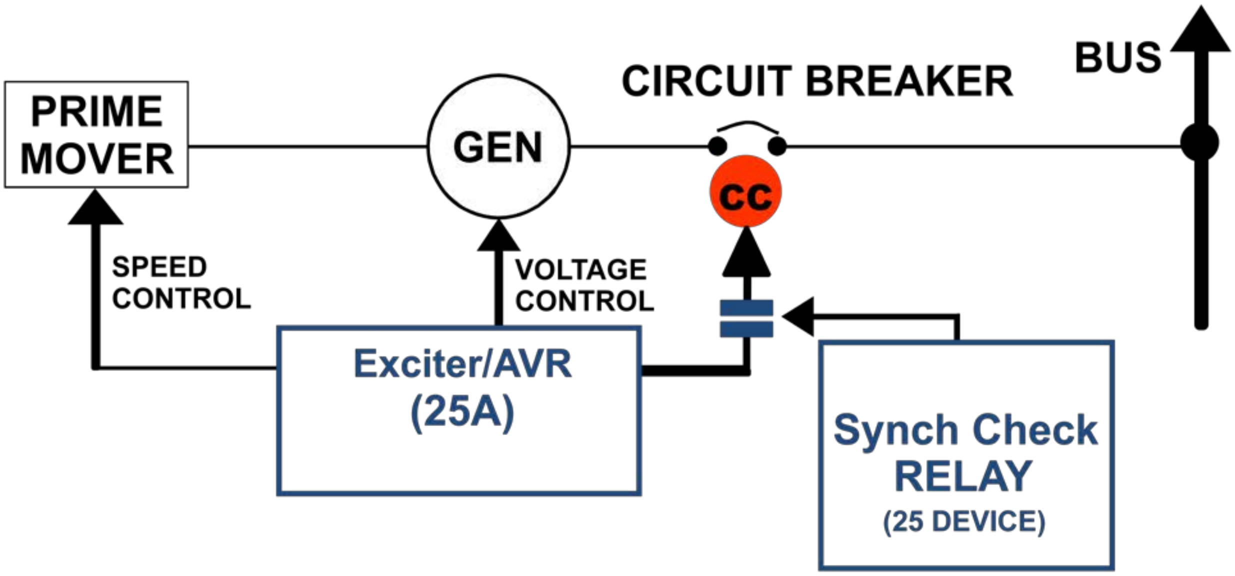


Figure 16: One Line Diagram- Auto Synchronizer with Permissive (25A, 25)

Redundancy

As stated earlier, the need to stay in AVR mode is critical. Having a solid loss of sensing scheme is critical, as was discussed in the protection section. Having a redundant system could be just as crucial.

The cost of having a redundant system versus the loss of revenue if a failure occurs in a single channel unit must be weighed. Modern digital static AVR systems can come with a variety of redundancy such as redundant controllers, redundant bridge and redundant power sources. Figure 17 is a picture of a typical redundant digital static AVR.

- **A-** Two digital AVR controllers. Each controller has identical functionality. The backup controller will always track the main controller in case of a transfer caused by an external or internal command.
- **B-** Five (5) Rectifier Bridge connected for N+ 1 redundancy. This means that four (4) bridges are able to carry the full load. The unit runs with five bridges sharing the load. If one bridge fails, the other bridges can handle the load.

Figure 17: Static Exciter with Redundancy

Programmable Logic

Programmable logic is the means use to set up the inputs and outputs used to perform different commands related to control, protection, monitoring, and reporting. In the early days of digital

AVR controls, the interface programs to set up the logic was not user friendly and could cause delays in designing and commissioning of an AVR system.

Presently, much advancement has been made with the graphical user interface of these programs. Interface programs are now created with the end user in mind so developing and modifying logic is a straightforward procedure. Modern programmable logic is equipped with numerous functional blocks, inputs, outputs, logic gates, latches, and timers. See Figure 18.

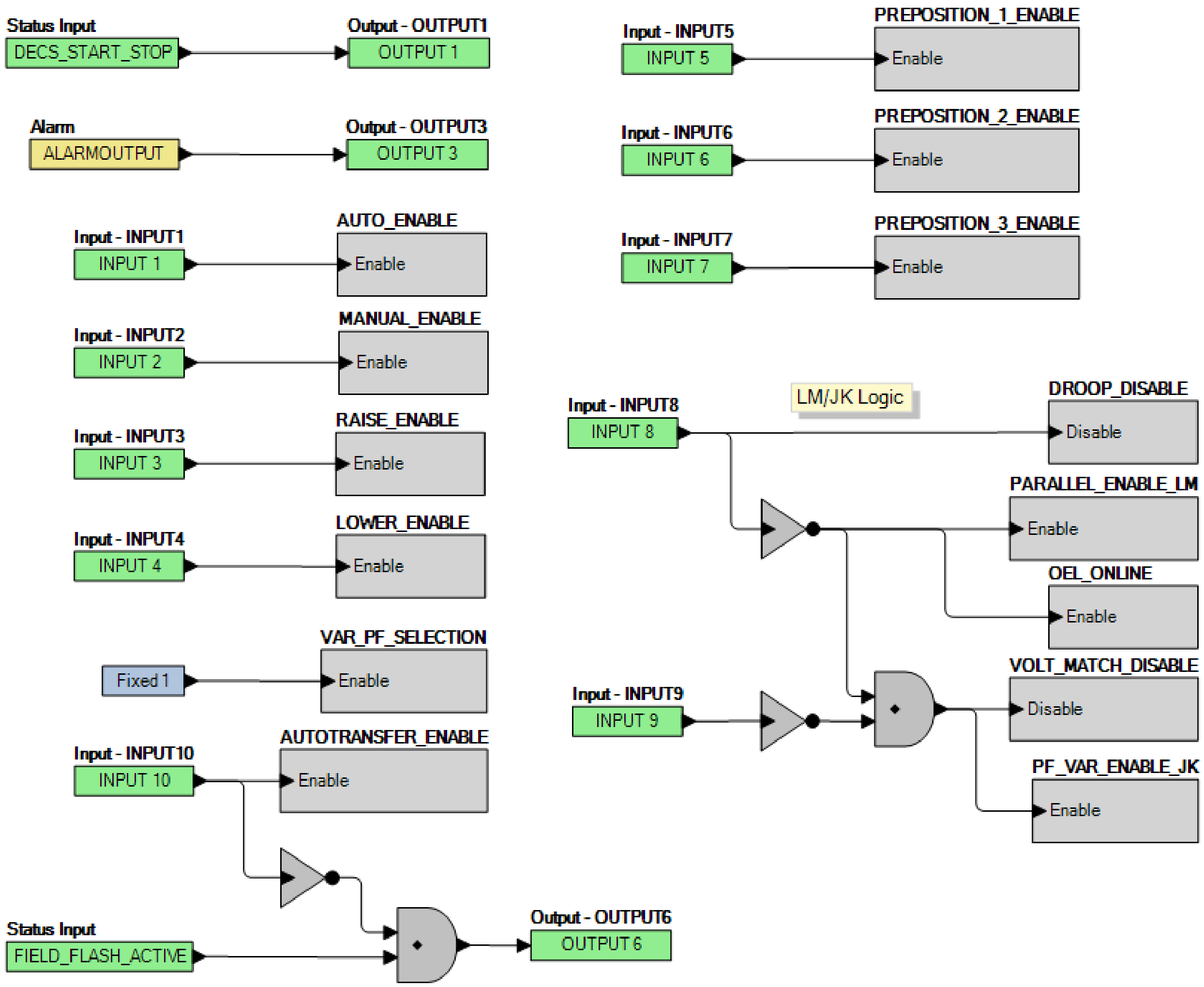


Figure 18: User Friendly Programmable Logic

Conclusion

For over 20 years, digital AVR controllers and the features they possess have dramatically increased the reliability of power systems. The advancement of available software tools decreased the amount of time needed to commission the exciter, perform periodic required testing, and analyze the system after a failure or fault. As manufacturers continue to seek user's input and consider their needs during the development process, it is exciting to consider the features that will be available in future controllers.

Reference

[1] Kral/Ecel Energy, David S., and Richard C. Schaefer/Basler Electric. "Easing NERC Testing with New Digital Excitation Systems." (2008): n. pag. *Basler Electric*. Aug. 2008. Web.

[2] Kiyong Kim; Rao, P.; Burnworth, J., "Self-Tuning of the PID Controller for a Digital Excitation Control System," *Industry Applications Society Annual Meeting*, 2009. IAS 2009. IEEE , vol., no., pp.1,8, 4-8 Oct. 2009.

[3] Schaefer, R.; Jansen, D.; McMullen, S.; Rao, P., "Coordination of digital excitation system settings for reliable operation," *Power & Energy Society General Meeting*, 2009. PES '09. IEEE , vol., no., pp.1,7, 26-30 July 2009.

[4] IEEE standard 421.5-2005, IEEE Recommended Practice for Excitation System Models for Power System Stability Study, 2005.

[5] Basler, M.J.; Schaefer, R.C., "Understanding Power System Stability," *Pulp and Paper Industry Technical Conference*, 2007. Conference Record of Annual, vol., no., pp.37,47, 24-28 June 2007.

[6] Buscher, D., "Avoiding loss of voltage sensing runaway for generator excitation systems," *Pulp and Paper Industry Technical Conference (PPIC), Conference Record of 2011 Annual IEEE*, vol., no., pp.120,123, 19-23 June 2011.

[7] "Introduction to Synchronizing." *Introduction to Synchronizing*. Proc. of Power Control and Protection Conference, Four Points Sheraton, Fairview Heights, IL. Highland: Basler Electric, 2012. N. pag. Print.

Biography

Gene Asbury is a Senior Application Specialist for Basler Electric Company and is based at the Corporate Office in Highland, IL. He has spent more than 25 years at Basler Electric in a variety of roles including Quality Control Supervisor, Technical Sales Specialist, Project Coordinator, Proposal Engineer, and finally Application Specialist for the Excitation group. Gene attended Southwestern Illinois College and received multiple degrees in Industrial Technology and Communication Electronics. Gene is an IEEE member.

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