Synchronous Machine Governor Upgrade

Fuhong Xie, Robb Wallen, Dan Berteletti, and Barry Mather

National Renewable Energy Laboratory

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List of Acronyms

ARIES	Advanced Research on Integrated Energy Systems
atm	atmospheric pressure
CGI	controllable grid interface
HHV	higher heating value
HIL	hardware in the loop
HRSG	heat recovery steam generator
IP	Internet Protocol
MVA	megavolt-ampere
NREL	National Renewable Energy Laboratory
PEGI	Power Electronics Grid Interface
PLC	programmable logic controller
PV	photovoltaic
PID	proportional-integral-derivative
rpm	revolutions per minute
VAR	volt ampere reactive
VFD	variable frequency drive

Executive Summary

Conventional generation sources play a critical role in the stability and reliability of the electric grid, particularly as a broader mix of energy sources is integrated. To optimize grid operations and ensure seamless integration with renewable technologies, it is essential to better emulate the grid- and plant-level impacts of conventional generation sources, such as natural gas driven heat recovery steam generators (HRSGs) and combustion turbines. This report develops a governor model in a programmable logic controller (PLC) to investigate the performance of the conventional generator under various dynamic operating conditions and to identify the impacts on grid stability in a controlled environment.

The governor model aims to enable hardware-in-the-loop (HIL)-based emulations of these conventional generation sources using the existing 2-MVA synchronous machine/generator that is driven by a flexible 2.5-MW variable-speed drive. This setup will allow us to replicate the dynamic characteristics and response behaviors of natural gas driven HRSGs and combustion turbines. The controls for the emulated conventional plants follow the industry standard and are adjustable, ensuring that they accurately reflect the operational capabilities and limitations of a real-world industrial system. These controls include load following capabilities, ramp up and down with adjustable rates, startup and shutdown sequences, and emissions characteristic emulations. By incorporating these adjustable functions, we aim to capture the nuanced impacts of conventional generation, such as their ability to provide ancillary services like frequency regulation, voltage support, and spinning reserve.

In this report, we simulate two types of dynamic operations: grid connected and islanded. For each dynamic operation, representative starting sequences are tested, including turbine purge, ignition, speed ramp-up, generator excitation and synchronizing, and breaker close. The HIL-based tests provide insights for field deployment. Specifically, the high-fidelity governor model provides results to predict the potential stability and reliability risks, and suggests possible integration measures (e.g., generation and load balancing, tuning of the governor control parameters).

Ultimately, this enhanced emulation capability will be integrated into the National Renewable Energy Laboratory's (NREL) Advanced Research on Integrated Energy Systems (ARIES) platform, enabling us to conduct comprehensive studies on the interactions between conventional and renewable energy sources. By better understanding these interactions, we can develop strategies to optimize the overall performance and reliability of the grid. This will support the deployment of advanced grid management techniques, such as demand response, grid-forming inverters, and energy storage systems.

The main contributions of this report are summarized as follows:

1. This report introduces a PLC-based governor model for gas turbine controls. The model accurately simulates the dynamic behavior of conventional generation sources under various operational scenarios.
2. The governor model is integrated with an HIL test bed that includes a 2.5-MW variable-speed drive and a 2-MVA synchronous machine. This setup enables the realistic, real-time emulation of conventional power plants, particularly natural gas driven HRSGs and combustion turbines.

3. The developed PLC-based controller is adaptable to various gas turbine configurations and allows for precise control over parameters such as ramp rates and droop controls. This flexibility makes it a valuable tool for future research and industry collaboration.
4. By incorporating the governor setups into ARIES, this report lays the groundwork for future studies on the interactions between conventional and other energy sources, enhancing the ability to develop advanced grid management strategies.

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1 Introduction and Background

1.1 NREL Power Electronics Grid Interface Platform

The National Renewable Energy Laboratory (NREL) Power Electronics Grid Interface (PEGI) platform is a cutting-edge research facility dedicated to advancing power electronics technologies that are crucial for the modern electric grid. As renewable energy sources and distributed energy resources are increasingly integrated into the grid, PEGI ensures efficient, reliable, and secure operations. The platform excels in testing and validating power electronics devices, such as converters and inverters, through advanced grid simulation and emulation capabilities. This enables the realistic replication of grid conditions, ensuring the performance and reliability of power electronics in real-world environments.

The PEGI platform consists of specialized equipment that can be used in combination with other Advanced Research on Integrated Energy Systems (ARIES) assets at NREL's Flatirons Campus for maximum adaptability. The result is a flexible research system capable of supporting many different types of experiments. The main PEGI assets include a 2-megavolt-ampere (MVA) photovoltaic (PV) inverter system, a 2.5-MVA synchronous machine, a medium-voltage impedance network, and the equipment-under-test pad. By supporting research in areas like converter and inverter technologies, grid-forming inverters, power quality, and advanced control strategies, PEGI could play a vital role in modernizing the grid and facilitating the seamless integration of renewable energy, enhancing grid stability, resilience, and efficiency.

1.2 Purpose and Importance of Governor Simulation

To support the rapid transition of the U.S. power system from a centralized conventional plant paradigm to one with a more diverse and distributed generation portfolio, NREL aims to better emulate the grid- and plant-level impacts of conventional generation sources, such as natural gas driven heat recovery steam generators (HRSGs) and combustion turbines. This understanding is crucial for ensuring grid stability and reliability as the energy landscape evolves. The project involves using a 2-MVA synchronous machine/generator driven by a flexible 2.5-MW variable-speed drive to accurately represent conventional power plants. By using industry-standard and adjustable controls, the project aims to engage future research collaborators and fairly incorporate the impacts and capabilities of conventional generation into energy transition research.

Governor simulation plays a vital role in this effort by providing insights into how conventional generation units respond to changes in grid frequency and demand. Governors are control systems that adjust turbine inputs to maintain a constant rotational speed, stabilizing the generator's output frequency. In a grid that is increasingly powered by intermittent and variable renewable energy, conventional generators' ability to provide frequency regulation and inertia becomes essential. Accurately simulating the governor responses allows NREL to evaluate how these units can support grid stability and dynamically interact with renewable sources.

Through detailed emulations and governor simulations, NREL can develop and validate new control strategies and grid management techniques that optimize the strengths of both conventional and renewable generation. This approach not only enhances the reliability and efficiency of the power system but also addresses potential stability gaps that might arise with higher integration levels of renewable energy. Ultimately, this research supports a smoother and more resilient transition in the power sector, helping ensure that the grid remains stable and reliable as the generation mix continues to evolve.

1.3 Challenges of Governor Simulation

In this project, the developed governor model communicates with a 2.5-MW variable-speed drive to control a 2-MVA synchronous machine/generator and emulates the dynamics of conventional generation sources like natural gas-driven HRSGs and combustion turbines. This setup needs to employ industry-standard, adjustable controls to accurately represent conventional power plants, which is crucial for engaging future research collaborators. But governor simulations face challenges, such as modeling complex nonlinear characteristics, ensuring real-time performance, seamlessly integrating with physical systems in hardware-in-the-loop (HIL) setups, and being scalable and flexible to meet various research needs and industry standards. Existing models in RSCAD and Simulink often face issues in these areas, necessitating more robust solutions.

To complete the detailed model of the governor, we follow the proposed three steps:

1. Start with the design parameters from an existing industry gas turbine and scale down the rating based on the NREL synchronous machine.
2. Design the dynamic model of the gas turbine and the HRSG in the industry-standard programmable logic controller (PLC) platform as well as the communication link and verify the governor model with simulations.
3. Evaluate the overall stability and performance of the PLC governor model with the NREL synchronous machine hardware.

To build such a governor model, we face a few major challenges. These challenges are summarized in Table together with the corresponding solutions.

Table 1. Challenges of the Governor Simulation

Challenge	Description	Solution
Complexity and accuracy	Requires detailed modeling of nonlinear characteristics and multiple feedback loops	Use PLCs for precise control.
Real-time performance	Ensures that the simulated responses match the actual system behaviors in real time	Use PLCs to provide precise real-time execution.
Integration with physical systems	Enables seamless interaction with physical components in HIL setups	Use direct hardware interfacing with PLCs.
Scalability and flexibility	Accommodates various system sizes and adapts to new technologies and strategies	Use PLCs to offer customization and scalability.

2 Modeling of The Governor

In this project, a sophisticated gas turbine simulator model is developed by ENTRUST Solutions Group for NREL. This comprehensive model simulates the operation of a gas turbine, an HRSG, and a steam turbine, all using the Allen-Bradley ControlLogix PLC.

The gas turbine is modeled based on Brayton cycle thermodynamic calculations, providing an accurate representation of its performance characteristics and operational dynamics. Similarly, the HRSG and steam turbine models are based on Rankine cycle thermodynamic calculations, ensuring precise emulation of their thermal and mechanical processes. ENTRUST designed the simulator to be highly flexible and fully configurable, allowing users to easily adapt the model to different gas turbine configurations and specifications through user entry data. This adaptability ensures that the simulator can be tailored to meet various research and operational needs, making it a valuable tool for studying the integration of conventional and renewable energy sources.

By incorporating detailed thermodynamic principles and advanced control systems, ENTRUST's gas turbine simulator model enables NREL to conduct in-depth analyses and optimizations of gas turbine performance within a simulated environment. This contributes to a better understanding of how conventional generation technologies can support and enhance the transition to a more sustainable electric grid.

2.1 Gas Turbine

There are three major components of every gas turbine: the compressor, the combustion chamber, and the turbine. Figure 1 shows the typical arrangement of a gas turbine with open exhaust.

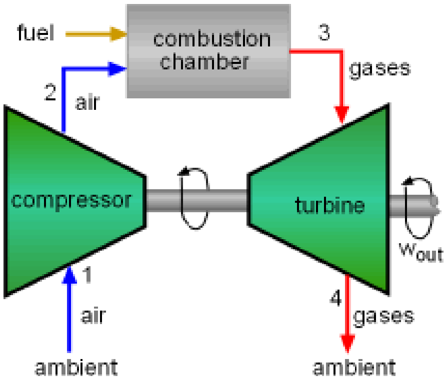


Figure 1. Typical structure of a gas turbine with open exhaust

2.1.1 Compressor

The compressor section of the gas turbine draws ambient air (1) into the compressor and compresses the air (2). As the air is compressed, the volume is reduced, which causes the air temperature to increase. This heated air (2) is then passed to the combustion chamber and is used for combustion air.

The compressor requires power to compress the air. Normally, in service operation, this power comes from the turbine section of the gas turbine, and approximately two-thirds of the power produced by the turbine section is used by the compressor. The remaining power drives the generator to produce electricity.

2.1.2 Combustion Chamber

Fuel (typically natural gas) is burned in a combustion chamber to raise the temperature of the air (3). The heated air (3) is then routed to the turbine. At this point, the air temperature could exceed 2000 °F.

2.1.3 Turbine

The turbine section of the gas turbine consists of several rows of blades. As the hot air passes through each row of turbine blades, the air volume expands, and the temperature decreases. This process transfers energy from the heated air to the turbine, which is then used to generate power. The air discharges from the turbine at slightly above atmospheric pressure (atm) and at a temperature exceeding 1000 °F.

There are two operating modes in the developed gas turbine model: simple-cycle mode and combined-cycle mode. In simple-cycle mode, the exhaust from the gas turbine is released directly into the atmosphere, wasting the exhaust heat. But in combined-cycle mode, the exhaust heat is directed to a HRSG. The HRSG uses this waste heat to generate steam, which is then used in a steam turbine to produce additional power. The amount of waste heat from the gas turbine is sufficient to generate an additional 50% to 60% of the gas turbine's output through the steam turbine. For instance, if the combustion turbine generates 100 MW, the steam turbine in combined-cycle mode can generate an additional 50 MW to 60 MW.

2.1.4 Gas Turbine Design Data

All gas turbines are designed with a specific, basic set of parameters. These basic design parameters determine the operation of the gas turbine and are key inputs into the model. When developing the model, we used the design parameters for a GE 7EA gas turbine; these are shown in Table 2 in both U.S. customary and metric units of measure.

Table 2. GE 7EA Design Parameters

Design Parameter	U.S. Customary Unit		Metric Unit	
Rated output	90	MW	90	MW
Design heat rate	10,480	Btu/kWh	10,990	kJ/kWh
Compressor ratio	12.6			
Inlet temperature	68	°F	20	°C
Barometric pressure	14.696	psia	1	atm
Firing temperature	2,055	°F	1,124	°C
Exhaust flow	643	lbs/s	292	kg/s
Exhaust temperature	998	°F	537	°C
Inlet pressure drops	3.5	in H_2O	0.008604	atm
Exhaust pressure	5.5	in H_2O	0.013521	atm

Operational Parameter	**Value**	**Value**	**Value**	**Unit**
MW ramp rate	Normal	Fast	Emergency	
Fast load ramp rate	3.35	13.35	40	MW/min
Turbine Acceleration Rate				
0 to 2,700 rpm	396	396	396	rpm/min
2,700 to 3,420 rpm	1,116	1,116	1,116	rpm/min
3,420 to 26,000 rpm	360	360	360	rpm/min
Inlet Guide Vane				
Fully closed	0	0	0	Degrees
Shutdown position	37	37	37	Degrees
Minimum (simple cycle)	42	42	42	Degrees
Minimum (combined cycle)	57	57	57	Degrees
Maximum	84	84	84	Degrees

2.2 Heat Recovery Steam Generator

An HRSG is a heat exchanger used in combined-cycle applications that recovers waste heat from the gas turbine and uses it to generate steam at a high pressure and a high temperature. Steam is used by the steam turbine to generate additional power. The HRSG consists of superheaters (SH in Figure 2), a reheater (RH in Figure 2), evaporators (EVAP in Figure 2), economizers (ECO in Figure 2), steam drums, and a condensate preheater (PH in Figure 2). This model uses a triple-pressure HRSG, meaning there are three sections: high pressure, intermediate pressure, and low pressure. Figure 2 shows the arrangement of these components in the HRSG.

The condensate pump supplies water from the condenser hot well to the condensate preheater within the HRSG. This water is then sent to the deaerator. The feedwater pump supplies water to the high-pressure and intermediate-pressure economizers and the low-pressure steam drum. There are three feedwater flow control valves to control the feedwater flow to each section of the HRSG. The feedwater is then heated in the sections of the HRSG and converted to steam, which is used to generate power in the steam turbine.

There are two economizers in the HRSG: one high-pressure economizer and one intermediate-pressure economizer. The economist preheats the feedwater before routing it to the steam drum. The economizers use the lowest-temperature gas in the high-pressure and low-pressure zones of the HRSG to heat the lowest-temperature feedwater to increase the efficiency of the system. There is a high-pressure, intermediate-pressure, and low-pressure evaporator in the HRSG. The evaporators circulate feedwater from the drum, through evaporation, and back to the steam drum to raise the temperature of the feedwater to the saturation temperature. Moreover, this model uses three steam drums: a high-pressure drum, an intermediate-pressure drum, and a low-pressure drum. Steam drums are used to separate steam from water. The steam drums operate in saturated conditions with water and steam coexisting. The saturated steam from the steam drums is routed to the superheaters. The water enters the steams drums from the economizers, where it is circulated with the water within the evaporator until the water reaches the saturation temperature.

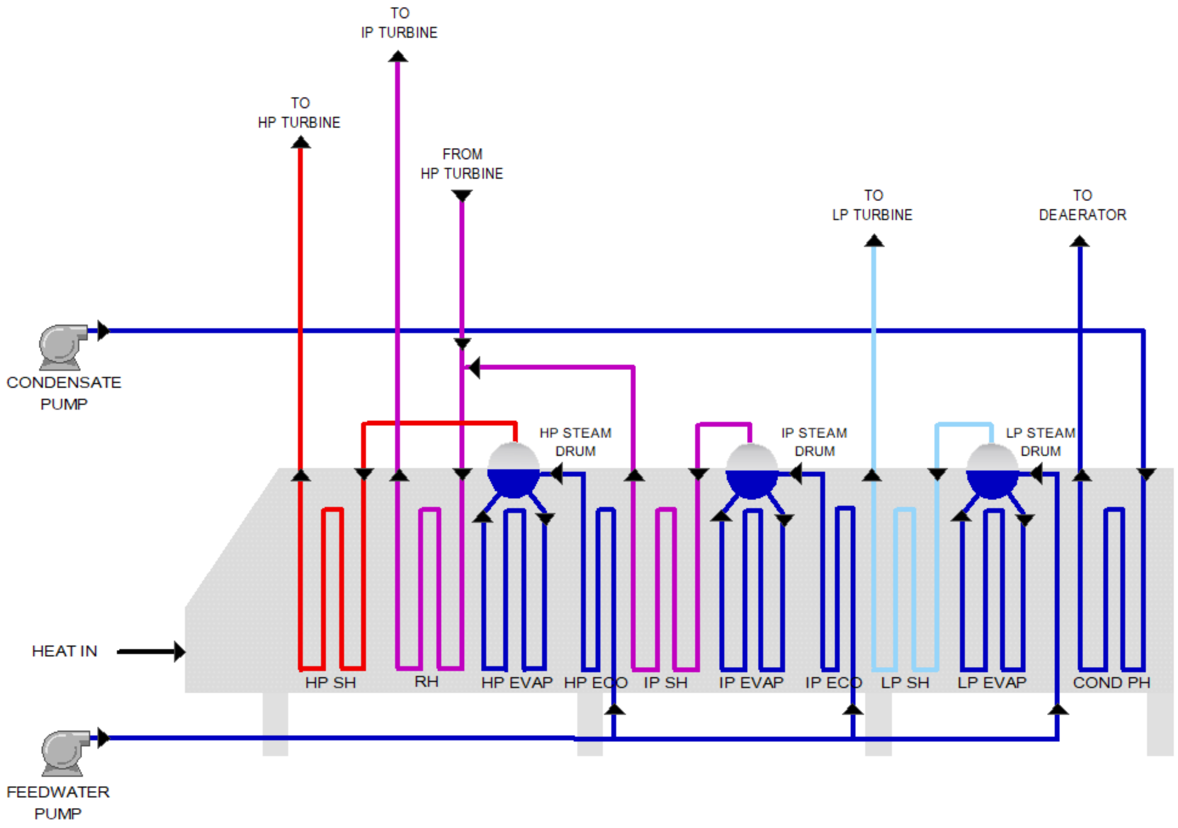


Figure 2. Typical arrangement of an HRSG

Then, the high-pressure, intermediate-pressure, and low-pressure superheaters add heat to the saturated steam generated in the steam drum to the superheated steam. The superheated steam is dry steam, and it is used to drive the steam turbine. The reheater in the HRSG then takes in cold reheat steam from the high-pressure steam turbine and reheats it to add superheat to the steam before sending the steam to the intermediate-pressure steam turbine.

The condensate preheater is the last section in the gas path of the HRSG. It uses the remaining heat from the gas to preheat the condensate from the condenser hot well. The condensate is then routed to the deaerator.

2.3 Steam Turbine

2.3.1 Rankine Cycle

The steam turbine uses a process that is known as the Rankine cycle. The Rankine cycle is a thermodynamic process that converts thermal energy or heat into mechanical energy. In a theoretical Rankine cycle, it is assumed that there are no losses in the steam turbine.

As illustrated in Figure 3, the cycle begins with isentropic compression (1–2), where saturated feedwater is pumped to a high pressure with minimal work input. Next, during isobaric heat transfer (2–3), the high-pressure water is heated (first in the deaerator using extraction steam, then in the HRSG by the gas turbine exhaust) until it becomes superheated steam. The steam then undergoes isentropic expansion (3–4) through high-, intermediate-, and low-pressure turbines, producing power as its temperature and pressure drop, though real turbines incur efficiency losses. Finally, in isobaric heat rejection (4–1), the steam is condensed back to saturated liquid in the condenser, completing the closed-loop cycle.

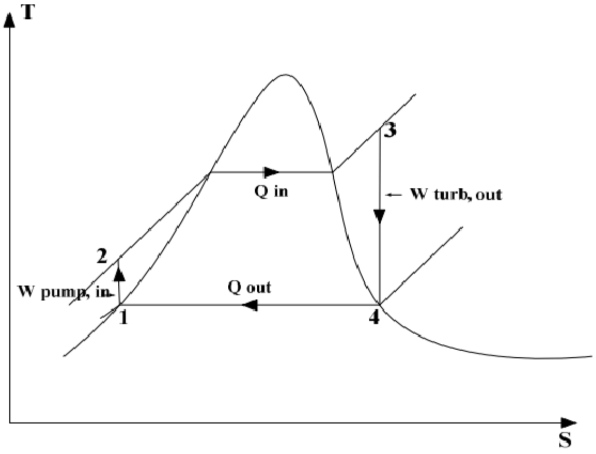


Figure 3. Rankine cycle temperature (T)–entropy (s) diagram

2.3.2 High-Pressure Turbine

There are three major components of the steam turbine: the high-pressure turbine, the intermediate-pressure turbine, and the low-pressure turbine, as shown in Figure 4.

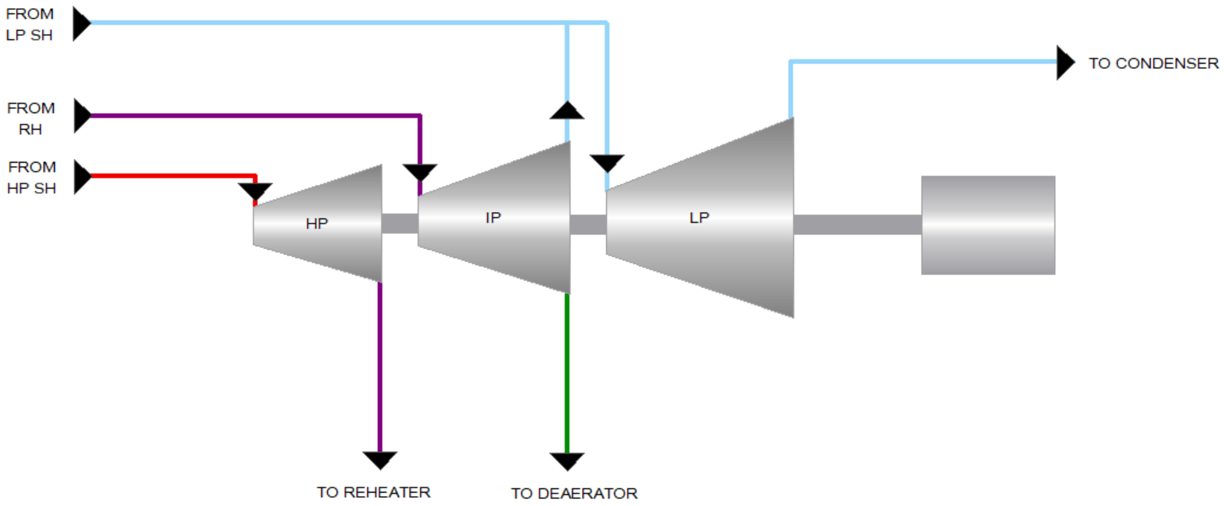


Figure 4. Steam turbine with high-pressure, intermediate-pressure, and low-pressure turbines

The high-pressure turbine takes steam from the high-pressure superheater in the HRSG. The steam passes through multiple rows of turbine blades. As this happens, the steam expands, and the pressure and temperature of the steam decreases. The energy in the steam is transformed from potential to kinetic energy, turning the turbine blades. When the steam pressure and temperature decrease to the point of having less than 200 °F superheat, the steam is then exhausted from the high-pressure turbine and returns to the reheater in the HRSG, where the steam is reheated to a higher temperature at additional degrees of superheat.

2.3.3 Intermediate-Pressure Turbine

The intermediate-pressure turbine takes steam from the reheater in the HRSG. This is steam that was exhausted from the high-pressure turbine and sent to the reheater to increase the temperature. The steam passes through multiple rows of turbine blades, where the steam expands and decreases in temperature and pressure. The energy from the steam is converted from potential energy in the steam to kinetic energy, turning the blades. The steam is then exhausted to the low-pressure turbine. Some of the steam from the intermediate-pressure turbine exhaust is routed to the deaerator and is used to heat the feedwater entering the economizers of the HRSG. This is done to improve the overall cycle efficiency of the turbine and HRSG.

2.3.4 Low-Pressure Turbine

The low-pressure turbine uses steam from the intermediate-pressure turbine exhaust and the low-pressure superheater in the HRSG. At this stage, the incoming steam is at the lowest temperature and pressure. As it passes through the blades, the steam expands and decreases in temperature and pressure. The potential energy in the steam is transformed into kinetic energy, turning the turbine blades. The steam is then exhausted to the condenser, where it is condensed and reused in the turbine cycle.

3 Model Implementation

3.1 Test Bed Setups

The topology of the governor simulator test bed is depicted in Figure 5. The governor model for the GE 7EA gas turbine, a 90-MW gas turbine, has been implemented on Studio 5000, the Allen-Bradley ControlLogix platform, using the parameters specified in Table 1. The governor simulator is designed to emulate the operational characteristics of both the simple-cycle gas turbine and the combined-cycle turbine, which includes the HRSG and the steam turbine. The simulator produces and transmits essential operational signals (e.g., speed, torque, and voltage) to the NREL LabVIEW equipment. This LabVIEW equipment functions as the supervisory control and data acquisition platform, which manages the control signals and collects measurement data throughout the simulation process.

In this setup, the prime mover is a 2.5-MW dynamometer motor, driven by a variable-frequency drive (VFD) that enables precise speed regulation. The VFD responds to the speed and torque signals from the governor controller and the emulation of a gas turbine, driving the 2.5-MW dynamometer motor via a high-speed shaft coupling to act as a generator. To regulate the generator’s terminal voltage, the NREL LabVIEW equipment sends excitation control signals to the generator exciter while simultaneously providing feedback on key operational measurements, such as speed and power, to the governor simulator for real-time control accuracy. The synchronous generator is connected to both a load bank and a 13.2-kV controllable grid interface (CGI) through circuit breakers to facilitate a comprehensive testing environment. This setup allows for the controlled and accurate replication of real-world operating conditions, ensuring a robust and reliable testing framework for system performance evaluations.

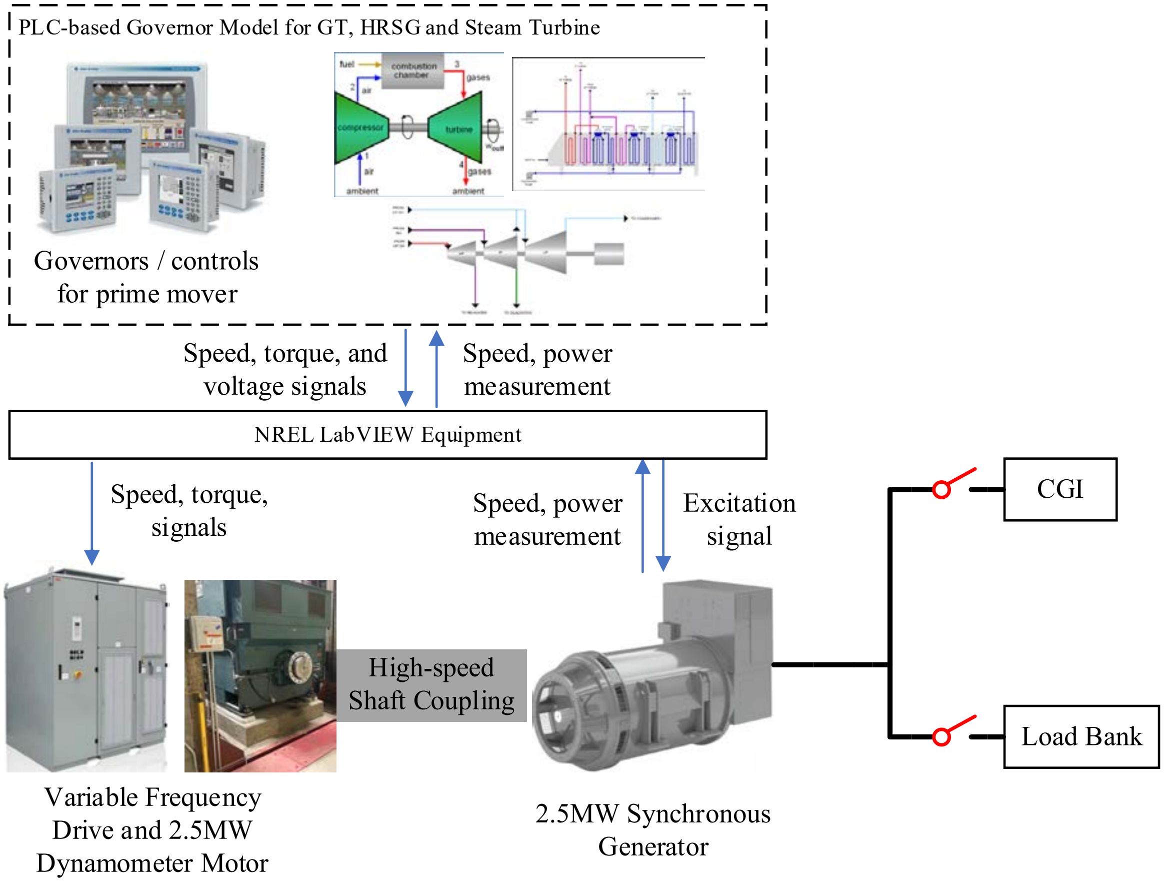
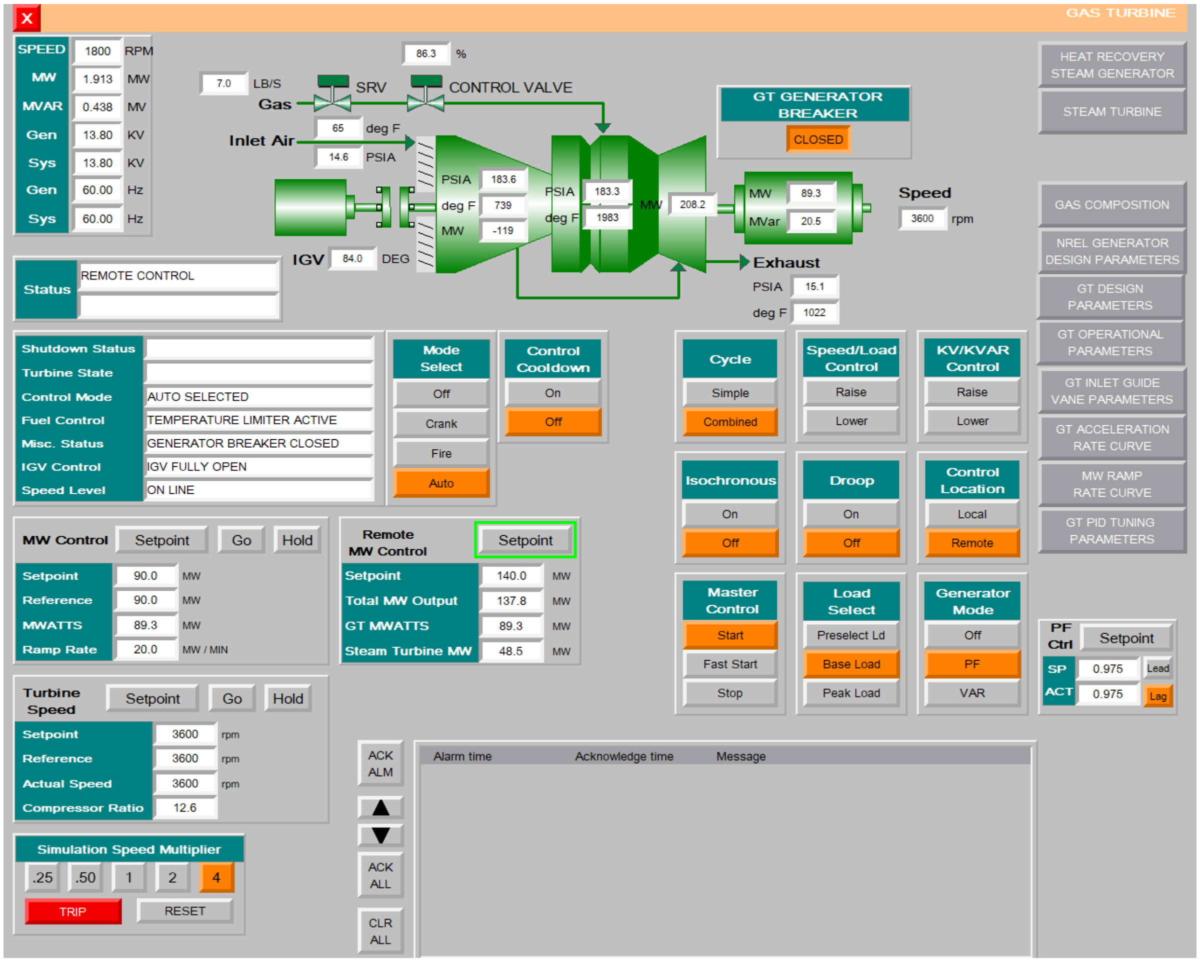


Figure 5. Test bed setup at NREL's Flatirons Campus

3.2 Control Interface

In addition to the core simulation capabilities, this project also develops an intuitive operator interface using Allen-Bradley FactoryTalk View, featuring a set of graphics that provide a clear visualization of the system's operations. As shown in Figure 6, the primary interface screens include detailed views of the gas turbine and the main control interface for both the HRSG and the steam turbine. These interfaces are complemented by user entry data windows, which empower the user to fine tune a wide array of parameters. These include adjustments for natural gas composition, generator design specifications (e.g., the 2.5-MW dynamometer motor onsite), gas turbine operational settings, gas turbine design configurations, inlet guide vane operations, gas turbine acceleration rates, megawatt loading rates, proportional-integral-derivative control tuning parameters, HRSG design characteristics, superheat pressure-drop curves, steam turbine design parameters, first-stage steam pressure curves, and condenser back-pressure curves.

This simulator not only provides a robust tool for modeling and analyzing the dynamic behavior of gas and steam turbines but also offers extensive configurability, making it an invaluable resource for researchers and engineers involved in the optimization and study of combined-cycle power plant operations.



SPEED	1800	RPM
MW	1.913	MW
MVAR	0.438	MV
Gen	13.80	KV
Sys	13.80	KV
Gen	60.00	Hz
Sys	60.00	Hz

Status	REMOTE CONTROL
Shutdown Status	
Turbine State	
Control Mode	AUTO SELECTED
Fuel Control	TEMPERATURE LIMITER ACTIVE
Misc. Status	GENERATOR BREAKER CLOSED
IGV Control	IGV FULLY OPEN
Speed Level	ON LINE

GT GENERATOR BREAKER: CLOSED

MW Control		
Setpoint	90.0	MW
Reference	90.0	MW
MWATTS	89.3	MW
Ramp Rate	20.0	MW / MIN

Remote MW Control		
Setpoint	140.0	MW
Total MW Output	137.8	MW
GT MWATTS	89.3	MW
Steam Turbine MW	48.5	MW

Turbine Speed		
Setpoint	3600	rpm
Reference	3600	rpm
Actual Speed	3600	rpm
Compressor Ratio	12.6	

PF Ctrl		
SP	0.975	Lead
ACT	0.975	Lag

Figure 6. Control interface for the developed governor model

3.3 Communication Setups

The configuration and commissioning process for the governor model involves several steps related to the Ethernet connection and Modbus table configuration for the ProSoft module and NREL LabVIEW equipment for Modbus based communication. The overall communication connection is shown in Figure 7.

Initially, the ProSoft module, which functions as the Modbus master, disconnected from the laboratory network and connected to a host workstation for IP address configuration. The NREL LabVIEW equipment is configured as the Modbus slave and the data points are set up according to a specific predefined communication setting before commissioning (e.g., starting address of inputs and data types). The ProSoft module's IP address is assumed to be 192.168.127.2, with configurations made through the ProSoft Configuration Builder Software as needed, where users can also adjust the Modbus commands, the register offsets, and the word swapping options.

To ensure accurate data exchange between the PLC based governor model and NREL's LabVIEW equipment, careful verification of Modbus points is essential. This includes ensuring correct register mapping, verifying data points in real time, and adjusting configurations based on the specific interpretations of the Modbus data by different manufacturers.

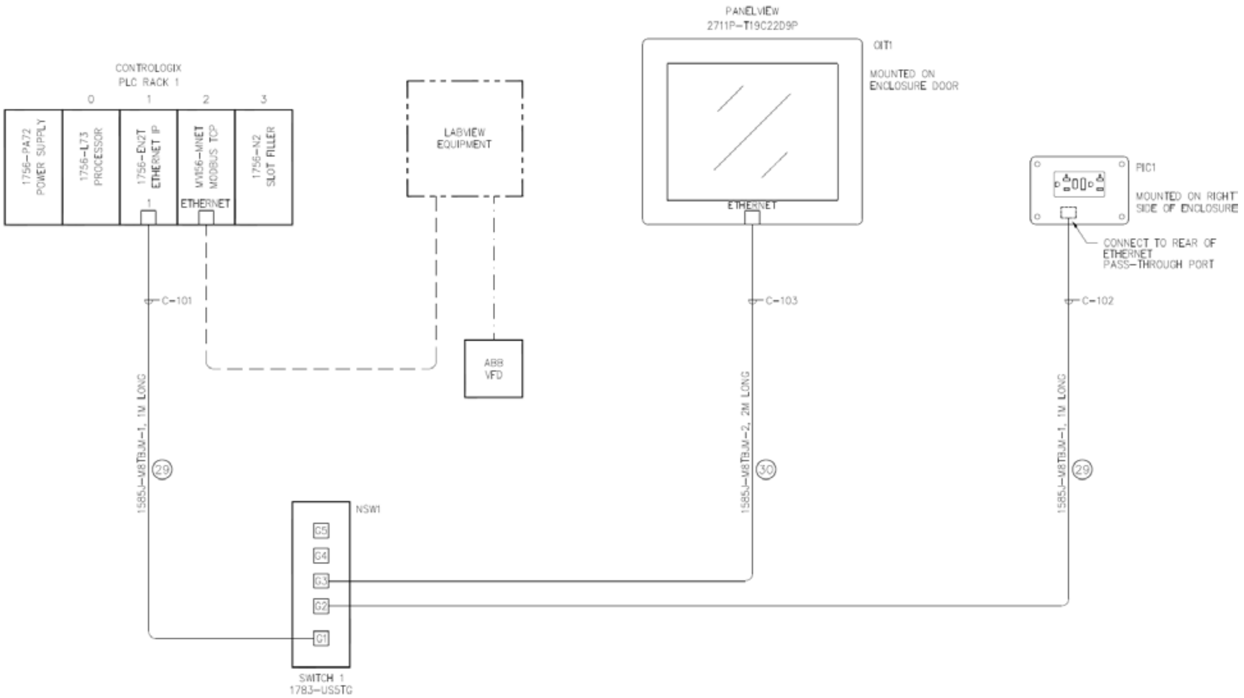


Figure 7. Communication network settings

3.4 PLC-Based Gas Turbine Model

The design diagram of the governor model is illustrated in Figure 8. The operation model for the GE 7EA gas turbine was developed using Studio 5000, based on specific design parameters. This model is structured into three primary sections: input data processing, control calculations, and gas turbine simulations.

At the beginning of the program, an execution timer is implemented to establish a consistent execution time step of 100 ms. Additionally, it monitors the heartbeat signal from the NREL LabVIEW equipment to ensure proper Modbus communications. After the governor model reads data through the Modbus link and the user interface, it proceeds to validate the input data for accuracy, ensuring the correct operating settings, valid data ranges, and appropriate data types.

The model subsequently calculates the higher heating value (HHV) based on the gas composition provided by the user, as illustrated in Figure 9. Typical HHVs for various gas compositions are outlined in Table 3. This step ensures that the gas turbine's performance is simulated using accurate and reliable data inputs. Four control schemes are implemented within the governor model to manage the generator's operation. When the droop control is activated and the generator is set to power dispatch mode (connected to the grid but not operating in isochronous mode), the user's megawatt command is adjusted based on the system frequency, the droop curve, and the deadband values entered in the user interface. The megawatt controls use the user's megawatt command as a target, with a proportional-integral-derivative (PID) controller calculating the control signal to adjust the power output accordingly.

The volt ampere reactive (VAR) controls regulate the generator's reactive power output. There are three conditions for the VAR system: (1) In off mode, the model uses the actual reactive power as the VAR set point without any control action. (2) In power factor mode or (3) in VAR mode, the user's input serves as the target, and the model adjusts the generator's exciter voltage set points to achieve the desired reactive power.

Speed controls manage the generator's rotational speed when the generator is ON. When turning ON the generator, the speed controls start with a ramp-up from zero speed to the purge speed necessary to meet National Fire Protection Association 85 requirements for purging combustible gases before ignition. The purge speed, typically provided by the manufacturer, ensures five volume changes of air in the turbine. Once purging is complete, the speed controls increase the generator speed to the light-off speed, which is also manufacturer specified, to achieve optimal airflow for fuel ignition. Once the lighting off is completed, the generator will then ramp up to the rated speed. When the generator speed reaches 95% of the rated speed and the generator is operated under power dispatch mode, or when the generator speed reaches 97% of the rated speed and the generator is operated under isochronous mode, the governor model will send a request to NREL's LabVIEW equipment to turn ON the generator exciter. When the generator speed reaches the rated speed and the generator is operated under power dispatch mode, the governor model will send a request to NREL's LabVIEW equipment to start the resynchronization process. During shutdown or trip conditions, the speed is ramped down to the cooldown speed. In this project, the rated generator speed is 1,800 revolutions per minute (rpm), with the purge speed, the light-off speed, and the cooldown speed set at 587 rpm, 150 rpm, and 0 rpm, respectively.

Next, control limiters are in place to prevent the governor model from exceeding the operational limits, such as maximum megawatt output (for both power dispatch mode and isochronous mode), turbine inlet temperature, and exhaust temperature. This comprehensive control system ensures optimal performance and adherence to operational safety standards. Then, gas valve controls use the outputs from the megawatt controls, speed controls, and gas turbine temperature limiters to calculate the valve position for the gas turbine. This valve position result will be used in the simulations of the gas turbine, the HRSG and the steam turbine.

Finally, the results from the governor simulations are processed and scaled to the actual size of the NREL hardware and sent to the NREL LabVIEW equipment. The results of the generator speed and gas valve position will be used for the VFD controls (e.g., the speed signal and the torque single), and voltage set points will be used for the exciter controls and the reactive power dispatch.

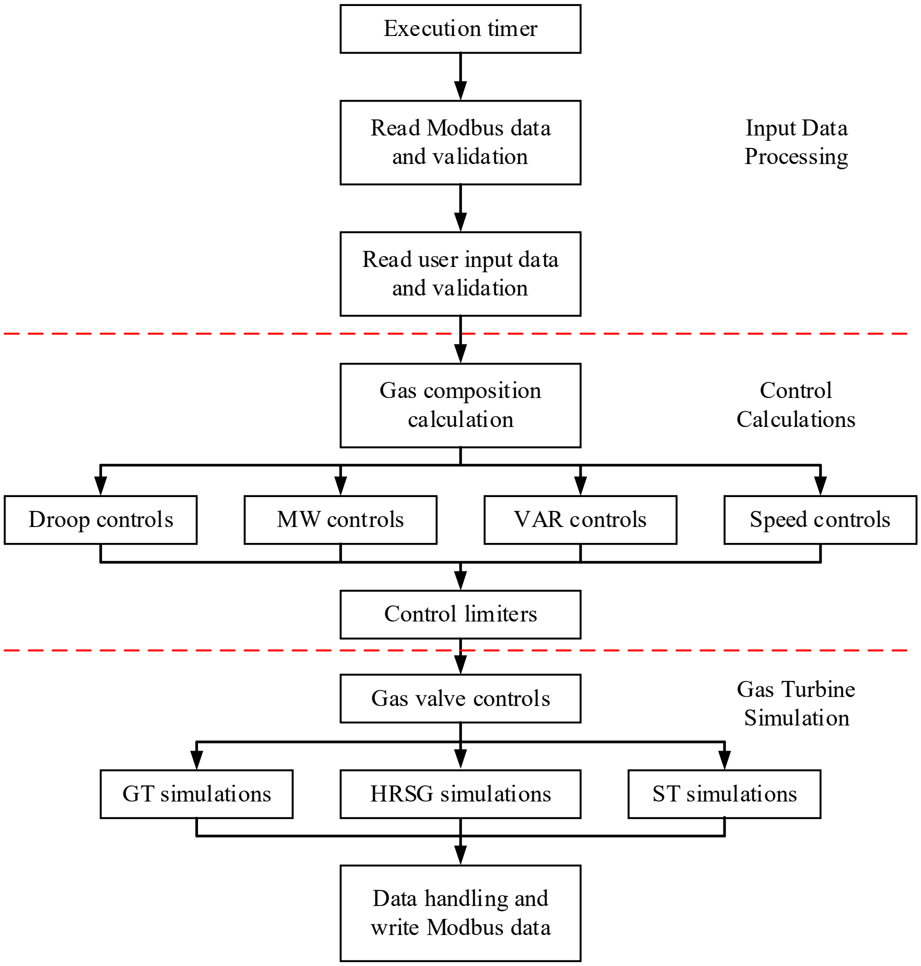
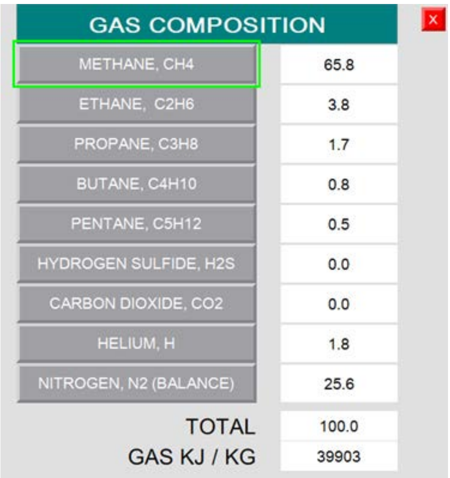


Figure 8. Overall model diagram for generator governor



GAS COMPOSITION

METHANE, CH4	65.8
ETHANE, C2H6	3.8
PROPANE, C3H8	1.7
BUTANE, C4H10	0.8
PENTANE, C5H12	0.5
HYDROGEN SULFIDE, H2S	0.0
CARBON DIOXIDE, CO2	0.0
HELIUM, H	1.8
NITROGEN, N2 (BALANCE)	25.6
TOTAL	100.0
GAS KJ / KG	39903

Figure 9. Test bed setup at NREL’s Flatirons Campus

Table 3. Typical HHVs of the Composite Gas

Gas	Canada	Kansas	Texas	HHV (Btu/ ft^3)	HHV (Btu/ lb)	HHV (kJ/kg
Methane	77.1	73.0	65.8	1011	23811	55384
Ethane	6.6	6.3	3.8	1783	2198	51633
Propane	3.1	3.7	1.7	2572	21564	50158
Butane	2.0	1.4	0.8	3225	21640	50335
Pentane	3.0	0.6	0.5	3981	20908	48632
H_2S	3.3	0.0	0.0	672	7479	17396
CO_2	1.7	0.0	0.0	0	0	0
N_2	3.2	14.5	25.6	0	0	0
He	0.0	0.5	1.8	0	0	0
Total gas	100.0	100.0	100.0			
Average HHV (Btu/scf)	1183.0	1014.6	822.4			
Average HHV (Btu/lb)	21798.7	20006.8	17155.4			
Average HHV (kJ/kg	50703.5	46535.5	39903.3			

4 Test Cases and Results

Table 4. Testing Scenarios

Scenario	Description
Isochronous mode	Isochronous mode is a very important scenario, especially to test the capability of the grid-forming and black-start-capable generator governor. In this case, the synchronous generator is connected to a dead bus with a load bank. The governor maintains the generator's speed (and therefore its frequency) constant regardless of the load variations. In this mode, the governor automatically adjusts the fuel or steam supply to ensure that the generator operates at a fixed speed, typically corresponding to the system's nominal frequency (60 Hz).
Grid-connected mode	This is the most critical scenario to test for the governor simulator. In this case, the synchronous generator is connected to the CGI through the breaker. A connection logic is developed to control the generator excitation and circuit breaker. A few different loading conditions are tested in this case for both the simple-cycle operation and the combined-cycle operation.

4.1 Isochronous Mode

In this scenario, the test system is blacked out, and the circuit breaker for the CGI is open to test the black-start capability of the generator governor and the isochronous operation in simple-cycle mode. The objective of this case is to test the generator startup sequence and use the generator as the main source to energize the dead bus and supply a load bank.

The black-start sequence is performed as follows:

1. The PLC-based governor model verifies the communication status of the NREL LabVIEW equipment and ensures that all essential devices (e.g., VFD, generator exciter, and breaker) are available and properly connected before proceeding.
2. After initializing the startup sequence, the governor model first ramps the generator up to the purge speed (587 rpm, defined in the user interface). It maintains the generator speed at the purge speed for 2 minutes (defined in the user interface) to mimic the starting sequence for an actual gas turbine.
3. Then, the governor ramps the generator speed down to the light-off speed (150 rpm, defined in the user interface) to simulate the ignition process.
4. The governor model ramps the generator at full speed (1800 rpm, defined in the user interface). When the generator speed is lower than 1350 rpm, the generator acceleration rate is 198 (unit in round/minute^2). When the generator speed reaches 1350 rpm, the generator acceleration rate is 580 (unit in round/minute^2).
5. When the generator speed reaches 1728 rpm (96% of the rated speed), the governor model issues the request via the NREL LabVIEW equipment to close the breaker for the dead bus and load bank.
6. Once the breaker is successfully closed and the generator reaches 1746 rpm (97% of the rated speed), the governor model sends a request to start the generator exciter with the voltage set point from the governor. Then the governor will continue to ramp up the generator speed to the full speed.

Figure 10 and Figure 11 show the measurement of speed, frequency, and voltage from the NREL synchronous generator. Note that when the generator speed is lower than 300 rpm, the frequency measurement is forced to zero.

Figure 12 shows the active and reactive power measurement at the generator electric terminal. The circuit breaker for the load bank is closed at 948 s, and the synchronous generator energizes the dead bus with active power of 0.01 MW. A three-phase load bank is connected to the dead bus, and multiple load changes are conducted in this case. For example, the load bank jumps from 0 MW to 0.3 MW at 1200 s. As a result, the generator speed drops to 1750 rpm, and the frequency drops to 58.25 Hz. The maximum voltage ripple is 0.01 p.u. The speed returns to 1800 rpm at approximately 1250 s. A zoomed-in plot for the generator speed, voltage, and active power is shown in Figure 13.

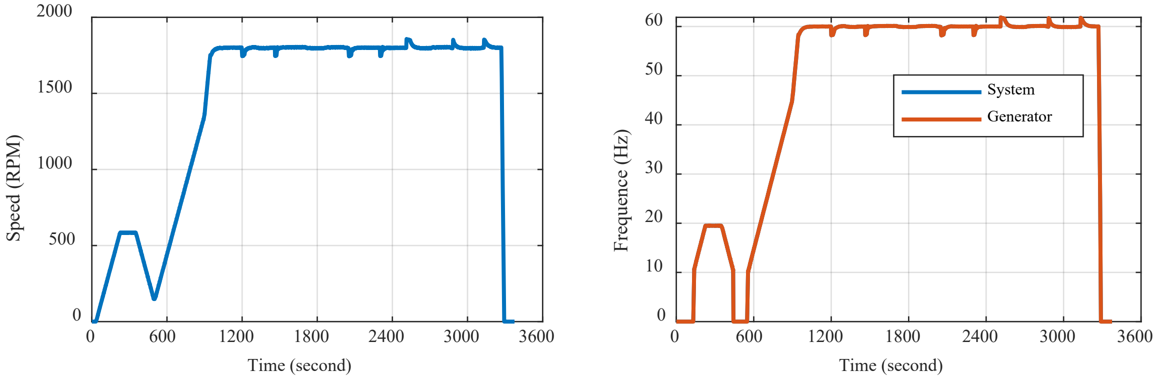


Figure 10. NREL synchronous generator speed and frequency

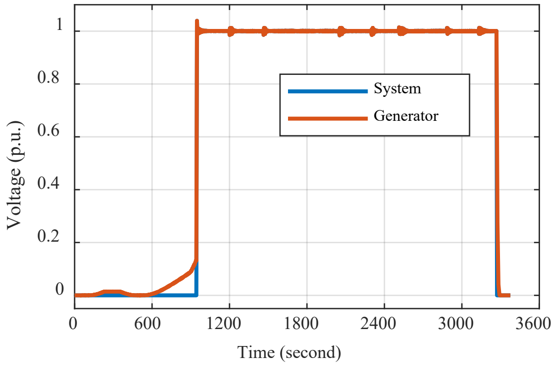


Figure 11. Synchronous generator voltage

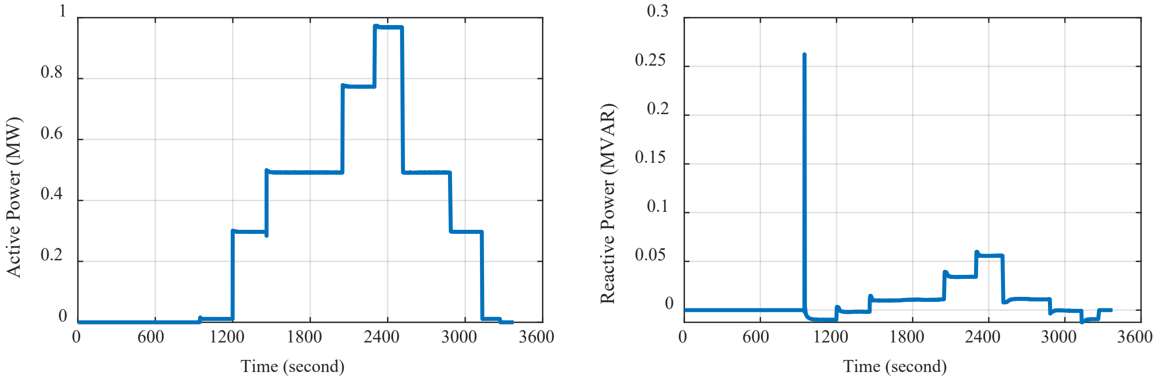


Figure 12. Synchronous generator active and reactive generator for load step changes

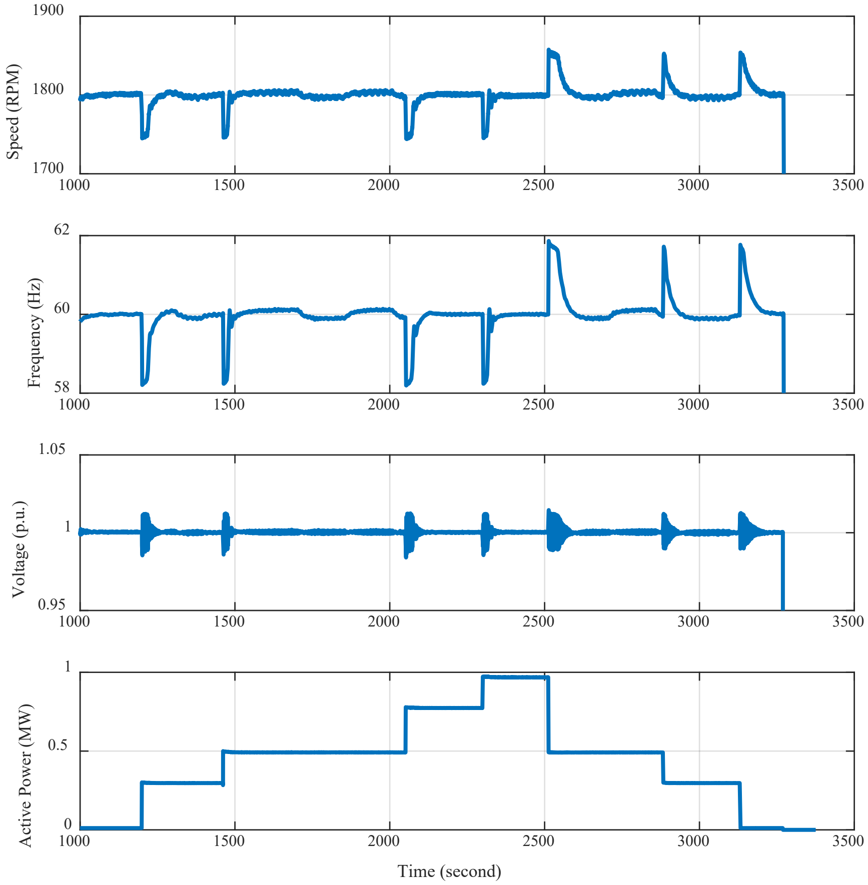


Figure 13. Zoomed-in plot for generator measurements

Figure 14 through Figure 16 demonstrate the simulation results from the gas turbine. Figure 14 shows the measurement of pressure and temperature at both the inlet and outlet terminals for the compressor and gas turbine. For simple-cycle mode, the compressor inlet and gas turbine outlet are connected to the air, so the pressure is 1 atm. (The gas turbine outlet pressure can be slightly above atmospheric pressure.) The compressor outlet is connected to the combustor, and the combustor pressure drop is approximately 0.02 atm, defined by the user interface. The combustor is connected to the gas turbine; thus, the gas turbine inlet pressure is close to the compressor outlet pressure. The compressor outlet pressure is relative to the generator speed. The compressor inlet temperature is the air temperature, and the compressor discharge temperature rises as a result of the compression of the air. The combustor outlet (gas turbine inlet) temperature increase is a result of burning fuel in the combustor. The temperature is a function of the compressor outlet temperature (combustor inlet temperature), the air mass flow rate through the combustor, and the fuel flow rate and HHV of the fuel being burned. The gas turbine exhaust temperature is determined by the turbine inlet temperature and pressure, the exhaust pressure, and the turbine section efficiency. The turbine acts like a compressor in the reserve direction. Rather than increasing the pressure and temperature, the pressure and temperature are reduced as the exhaust flows in the turbine section.

Figure 15 shows the result for the position of the gas valve for the gas turbine as well as the voltage set point for the generator exciter. The gas valve position impacts the gas flow for the gas turbine; thus, it directly impacts the power output. In this scenario, the governor model reads the NREL generator frequency from Modbus and calculates the megawatt power needed to maintain the frequency at 60 Hz. Then this megawatt power set point is converted to the gas valve position for the gas turbine simulation.

Figure 16 shows the position of the gas turbine inlet guide vanes and the power from the Brayton cycle simulations. The gas turbine inlet guide vanes regulate the air flow through the gas turbine. In simple-cycle mode, the inlet guide vanes will typically stay at their minimum position. When the gas turbine outlet temperature exceeds 700 °F, the inlet guide vanes will ramp to the fully open position at the user-entered ramp rate. The inlet guide vanes will remain at the fully open position until the gas turbine's exhaust temperature decreases to 600 °F. At that point, the inlet guide vanes will move to the minimum opening. Moreover, the powers from the gas turbine simulation are shown on the right side of Figure 16. The yellow curve is the total power generated from the gas turbine, and the red line is the power used for the compressor. The blue curve is net power that can be used to drive the generators. In this test setup, the rated power for the gas turbine is 90 MW, and the rated power for the NREL synchronous generators is 2 MW; thus, scaling is applied to the laboratory tests, which converts the 90 MW from the gas turbine simulations to 1.4 MW for the NREL generator in the real world. When a 1-MW load bank is applied to the generator, the simulated gas turbine power out is approximately 64 MW.

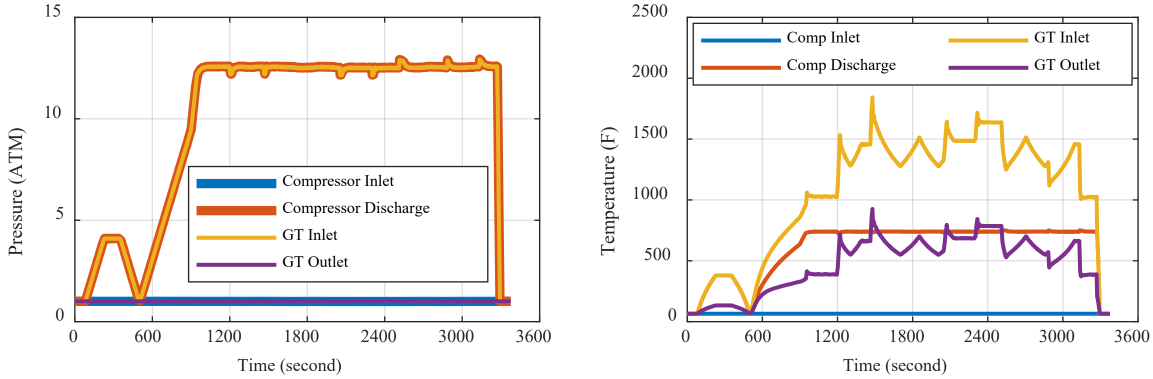


Figure 14. Measurements of pressure and temperature for the compressor and gas turbine

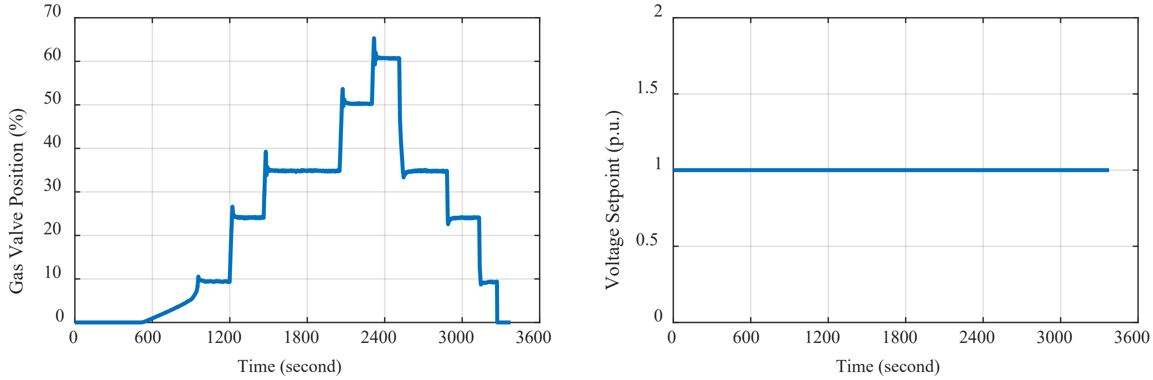


Figure 15. Gas control valve position and exciter voltage set points

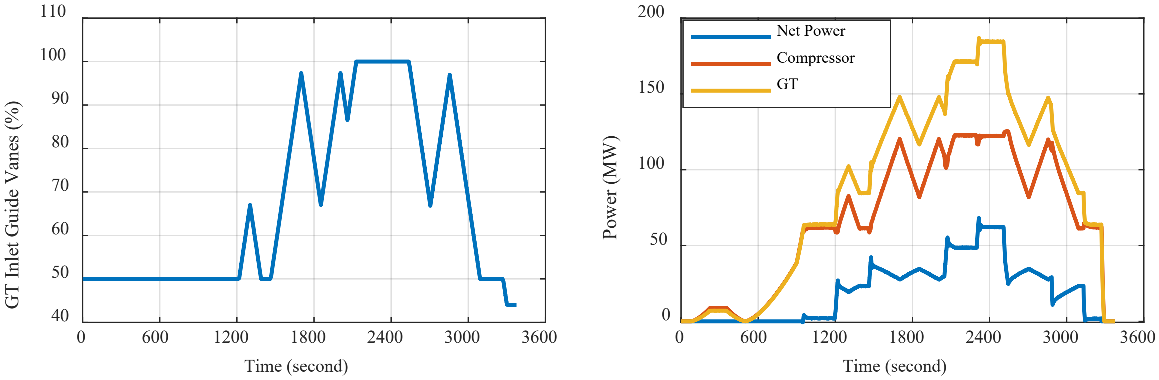


Figure 16. Gas turbine inlet guide vanes and power from the Brayton cycle

4.2 Grid-Connected Mode

In this scenario, the test system will connect to the main grid (CGI in this case) by closing the circuit breaker. The circuit breaker for the load bank remains open in this test. The objective of this case is to test the generator startup sequence for grid connection and to test the capability of the power dispatch in both simple-cycle mode and combined-cycle mode.

The grid-connection sequence is performed as follows: Steps (1)-(4) are the same as the black-start sequence. (5) When the generator speed reaches 1710 rpm (95% of the rated speed), the governor model sends a request to start the generator exciter with the voltage set point from the governor. Then the governor will continue to ramp the generator speed to the full speed. (6) When the generator reaches full speed, the governor model will send the request to the NREL generator synchronizer, and the synchronizer resynchronizes the generator with the CGI and closes the circuit breaker.

4.2.1 Simple Cycle

Figure 17 and Figure 18 show the measurement of the speed, frequency, and voltage from the NREL synchronous generator. Note that when the generator speed is lower than 300 rpm, the frequency measurement is forced to zero. The system frequency and voltage remain at 60 Hz and 1 p.u. because the generator is connected to the CGI.

Figure 19 shows the active and reactive power measurement at the generator electric terminal and active power command for the governor model. As mentioned, the 90 MW from the gas turbine simulation is scaled to 1.4 MW for the NREL generator in the real hardware; thus, for example, when 90 MW is dispatched to the governor model at 1874 s, the generator power output ramps to 1.407 MW. A zoomed-in plot for the speed, voltage, and active power is shown in Figure 20.

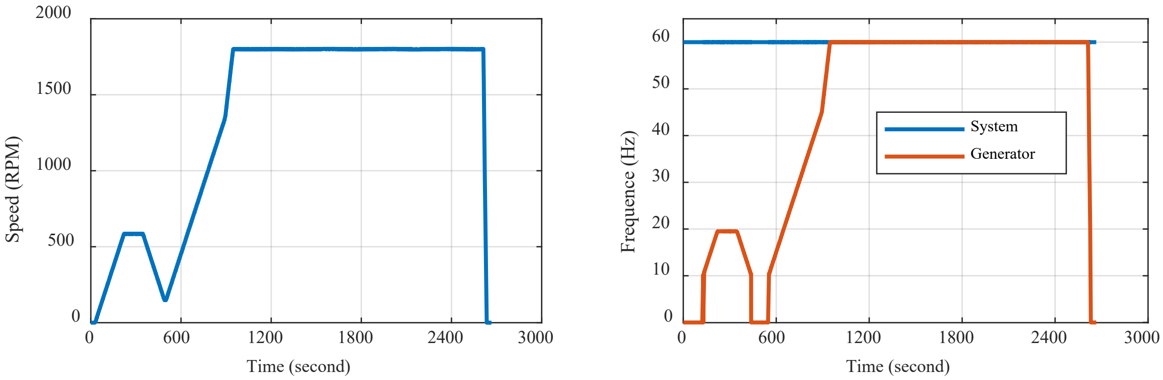


Figure 17. NREL synchronous generator speed and frequency

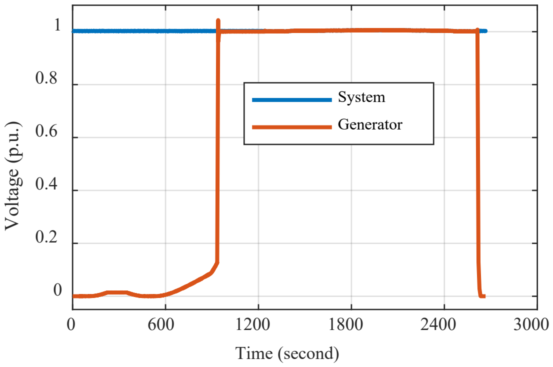


Figure 18. Synchronous generator voltage

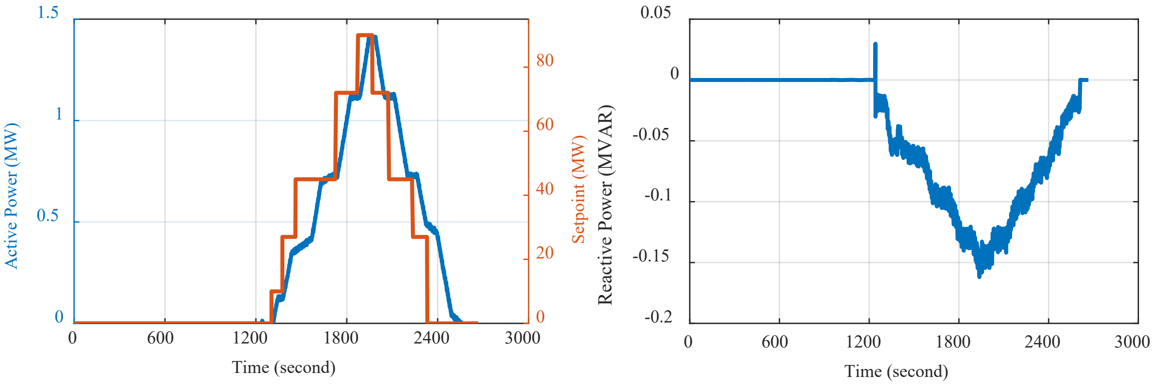


Figure 19. Synchronous generator active and reactive power for dispatches

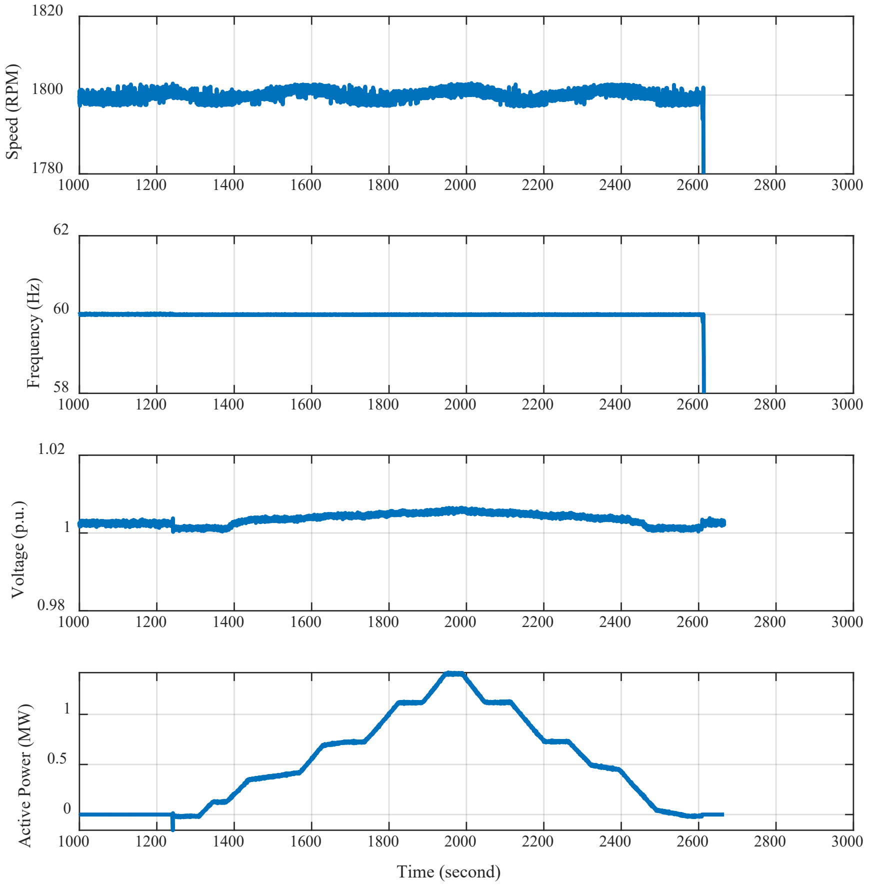


Figure 20. Zoomed-in plot for generator measurements

Figure 21 through Figure 23 demonstrate the simulation results from the gas turbine. Figure 21 shows the measurement of the pressure and temperature at both the inlet and outlet terminals for the compressor and the gas turbine. Like Figure 14, the pressures at the compressor inlet and gas turbine outlet are close to 1 atm. The compressor outlet pressure is relative to the generator speed, and the gas turbine inlet pressure is close to the compressor outlet pressure. The compressor inlet temperature is the air temperature, and the compressor discharge temperature rises because of the compression of the air. The combustor outlet (gas turbine inlet) temperature increase is a result of burning fuel in the combustor. The gas turbine exhaust temperature is determined by the turbine inlet temperature and pressure, the exhaust pressure, and the turbine section efficiency.

Figure 22 shows the result for the position of the gas valve for the gas turbine and the active power set point for the governor as well as the voltage set point for the generator exciter. In this scenario, the governor model reads the power command from the user interface, and then this megawatt power set point is converted to the gas valve position for the gas turbine simulation. Open-loop control is used for power dispatch controls.

Figure 23 shows the position of the gas turbine inlet guide vanes and the power from the Brayton cycle simulations.

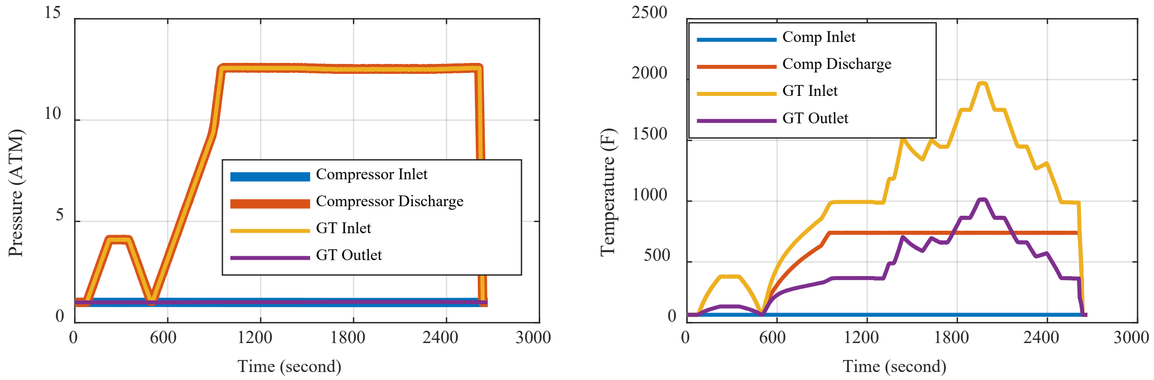


Figure 21. Measurements of pressure and temperature for the compressor and gas turbine

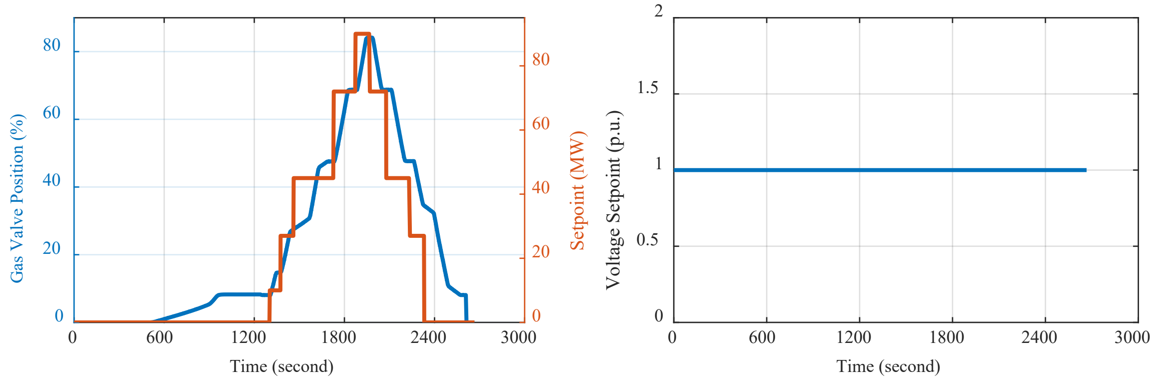


Figure 22. Measurements of pressure and temperature for the compressor and gas turbine

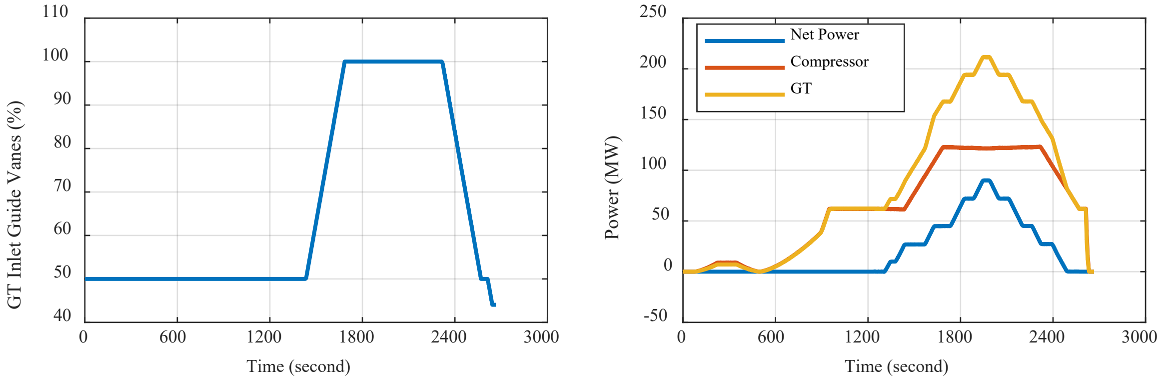


Figure 23. Compressor inlet guide vanes and power from the Brayton cycle

4.2.2 Combined Cycle

In combined-cycle mode, the HRSG and the steam turbine are used in the governor model. The gas turbine exhaust heat is routed to the HRSG, and it uses the waste heat to generate the steam used in a steam turbine; thus, the steam turbine can generate additional power. Typically, the waste heat from the gas turbine is enough heat to generate an additional 50% to 60% of the gas turbine's output through the steam turbine; thus, in this case, the rated power for the steam turbine is set up as 60% of the gas turbine, and it can generate approximately 54 MW at full capacity.

Moreover, regarding the coupling and scaling between the governor model and the NREL synchronous generator in the real hardware, this case only scales the power from the gas turbine to the actual generator. That is because in this test setup, we want to maintain the dynamics on the main shaft between the VFD and the generator. If the total power from the gas turbine and the steam turbine is scaled together to the actual generator, the dynamics on the high-speed shaft could be misrepresented because there are two shaft connections in the governor model (between the gas turbine and the generator and between the steam turbine and the second generator).

Figure 24 and Figure 25 show the measurement of the speed, frequency, and voltage from the NREL synchronous generator. Figure 26 shows the active and reactive power measurement at the generator electric terminal and the active power command for the governor model. A zoomed-in plot for the generator speed, voltage, and active power is shown in Figure 27.

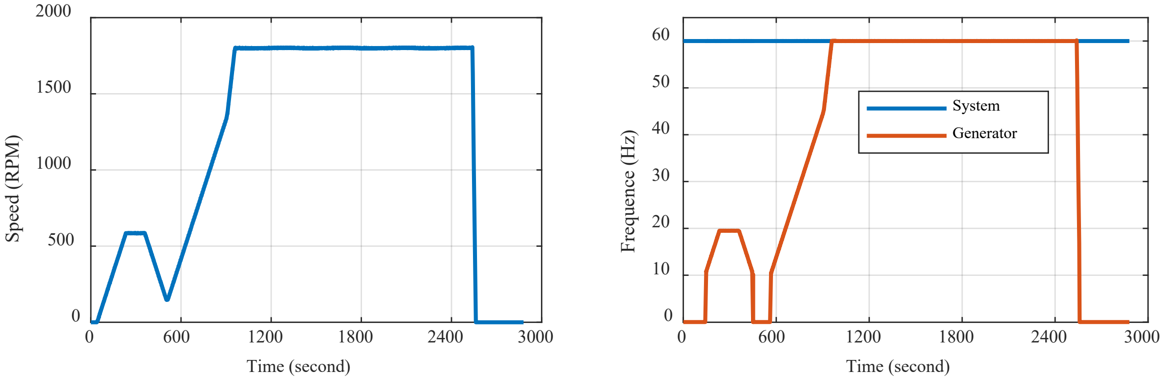


Figure 24. NREL synchronous generator speed and frequency

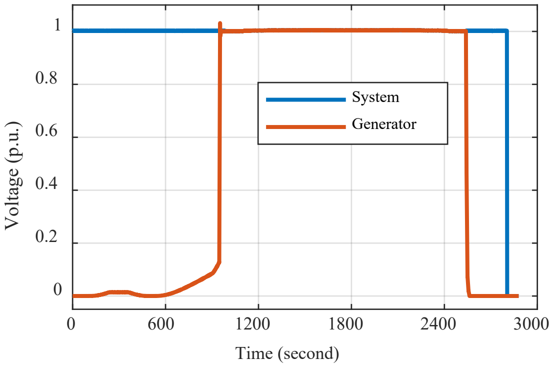


Figure 25. Synchronous generator voltage

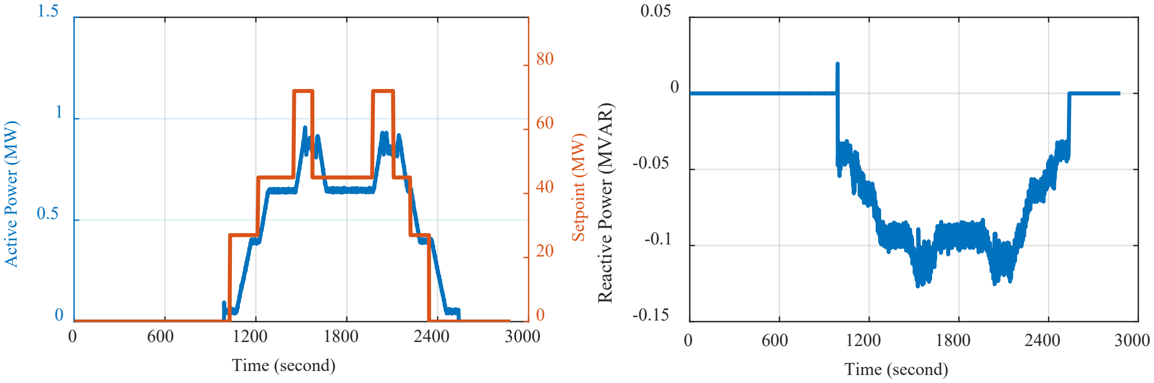


Figure 26. Synchronous generator active and reactive generator for load dispatches

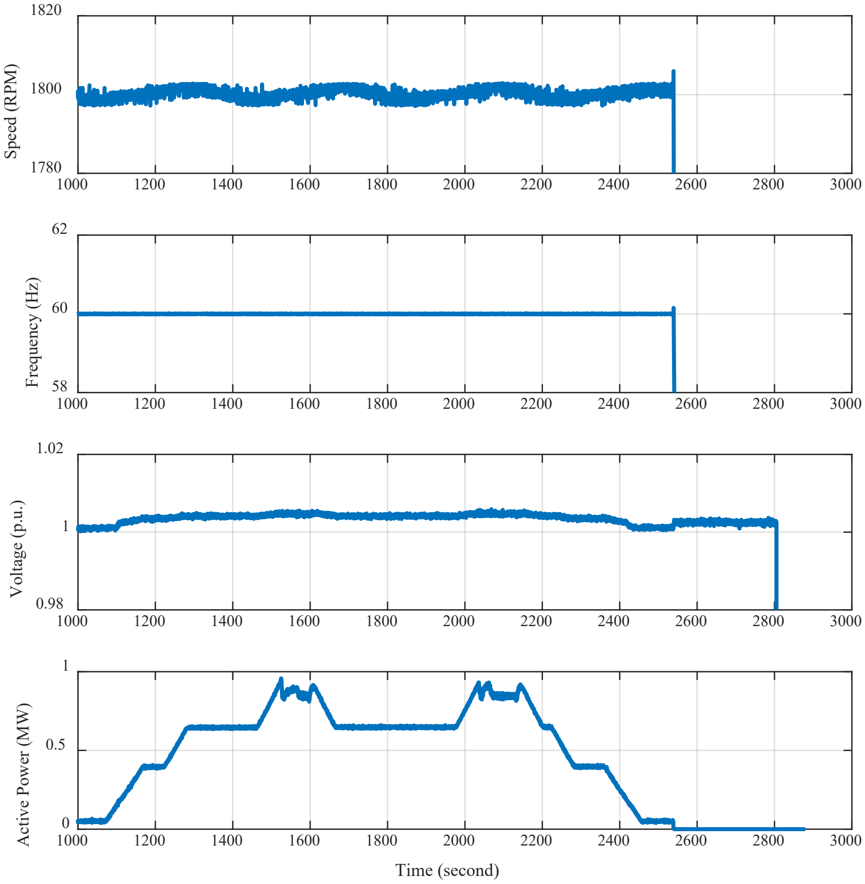


Figure 27. Zoomed-in plot for generator measurements

Figure 29 through Figure 30 demonstrate the simulation results from the gas turbine. Figure 29 shows the measurement of the pressure and temperature at both the inlet and outlet terminals for compressor and the gas turbine. Figure 28 shows the result for the position of the gas valve for the gas turbine and the active power set point for the governor as well as the voltage set point for the generator exciter.

Figure 30 shows the position of the gas turbine inlet guide vanes and the power from the Brayton cycle simulations. In combined-cycle mode, the inlet guide vanes will not begin to open until the gas turbine outlet temperature reaches the rated temperature (1020 °F, defined in the user interface). At that point, a PID controller will open the inlet guide vanes as needed to maintain the gas turbine exhaust temperature at the rated temperature until the inlet guide vanes are fully open, as shown on the left side of Figure 30 (the oscillation in the gas turbine inlet guide vanes position). At that point, the gas turbine outlet temperature will begin limiting the fuel flow to prevent exceeding the rated exhaust gas temperature, as shown on the left side of Figure 29 (the oscillation in the gas turbine gas valve position).

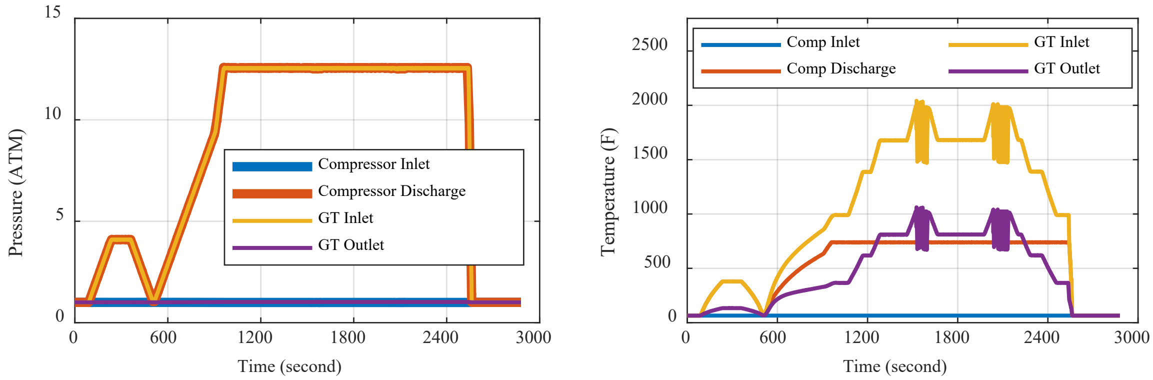


Figure 28. Measurements of pressure and temperature for the compressor and gas turbine

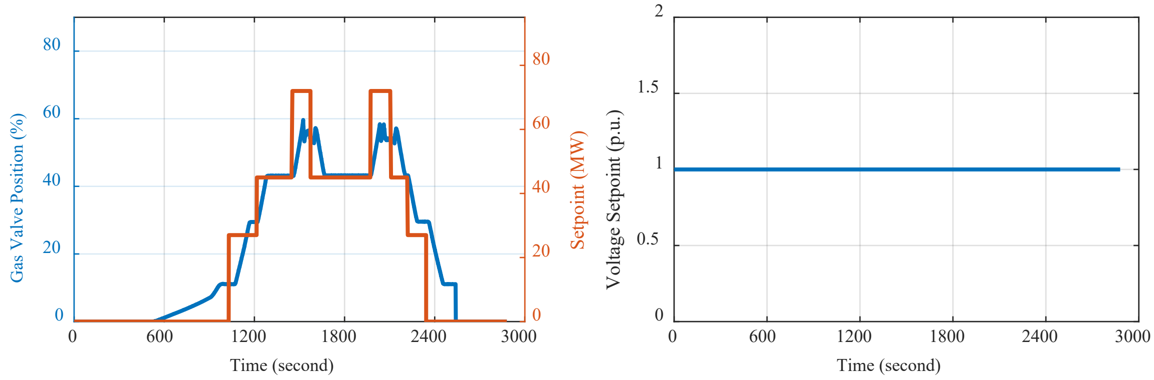


Figure 29. Test bed setup at NREL's Flatirons Campus

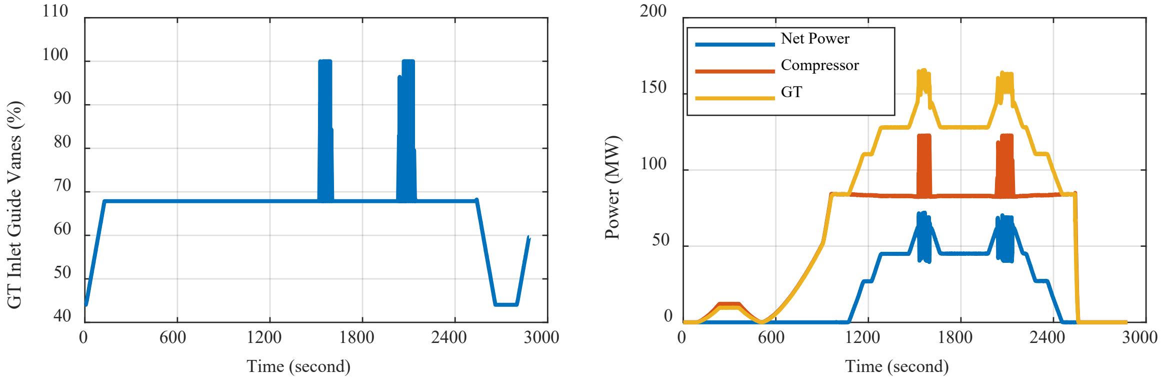


Figure 30. Compressor inlet guide vanes and power from the Brayton cycle

Figure 33 shows the pressure and temperature results at three HRSG sections. These results will be then routed to steam turbines with different pressures. Figure 32 shows the input pressure and temperature for the high-pressure steam turbine. The circuit breaker closes for the steam turbine when the pressure is higher than 40 atm and the temperature is higher than 600°F; however, there is not an actual breaker for the steam turbine, and "close the breaker" means that the steam turbine can generate power in the model. Figure 31 shows the quantity of the power inside the governor model. When the power set point is 72 MW, the power generation from the gas turbine is limited by the temperature controller (the gas turbine outlet temperature is limited to below 1022°F). After closing the breaker for the steam turbine, the total combined output can meet the power set point.

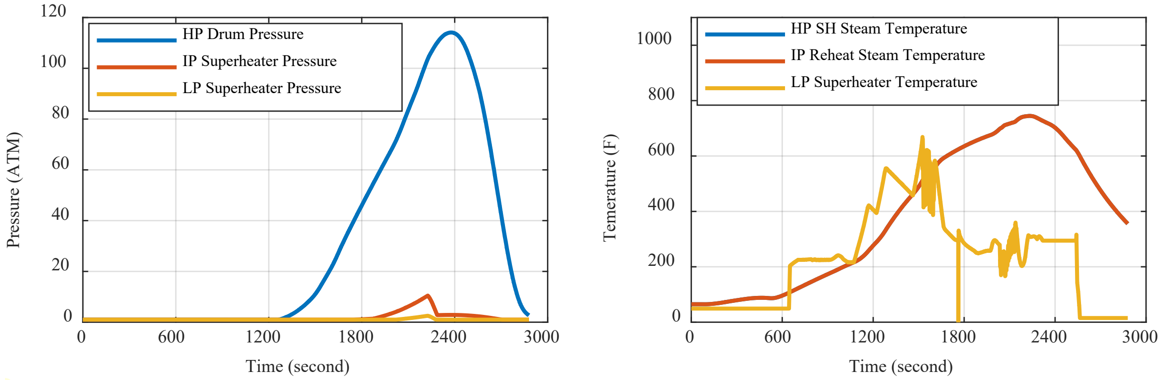


Figure 31. Measurements of pressure and temperature from the HRSG

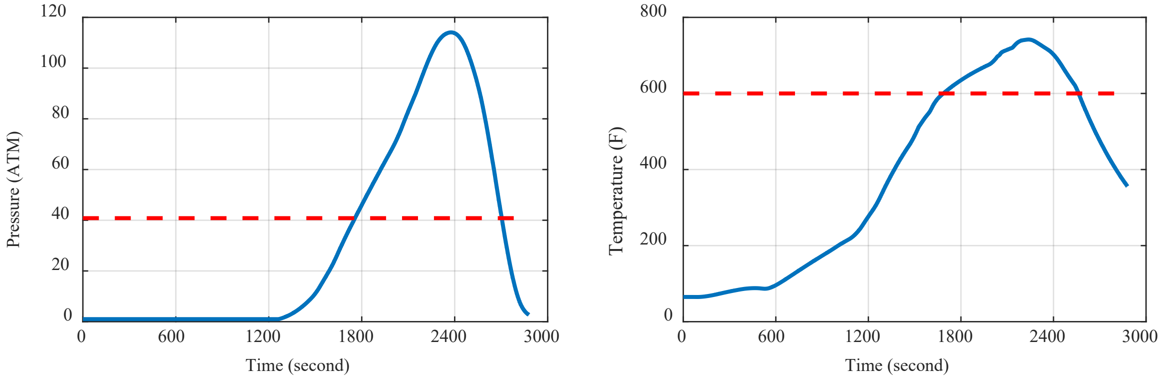


Figure 32. Main pressure and temperature inputs for the steam turbine

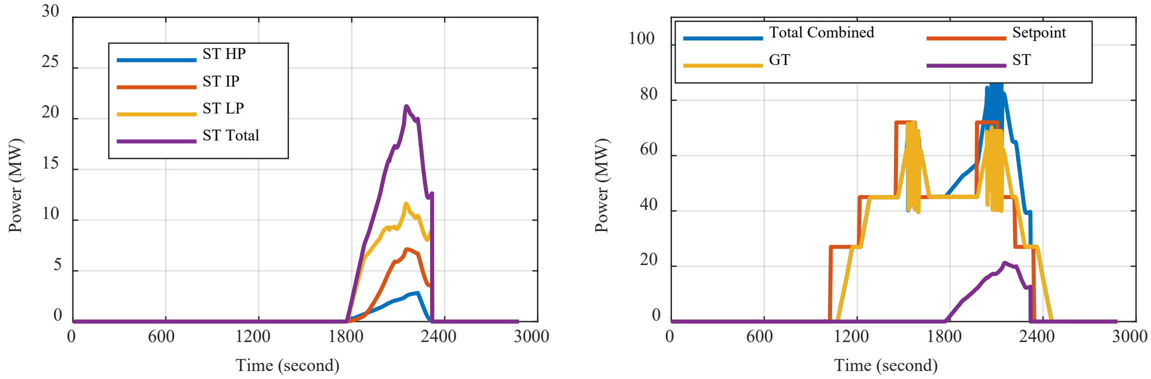


Figure 33. Active power from the steam turbine

5 Conclusion

5.1 Lessons Learned

The comprehensive tests with the developed generator governor model and the actual synchronous generator provide insights into the system capability of the NREL PEGI platform, especially the performance of the 2.5-MW dynamometer system. The lessons learned from this study are organized as follows:

- **Complexity in governor modeling**: Accurately simulating the dynamic behaviors of gas turbines and synchronous generators in real time is a significant challenge due to the nonlinear nature of the system and the multiple feedback loops involved. This project highlighted the need for precise control and input data to ensure reliable performance.
- **Integration with hardware**: Developing an HIL-based setup for synchronous machine governor modeling demonstrated the importance of seamless communications between the PLC-based governor model, the synchronous machine, and the test bed infrastructure. Ensuring real-time data exchange and maintaining system stability during simulations were critical aspects learned during testing.
- **Scaling and emulation**: Scaling down real-world power plant parameters to match the NREL test bed equipment was a critical step. The need for accurate scaling of power outputs and thermal properties while retaining system behavior was underscored.
- **Real-world insights**: The simulation of grid-connected and islanded operations provided valuable insights into potential stability risks, grid interactions, and the governor's role in maintaining frequency and voltage stability during dynamic load changes.

5.2 Future Work

This generator governor model can serve as a baseline model for conventional generator controls, and with this governor model, transient stability studies can be performed to investigate the stability and reliability of the grid from the following aspects:

- **Enhanced control strategies**: Future research could explore advanced control strategies, such as adaptive governor controls or machine learning-based predictive algorithms, to further improve the responsiveness and accuracy of the system under various conditions.
- **Integration with renewable energy**: As renewable energy sources become more prevalent, the emulation of conventional power generation in combination with renewables needs further refinement. Future work should focus on optimizing the interactions among gas turbines, synchronous generators, and grid-forming inverters to support grid stability with high levels of renewable penetration.
- **Expanded test scenarios**: Expanding the range of test cases to include more complex scenarios, such as hybrid energy systems with storage and inverter based resources, will provide a more comprehensive understanding of the model's limitations and strengths.
- **Field deployment and real-world validation**: Field tests to validate the model's performance in real-world grid environments could help further refine the emulations. Collecting operational data from real power plants and integrating them into the model would bridge the gap between simulations and field performance.