energy from the water in the main water tank. The temperature, pressure, level, and flow rate of water
in the boiler system were kept constant using eleven sensors, three actuators (two pumps and a heater), and six valves. An operator was able to control five setpoints via the operator workstation (OWS). Boiler process

P2: TURBINE PROCESS

An actual rotating machine was closely simulated using a GE Rotor Kit (Bently Nevada Asset Condition
Monitoring), which consisted of a motor system with a direct-current motor speed control device and a rotor system that allows for coupling and included a rotor shaft, two balance wheels, two journal bearings, and a bearing block. The motor speed was synchronized with the rotating speed of the thermal power generator model in the HIL simulator. The turbine system included a speedometer and
four vibration-monitoring proximity probes to maintain a motor speed constant, where the operator can
adjust the turbine rotations per minute (RPM) setpoint using a human-machine interface (HMI).

P3: WATER-TREATMENT PROCESS

The water-treatment process involved the pumping and release of water between the upper and lower
reservoirs using the hydropower turbine model in the HIL simulation. The water-treatment system included seven sensors, one actuator, and an outflow control valve to control the flow and pressure from the return water tank (P3b) to the main water tank (P3a), as well as the water level in the main water tank. The hydraulic pressure, flow rate, and water level of the upper water tank were transmitted
to the HIL simulator in real time to determine the power generation.

P4: HARDWARE-IN-THE-LOOP SIMULATOR

The simulation system consisted of two synchronous generator models (i.e., steam-turbine power generator and pumped-storage hydropower generator) and one power grid model, which included the local load demand and was connected to an infinite bus.

An HIL-based simulator was developed to combine the three control systems for the boiler, turbine, and water treatment processes to form a combined power generation system. Specifically, the temperature and pressure of the boiler system were used to determine the pressure and temperature of the steam entering the steam turbine model (STM) (P4.1). The output power of the STM was controlled by an internal steam governor, and the power generator model (P4.2) generated the corresponding electrical power. Further, the hydro turbine model (HTM) (P4.3) and power generator model (P4.4) calculated the generated output power based on the discharge from the water treatment system, where both models were controlled to ensure that the frequency of the microgrid load was 60 Hz (P4.5). The power generated based on the input load was dependent on the opening and closing rates of the valves of the thermal power plant and pumped-storage power plant. Thus, the opening and closing rates of the valves in the control systems for the boiler and water treatment systems were determined.

Testbed Components

The three real-world processes were controlled by three different controllers. Specifically, the boiler process was controlled by Emerson's Ovation DCS for the water level, flow rate, pressure, temperature, water feed pump, and heater control. The turbine process was controlled by GE's Mark Vle DCS for speed control and vibration monitoring, and the water treatment process was controlled by a

Siemens

S7-300 PLC for water level and pump control. In the HAI testbed, the HIL simulations were conducted

using a dSPACE® SCALEXIO system interconnected with the real-world processes using a S7-1500

PLC (Siemens) and with an ET200 remote IO devices.