Modeling and Pretuning Governor and Exciter Through Hardware-in-the-Loop Simulation

Asad Mohammad and Ashish Upreti
Schweitzer Engineering Laboratories, Inc.

Original release November 2022

Modeling and Pretuning Governor and Exciter Through Hardware-in-the-Loop Simulation

Asad Mohammad and Ashish Upreti
Schweitzer Engineering Laboratories, Inc.

***Abstract*—Hardware-in-the-loop (HIL) testing offers an excellent approximation of any real-world application in a simulation environment. This paper explains how an IEEE model of a synchronous machine is set up for generation and controlled by an actual governor and exciter. This study discusses the requirements for such a setup, the design of the software model, and the interface with actual hardware. Simulation tests are presented to show a comparison between the software model and the hardware response to transients upon generator loading.**

***Index Terms*—Digital simulation, hardware-in-the-loop simulation, power system modeling, real-time systems.**

I. Introduction

Hardware-in-the-loop (HIL) simulation is quickly becoming an industry standard for testing control methodologies in new or old installations. HIL testing provides a safe laboratory environment for the validation of the system design and for making modifications, thereby avoiding any adverse consequences and rework in the field. There are several control systems that monitor the system and take necessary action when certain conditions are met (e.g., load-shedding conditions or protection system considerations) and there are also control systems that actively control a device or piece of equipment (e.g., a system that controls a generator's power output and voltage). These control systems can be tested and tuned extensively in a laboratory environment, which minimizes functional errors before deployment into the field.

This paper discusses how HIL testing was used to approximate the model of a generator control system with governor and exciter controls in software, using the control block diagrams available for the governor and exciter. The power system had eight generators that had to be modeled accurately for transient stability analysis; however, the response of the machine with the control system and its tuning parameters was unknown. This test system was built to help design the proportional integral derivative (PID) control of the governor and exciter for a diesel engine-based generator so that good approximations of the control system could be used for all generator models. The HIL testing helped determine the PID control parameters for governor and exciter controls in addition to microgrid controller and protection testing [1] [2], which allowed for a seamless transition of the settings to the field to commission the generator.

II. Hardware-in-the-Loop Design

The hardware setup included a real-time digital simulator (RTDS) with interface input/output (I/O) cards and Generic Object-Oriented Substation Event (GOOSE) communications, a governor, an exciter, a feeder protective relay, and an amplifier. A similar setup is seen in [3], where the same automatic voltage regulator (AVR) exciter is used for a power system stabilizer (PSS) tuning study featuring a different real-time simulator.

The system design includes the following components:

- The RTDS simulates the IEEE synchronous machine model and the rest of the electrical system. An I/O cubicle of the RTDS interfaces directly with RTDS computers through gigabit transceiver analog output (GTAO), gigabit transceiver analog input (GTAI), gigabit transceiver digital input (GTDI), and gigabit transceiver digital output (GTDO) cards.
- A simple governor, most applicable for diesel engines and gas generators for small-to-medium-size generation, provides the output that gives the angle set point to the actuator.
- The AVR exciter is a robust device with an excitation system most applicable for static excitation and brushless excitation. The exciter output is dc voltage that is provided to the generator excitation. In this study, the output of the exciter was fed to a brushless excitation system modeled in a real-time simulation software package.
- The feeder protective relay used to interface with the generator controls has automation logic setup for automatic loading and unloading of the generator.

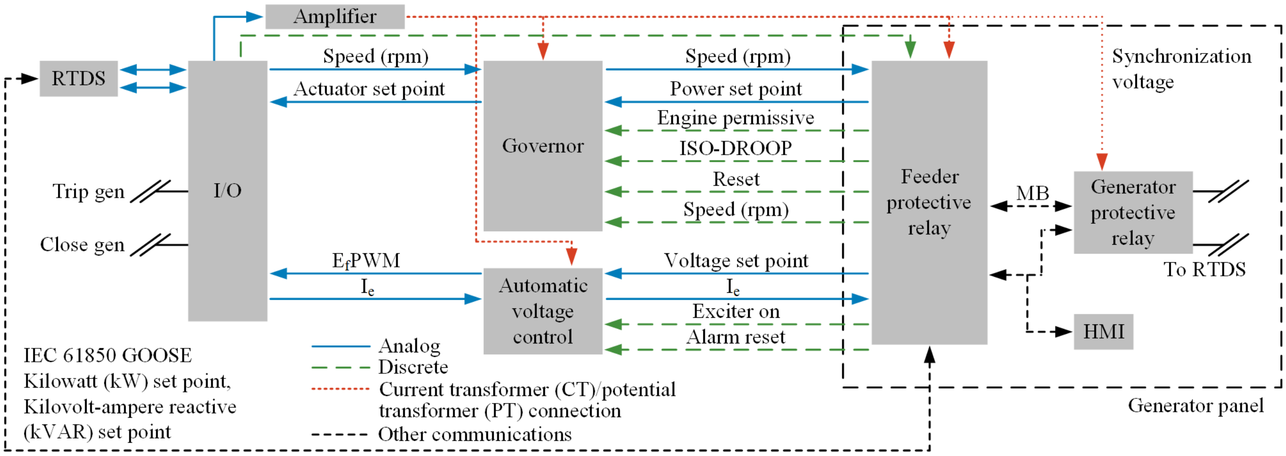

Fig. 1. Diagram of HIL setup.

The system design is shown in Fig. 1.

III. Machine and System Model

A simple system was designed with a synchronous machine, load, and static source. The generator was connected to the source model or tested standalone as required. The feeder protective relay issues set points to the governor and exciter, which in turn control the power and voltage output of the generator. Transient stability tests were performed using the load models and source by making step changes in real and reactive power. These are discussed further in Section VII.

The machine model in the real-time simulation software package has inputs of torque and excitation. Its feedback is frequency, field current, and internal terminal voltage. Torque is provided by the governor through an actuator model and excitation is provided by the AVR to the diode rectifier circuit. The RTDS provides an excellent real-time simulation environment because the simulations happen at the time step of 50 microseconds and the hardware receives measurements and feedback in real time through these simulations.

The machine in the system is rated for 6 megavolt-amperes at a 0.8 power factor. The prime mover is a diesel engine rated for 5.5-megawatt output.

IV. Governor

The governor is essential for the frequency, speed or real power control of the generator. The governor controls the speed of the generator based on the prime mover's current state inputs. The governor in this setup was electronic, with an interface screen for settings and monitoring [4]. The set of inputs and outputs interfaced with the governor are shown in Table I, and the setup diagram is shown in Fig. 2.

The governor requires the speed input to come in directly from a magnetic pickup that monitors the actual revolutions per minute of the generator shaft. The governor looks at the count of zero crossings received from the magnetic pickup to measure the speed. In the simulation, this was achieved by simulating a sine wave with a frequency equal to the revolutions per minute of the machine. There was no noticeable error.

TABLE I. I/O Interface to Governor Control

Name	I/O Type	Signal Type
Speed (rpm)	Analog input	–10 V to +10 V
Currents (x3)	Input	0–5 A
Voltages (x3)	Input	0–110 V (line-to-line)
Power set point	Analog input	–2.5 V to +2.5 V
Actuator set point	Analog output	0–20 mA

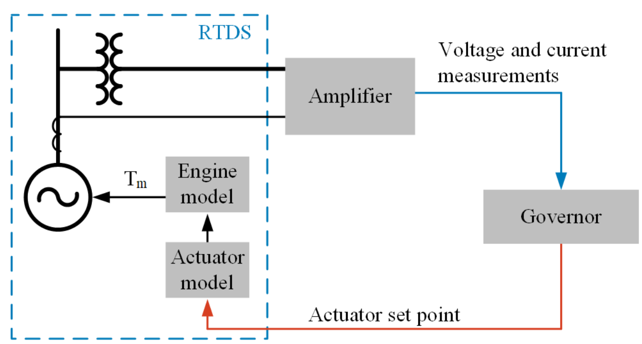

Fig. 2. Governor HIL setup.

Because the RTDS interface I/O cards accept only –10 volts to +10 volts signal as an analog signal, the actuator set point was converted using an intermediate relay that accepts a range of as much as 20 milliamperes current signal. The actual field actuator takes a 0 to 200 milliamperes signal, which is user-configurable in the governor software.

The governor software model was prepared based on the model drawing, available in [5]. The model shown in Fig. 3 is a simple proportional integral (PI) controller; however, based on the settings in the hardware, a compensator (derivative) component was added to imitate the response of the controller.

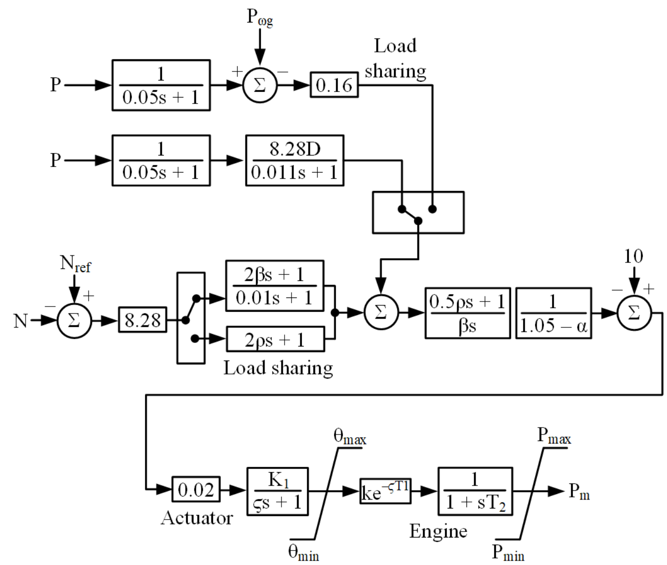

Fig. 3. Governor model [5].

A. Governor Settings

The governor has several settings required for setup and function. The governor usually operates in speed control mode or isochronous mode, where power output depends on the demand of the system at 60 hertz. For the purpose of control through the feeder protective relay, the device needs to be in power control mode or droop mode, where the power output of the machine is fixed based on the set point at 60 hertz. Relevant digital inputs need to be set in order to accept the analog set point for power.

The PID is set using proportional (P), reset (I), and compensation (D) settings in the governor software. A gain multiplier can be used, if the revolutions per minute goes beyond certain limits, to amplify and improve the transient response of the machine.

B. Actuator Model

The governor puts out a signal in the range of 0 to 20 milliamperes. As explained, this is converted to a per-unit scale ranging from 0 to 1 per unit. Actuator ranges for shaft travel are 0 to 30 degrees, which in per unit scales between 0 and 1 per unit. The rate at which the change from the governor is accepted is governed by the speed of the servomechanism motor controlling the actuator's shaft position.

C. Engine Model

The engine is the prime mover for the generator. The generator considered for this model is a 5.5-megawatt, 16-piston diesel engine. However, because the model is in per unit, the engine design is limited to response time and the amplification of output power is based on the actuator shaft position, which in turn controls the fuel valve. The lag in the output power is reflected in Fig. 3. The output of the engine model is the torque in per unit scaled according to the rating of the engine.

V. Automatic Voltage Regulator/Exciter

The AVR regulates the terminal voltage of the generator by controlling the field circuit excitation. The AVR gives the set point to the excitation control system, which in turn regulates the dc field current on the rotor circuit. Several types of excitation control systems are available; however, a brushless excitation system is modeled in this system. The output current from the exciter is dc voltage in the form of pulse-width modulation (PWM) signal. A PSS interface is not required for this system as it is islanded from the utility. The inputs and outputs for the AVR are listed in Table II.

TABLE II. I/O Interface for Exciter Control

Name	I/O Type	Signal Type
Field current	Analog input	–10 V to +10 V
Currents (x1)	Input	0–5 A
Voltages (x3)	Input	0–110 V (line-to-line)
Voltage set point	Analog input	0 V to +5 V
Field voltage (PWM out)	Analog output	–10 V to +10 V

A. Automatic Voltage Regulator and Settings

The AVR runs the PID control for the excitation system. The PID model is based off the IEEE type AC7B exciter model [6] as recommended by the exciter manual. Because the exciter includes the PID and dc output for the excitation system, the model of the AVR and excitation system is as shown in Fig. 4. The AVR has several modes of control, such

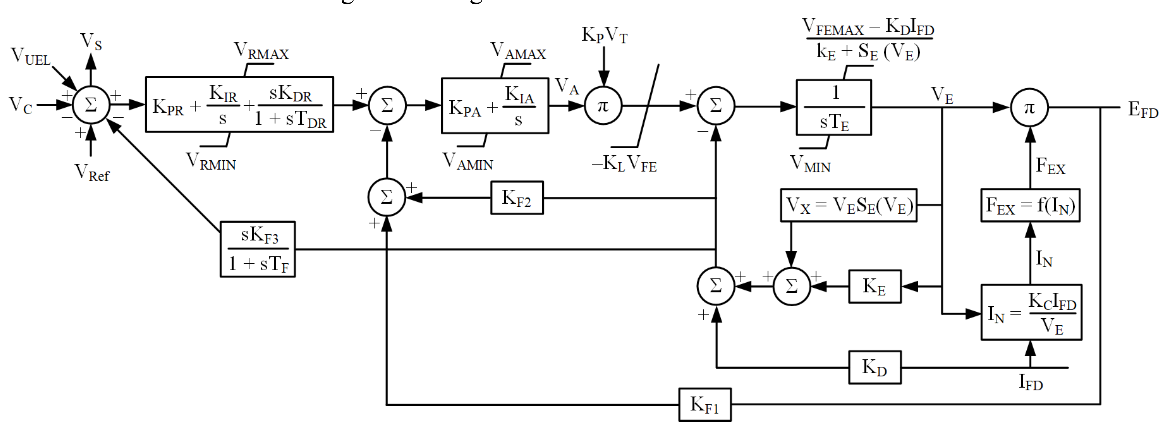

Fig. 4. IEEE type AC7B AVR exciter model [6].

as power factor control mode, voltage control mode, and volt-ampere reactive (VAR) control mode; voltage control mode is used in this test case. Voltage droop mode would be most beneficial when multiple generators are connected to the same bus without any impedance or step-up transformers in them.

B. *Excitation System*

The excitation is dc voltage output from the exciter, which in turn is fed as input to a rotational exciter, as shown in Fig. 5. The block diagram of a brushless excitation system is shown in Fig. 6. Because this voltage cannot be fed directly into the simulation, an analog output had to be configured to simulate the excitation output. This feature is made available by accessing a simulation option of the device. For more on brushless exciter and rectifier circuit modeling, see [6] and [7].

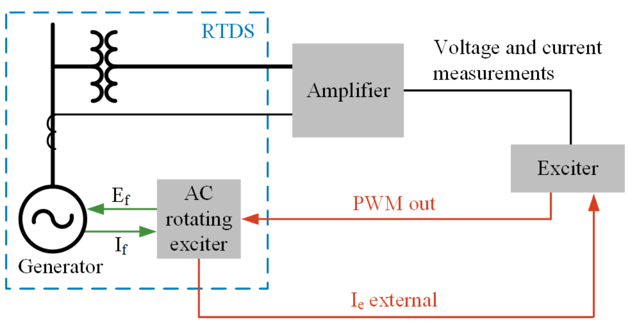

Fig. 5. Exciter HIL setup.

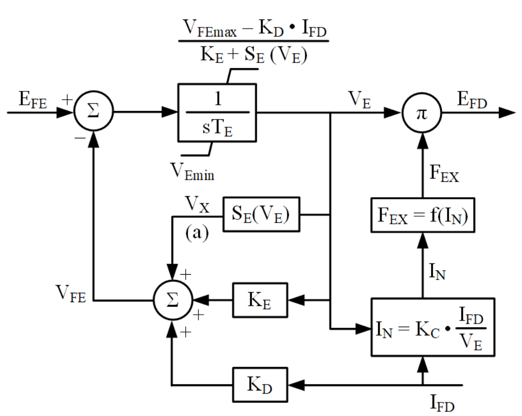

Fig. 6. AC rotating exciter with noncontroller rectifier model [3].

The rotational exciter is modeled as a section of the IEEE type AC7B model, as shown in Fig. 6. The parameters of K_C and K_D are provided in the IEEE model [6].

VI. Interface Relay Control Setup

A feeder protective relay was used to provide control set points to the governor and exciter. The set points in the relay are based on the demand set points, which are user-settable from the front human-machine interface (HMI) panel. The logic for the automated control of the generator is implemented in the automation logic application in the interface relay.

The interface relay is used for the following functions:

- Ramp up of power
- VAR output control
- Mode switching
- Ramp down of power (unloading) and tripping
- Synchronization

This interface relay uses sync-check (25A) and interfaces with another protective relay for tripping and closing the generator. The generator protective relay can trip and close the generator through its respective coils.

VII. Software Versus Hardware Model

The goal of developing this setup was to control a simulation machine using a control relay. In addition, the model of the governor and exciter was developed in software. Because one set of a governor and exciter was available, the software control diagram of the exciter and governor was set up to have multiple generators operating in parallel.

The software model was set up to match steady-state operation and transient conditions to an error of less than five percent.

The generator and exciter both have PID gain multiplication constants that needed to be correctly reflected in the software models.

A series of load acceptance and rejection tests were performed on the governor to compare the transient responses. A load acceptance or rejection test shows the performance of the governor and exciter control system for transient disturbances. It helps to tune the PID parameters of the governor controller for desired stability and time domain characteristics. A voltage step change is performed to test the performance of the excitation system, and the output is in VARs a machine can exchange with the power system. Table III shows the list of tests performed.

TABLE III. Generator Control Validation Tests

Name	Test
Load acceptance (in megavolt-amperes [MVA])	10%, 20%
Load rejection (in MVA)	10%, 20%
Voltage step change (in percent)	±5%, ±10%

Fig. 7 and Fig. 8 show the response of the machine simulation (in blue) and the hardware response (in red) to the software model. A sample load acceptance test where the machine loading is changed from 2 megavolt-amperes at 0.8 power factor to 3 megavolt-amperes at 0.8 power factor is represented here to show the validation of the governor and AVR models. The voltage comparison in Fig. 8 shows a steady error, because the hardware had a small difference in the initial operating set point of 1 per unit.

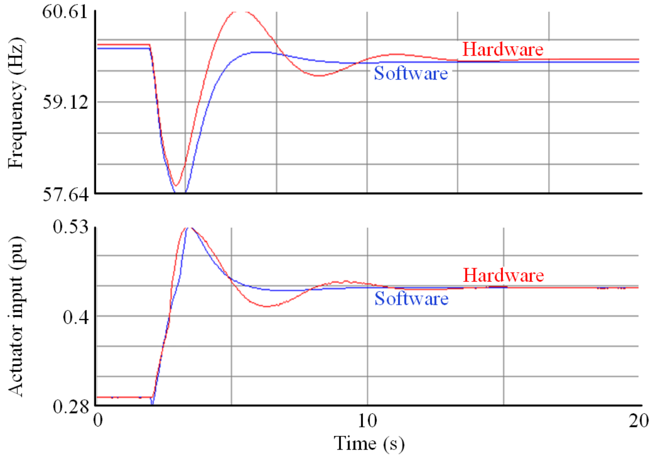

Fig. 7. Frequency response for load acceptance.

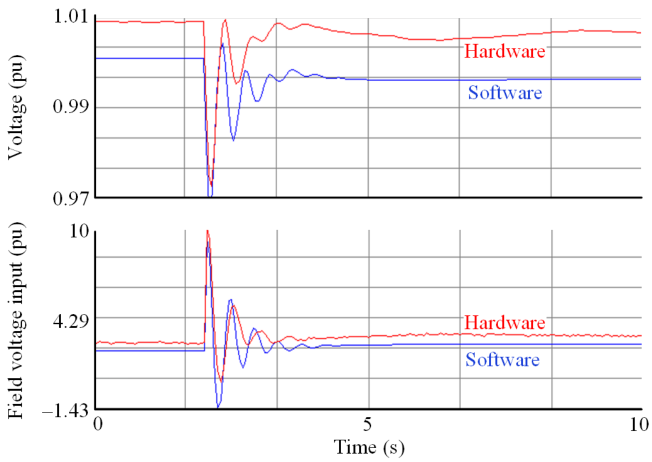

Fig. 8. Terminal and field voltage response to step change.

VIII. Observations From Comparison

Some of the observations made from the comparative testing are as follows. The error percentage in steady state is less than five percent for the governor and exciter. This is within acceptable limits for transient stability testing and generator control system validation.

Transient error observed in the governor is higher for the first peak; this is due to a gain multiplication factor of 2 when frequency goes out of bounds by 25 revolutions per minute or 2 hertz, approximately.

The AVR model follows the actual exciter closely in its response. However, the PWM simulation output from the exciter is limited to a range from 0 to 99 percent of the actual output. Hence, overexcitation limits are hit in extreme conditions, whereas this restriction is removed from the software model.

IX. Conclusion

The HIL testing of the actual exciter and governor was a useful setup that helped in the following ways.

The setup increased the understanding of closed loop control of the exciter and governor, as well as their operation. It also increased the understanding of hardware and settings control of third-party equipment.

The HIL simulation also allowed for testing the logic of the interface relay for generator control. This testing led to safe understanding of the operation of the generator, which can help in future training of prospective individuals for site testing.

Finally, it allowed for the creation of a benchmark exciter and governor model in simulation software.

References

[1] M. Joshi, G. Smith, P. V. Sangaraju, A. Upreti, and M. Kazmi, "Integrated power management and protection system for a remotely located islanded facility," in *Proc. 48th Annual Western Protective Relay Conf.*, virtual format, Oct. 2021.

[2] M. Joshi, S. L. Barndt, A. Anujan, C. Vellaithurai, M. Appannagari, and B. Nafsinger, "Reliable protection using a system preservation scheme," in *Proc. 47th Annual Western Protective Relay Conf.*, virtual format, Oct. 2020.

[3] M. S. Almas, L. Vanfretti, and L. Vanfretti, "Experimental performance assessment of a generator's excitation control system using real-time hardware-in-the-loop simulation," in *Proc. IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, pp. 3756–3762.

[4] Woodward, Inc., *2301E Digital Load Sharing and Speed Control for Engines*, [Online]. Available: https://www.woodward.com/-/media/publication-assets/technical-manual/2019/4/18/18/21/26641.pdf

[5] Electrical Transient and Analysis Program (ETAP), "Transient stability software dynamic modeling—governor models," [Online]. Available: http://www.etap.com.

[6] *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*, IEEE Std 421.5-2016, Aug. 2016.

[7] T. Bertes, "Model development and validation of brushless exciters," in *Proc. 2015 IEEE Eindhoven PowerTech*, pp. 1–6.