CASE STUDY

National Renewable Energy Laboratory—Golden, Colorado

NREL Selects SEL Microgrid Controller for the Energy Systems Integration Facility

After prevailing in a competitive, rigorous procurement process, SEL's microgrid controller will help further microgrid research for the U.S. National Renewable Energy Laboratory.

Golden, CO—In 2017, the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) invited microgrid controller manufacturers to participate in a 21-week evaluation to determine the best controller for the Energy Systems Integration Facility (ESIF).

Located on the NREL campus in Colorado, the ESIF (shown in Figure 1) is the United States' premier facility for the research, development, and demonstration of integrated technologies and strategies that are shaping the nation's energy system.

Figure 1—The NREL ESIF
(photo courtesy of Dennis Schroeder)

The ESIF includes a research platform for distributed energy and microgrid devices and systems. To enhance their research capabilities, engineers at NREL sought to identify the best possible microgrid controller for this platform, where end devices and communications protocols are routinely changed. NREL required a microgrid controller that could be easily modified to evaluate the performance of different device types without significant effort.

Beyond choosing a controller, NREL also intended to:

- Gain intimate familiarity with microgrid control technology.
- Compare multiple controller functions to inform the lab's R&D direction.
- Gain insights to inform testing standards.
- Offer participants a state-of-the-art facility to help advance existing technology and encourage private-sector innovation.

The SEL Solution

The core of the SEL microgrid controller combines an SEL Real-Time Automation Controller (RTAC) with POWERMAX® Power Management and Control System Microgrid Libraries. These libraries contain features for implementing a microgrid that have already been tested, proven, and deployed on other microgrids.

Because the NREL evaluation considered both microgrid performance and cybersecurity, the SEL solution also incorporated an SEL-2740S Software-Defined Network Switch. This approach ensured the security of data streams without affecting the performance of the microgrid controls. While traditional networking has security functions at the edges of large networks, software-defined networking (SDN) enhances security by creating many small networks with security functions performed at each host (see Figure 2).

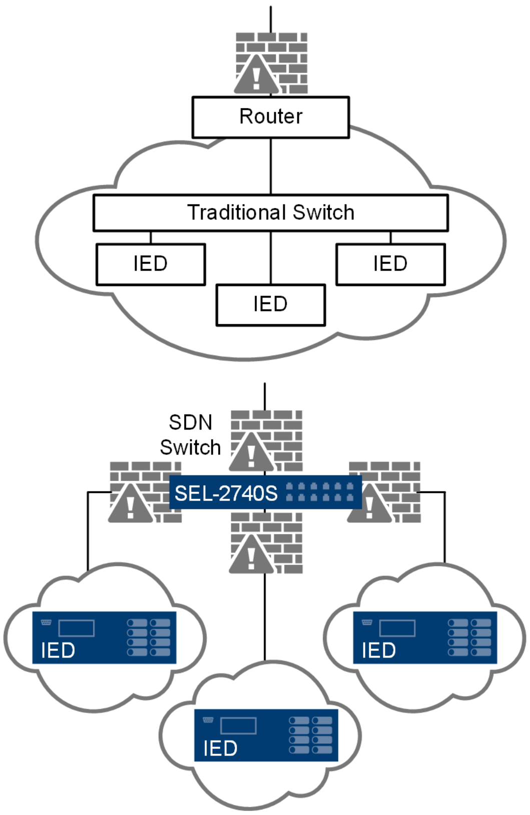

Figure 2—Traditional Networking Versus SDN

According to SEL Automation Engineer Will Edwards, the overall goal for each microgrid controller evaluated by NREL was to maximize profitability by minimizing the microgrid's cost of ownership. An outline of the microgrid cost factors and other inputs to the SEL economic dispatch model is shown in Figure 3.

Because hardware-in-the-loop (HIL) testing is crucial to microgrid controller development, as well as evaluation, SEL ran more than 60 rounds of HIL testing during the development and evaluation of this solution for NREL. Figure 4 shows how the development progress was tracked. This extensive testing resulted in major improvements to the overall system performance.

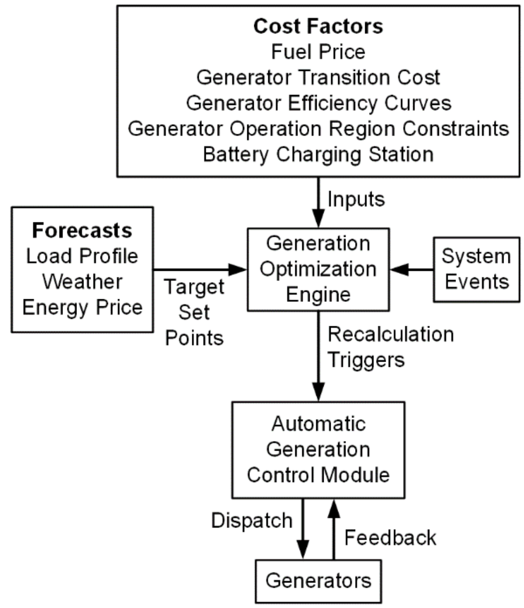

Figure 3—SEL Economic Dispatch Model

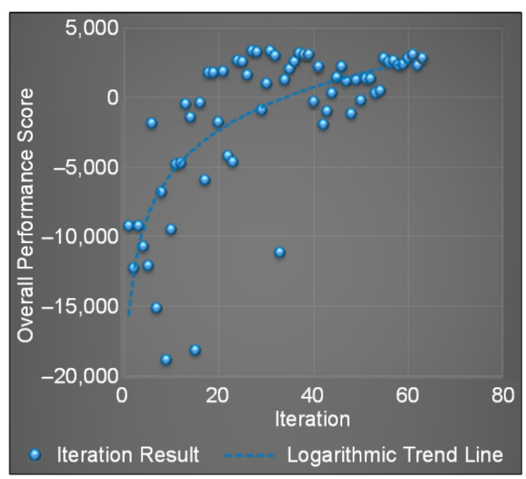

Figure 4—HIL Testing Results

Test Model

The NREL evaluation testing used an open-source feeder model (Figure 5) known as the μGrid Hardware-in-the-Loop Open-Source Testbed (GHOST) (available for download at https://github.com/PowerSystemsHIL/EPHCC/tree/master/DistributionSystems/SimulinkOpal/Ghost).

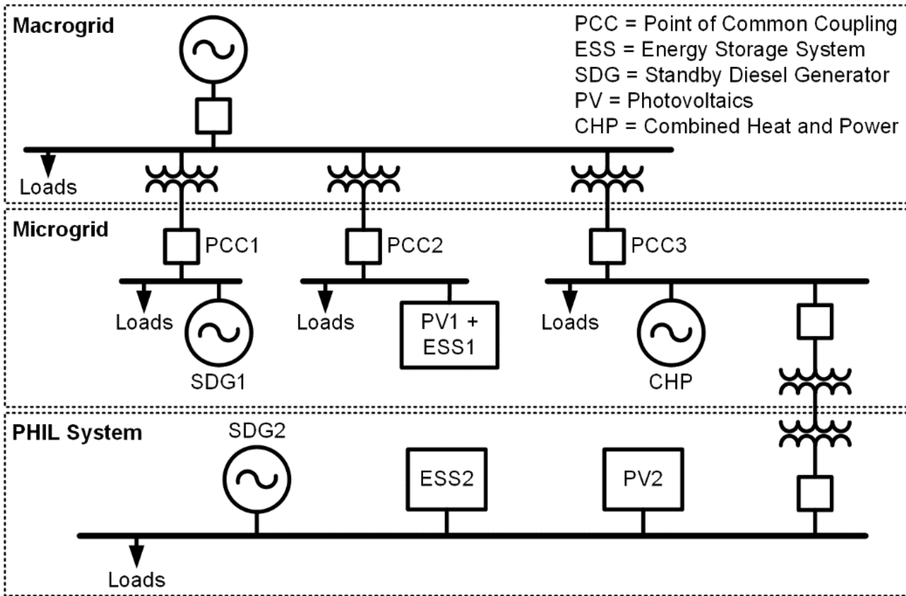

Figure 5—Single-Line Diagram of Feeder Model for CHIL Testbed

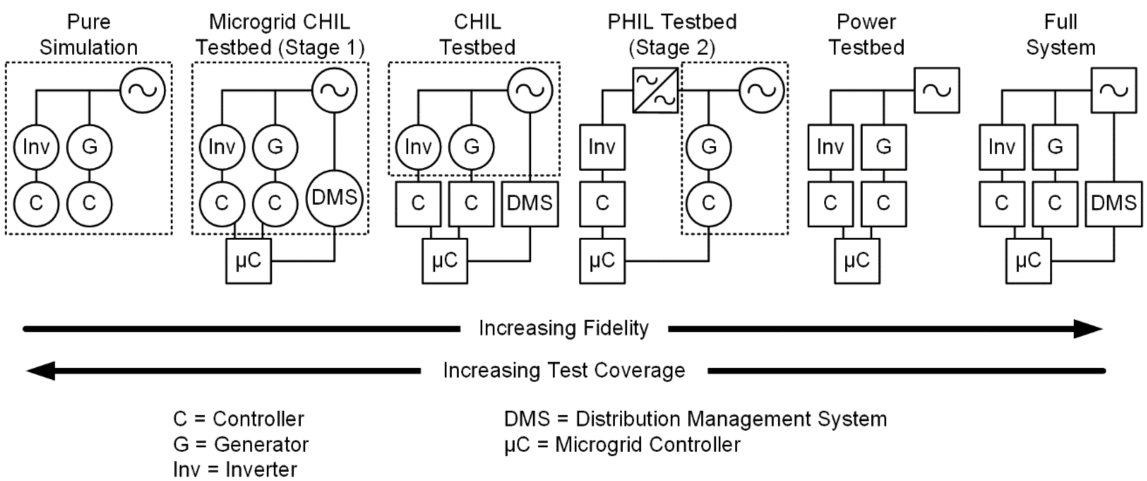

Figure 6—Range of Microgrid Controller Testbeds

The GHOST model requires the OPAL-RT OP5600 platform with a minimum of 12 CPU cores and a host PC for model control and data acquisition. The model can be modified for use with other simulation systems.

Microgrid performance validation requires testing the control strategy and confirming that system objectives are met. There are several methods of system testing, each with tradeoffs for test coverage and system fidelity. Figure 6 shows the range of options for testbeds. The objects inside the dashed boxes are simulated. HIL testing prior to commissioning provides an environment that facilitates broad test coverage without impacting live system operations. The microgrid controller hardware-in-the-loop (CHIL) testbed was chosen for Stage 1 to allow each microgrid controller to be tested with simulated device interfaces and power system responses. CHIL testing reduces the testbed configuration complexity and equipment cost. The power hardware-in-the-loop (PHIL) testbed was chosen for Stage 2 in order to incorporate physical devices into the testbed to validate the control interfaces and add fidelity to the physical responses of the power system.

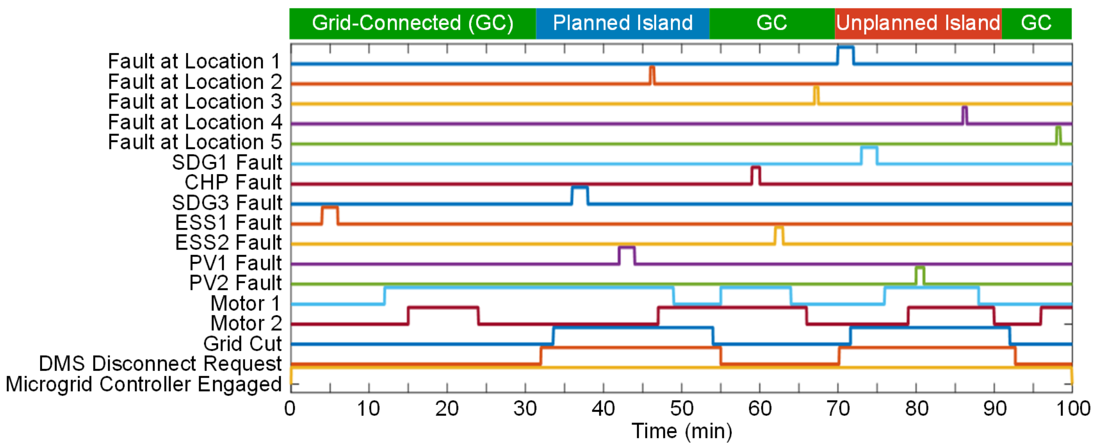

Figure 7—Test Sequence Contingency Stimuli

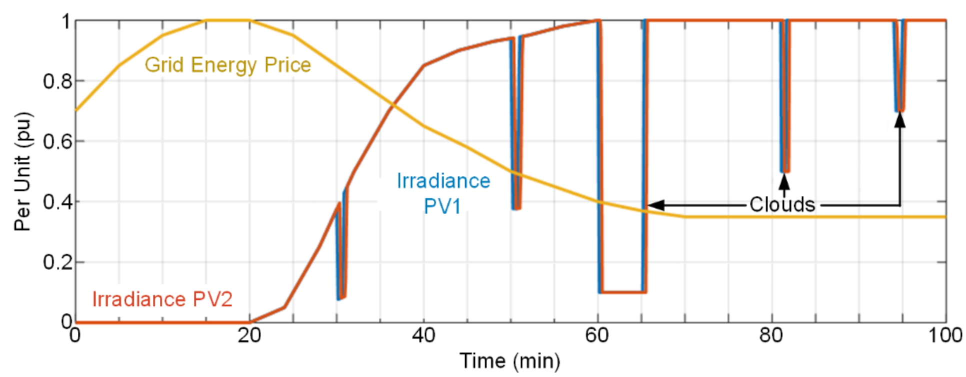

Figure 8—Forecastable and Unpredictable Event Example

Dual-Stage Evaluation

Stage 1: CHIL Testing

In the first stage of the evaluation, NREL accepted applications from microgrid controller manufacturers who met various minimum functionality requirements. Five manufacturers were invited to test their devices in the CHIL testbed shown in Figure 5.

NREL evaluated each microgrid controller with multiple 100-minute dynamic tests. The test sequence (see Figure 7) was as follows:

1. Microgrid connected to grid.
2. Planned island.
3. Microgrid reconnected to grid.
4. Unintentional island.
5. Microgrid reconnected to grid.

The testing combined forecastable events (like changes in the price of energy) and unpredictable events (like the loss of a generator, a microgrid fault, or the loss of sunlight to a photovoltaic system), as shown in Figure 8. The microgrid controller was required to handle these events autonomously.

"There's no one right answer to this, which is also very interesting," said Brian Miller, NREL Strategic Team Lead for Microgrids. "Each microgrid controller may choose a different way of achieving the same objectives."

Stage 2: PHIL Testing

Based on the results of the first evaluation stage, two manufacturers, including SEL, were chosen to participate in the second stage, which tested the microgrid controller performance in a PHIL testbed.

Stage 2 used the same test sequence format as Stage 1, but while all three sections of the power system in Stage 1 were simulated (see Figure 5), Stage 2 used physical components and a grid simulator for the PHIL portion of the system.

According to Edwards, "[NREL evaluators] were trying to push the envelope on testing mechanisms. This was part of an evaluation of technology, so they didn't want to just look at features on paper, they wanted to stretch the proof of functionality."

Stage 2 also evaluated microgrid controller cybersecurity in a cyber-physical testbed. While Stage 1 evaluated cybersecurity control features theoretically, Stage 2 applied real cybersecurity tools and analysis techniques to evaluate the two Stage 1 finalists.

The cybersecurity evaluation consisted of the following:

- Network reconnaissance.
- Packet capture.
- Packet replay.
- Denial of service.
- Password cracking.
- Penetration testing.

Ultimately, the SEL microgrid controller not only achieved the highest performance scores, but the NREL assessment also determined that the SEL microgrid controller system contained no major security vulnerabilities.

Key Performance Parameters

The key performance parameters (KPPs) used by NREL to evaluate competing microgrid controllers are shown in Figure 9.

To determine the relative importance assigned to each KPP, NREL held two public focus groups—one for manufacturers and one for microgrid owners. Based on the performance metric priorities provided by the focus groups, NREL translated power system KPPs into U.S. dollars to mimic a microgrid operator's bill.

The following subsections describe the most important microgrid control system considerations and include the methodology behind the calculation of each KPP. The KPP equations provided a mechanism to change the performance objectives, allowing different metrics in different types of microgrids to be prioritized in the evaluation method.

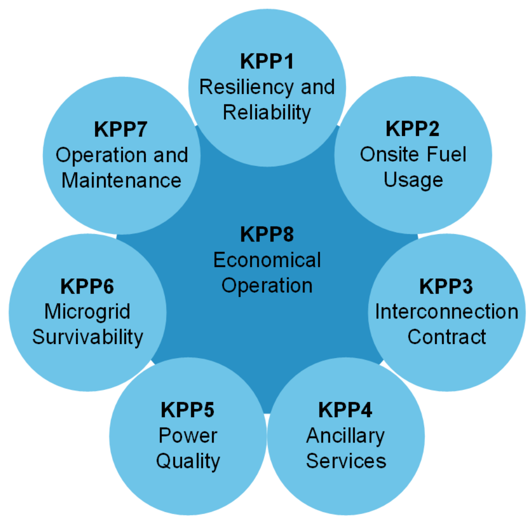

Figure 9—KPPs

KPP1: Resiliency and Reliability

KPP1 measured the microgrid controller's ability to supply power to customers. It calculated the energy delivered to each load category (critical, priority, and interruptible). Energy prices differed considerably by load category, and a financial penalty was added for outages on critical and priority loads.

Table 1 shows the KPP1 price factors. Penalty values are shown in red and italics.

Table 1 KPP1 Price Factors

Description	Unit Price
Energy delivered to critical loads (E_C)	P_{11} = \$0.33/kWh
Energy delivered to priority loads (E_P)	P_{12} = \$0.30/kWh
Energy delivered to interruptible loads (E_I)	P_{13} = \$0.267/kWh
Energy outage of critical loads (E_{CO})	*P_{15} = \$1.50/kWh*
Energy outage of priority loads (E_{PO})	*P_{16} = \$0.67/kWh*
Energy difference in ESS at end of sequence (E_{ESS})	P_{17} = \$0.33/kWh

The final KPP1 value was calculated as:

$$KPP1 = E_C P_{11} + E_P P_{12} + E_I P_{13} - E_{CO} P_{15} - E_{PO} P_{16} + E_{ESS} P_{17}$$

Figure 10 shows the SEL microgrid controller testing results for KPP1. While not a load class or KPP1 price factor, motor values are included to illustrate their impact on actual load priorities.

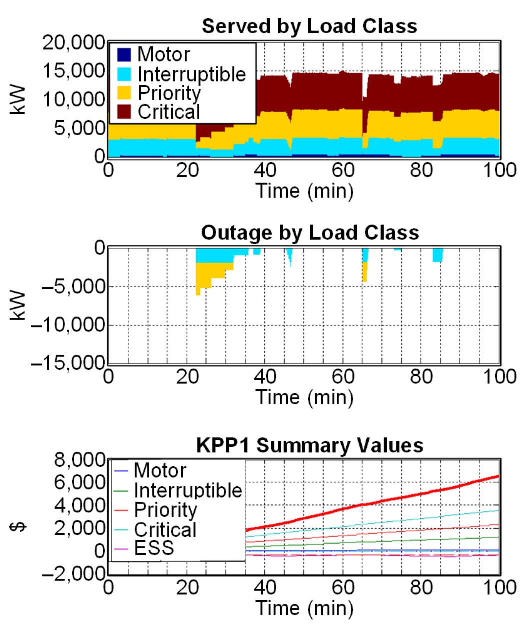

Figure 10—KPP1 Summary Charts

KPP2: Onsite Fuel Usage

KPP2 measured generator fuel usage within the microgrid. Table 2 shows the KPP2 price factors. Operation costs are shown in red and italics.

Table 2 KPP2 Price Factors

Description	Unit Price
Diesel fuel used (F_D)	*P_{21} = \$3.10/gal*
Natural gas used (F_{NG})	*P_{22} = \$0.87/m^3*
Energy delivered as heat (E_H)	P_{23} = \$24.50/MBtu

The final KPP2 value was calculated as:

$$KPP2 = -F_D P_{21} - F_{NG} P_{22} + E_H P_{23}$$

Figure 11 shows the SEL microgrid controller testing results for KPP2. The pie chart illustrates the energy sources chosen by the microgrid controller to maximize the KPP2 value.

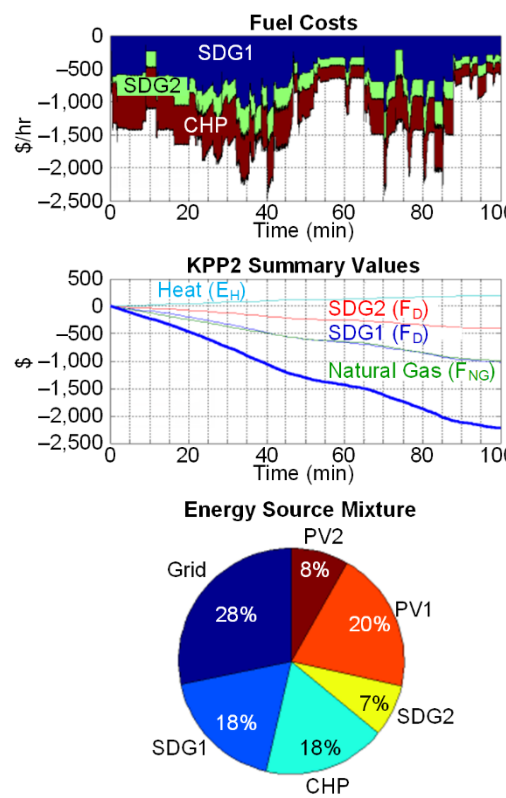

Figure 11—KPP2 Summary Charts

KPP3: Interconnection Contract

KPP3 measured the import and export of power at the PCC connections. A contract defining energy prices and limiting the import and export of power governs how microgrids are connected to the bulk grid. For this evaluation, the limits were as follows:

- Active power import: 12 MW
- Active power export: 6 MW
- Reactive power: 5 MVAR

The instantaneous price of energy (p_{31}) during the test sequence varied between P_{31} (\$0.087/kWh) and P_{32} (\$0.250/kWh) to test the controller's ability to handle price fluctuations and make cost-conscious energy management decisions (e.g., by dispatching energy from a battery). The prices of energy sold and energy over the limits were always proportional to p_{31}; coefficients penalized the use of energy over the limits ($k_{BO} = 3$, $k_{EO} = 0.5$).

Table 3 shows the KPP3 price factors. Penalty values are shown in red and italics. The unit prices reflect the average price of energy during the test.

Table 3 KPP3 Price Factors

Description	Unit Price
Exported energy (E_E)	$P_E = p_{31}$ (\$/kWh)
Exported energy over limit (E_{EO})	$P_{EO} = p_{32}$ (\$/kWh) ($p_{32} = p_{31} \bullet k_{EO}$)
Imported energy (E_B)	*$P_B = p_{31}$ (\$/kWh)*
Imported energy over limit (E_{BO})	*$P_{BO} = p_{33}$ (\$/kWh) ($p_{33} = p_{31} \bullet k_{BO}$)*
Reactive power over limit (E_{RP})	*P_{33} = \$0.125/kVARh*

The final KPP3 value was calculated as:

$$KPP3 = E_E P_E + E_{EO} P_{EO} - E_B P_B - E_{BO} P_{BO} - E_{RP} P_{33}$$

Figure 12 shows the SEL microgrid controller testing results for KPP3.

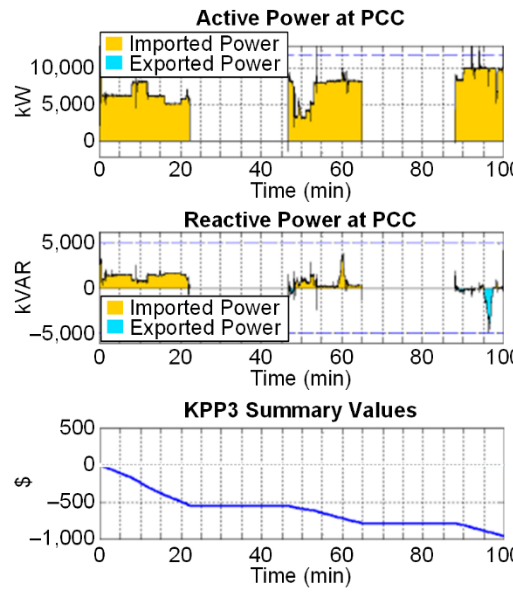

Figure 12—KPP3 Summary Charts

KPP4: Ancillary Services

KPP4 measured the microgrid controller's ability to generate additional revenue by providing services to the DMS on request. Some requests were mandatory, such as disconnect requests, and violations were penalized.

Table 4 shows the KPP4 price factors. Penalty values are shown in red and italics.

Table 4 KPP4 Price Factors

Description	Unit Price
Meeting dispatch command premium from grid to microgrid (T_{DP})	P_{41} = \$7.87/min
Meeting demand command premium from microgrid to grid (T_{DM})	P_{41} = \$7.87/min
Following volt/VAR support premium (T_{VV})	P_{43} = \$49.85/min
Following demand response curve (T_{FkW})	P_{44} = \$96.69/min
Violating planned disconnect request (T_{DR})	*P_{45} = \$6.50/min*
Meeting power factor request (T_{PF})	P_{46} = \$3.73/min
Unplanned disconnect or failure to disconnect (T_{UD})	*P_{47} = \$8.80/min*

The final KPP4 value was calculated as:

$KPP4 = T_{DP}P_{41} + T_{DM}P_{41} + T_{VV}P_{43} + T_{FkW}P_{44} – T_{DR}P_{45} + T_{PF}P_{46} – T_{UD}P_{47}$

The envelope for all DMS power control command evaluations was as follows:

- Tolerance = 5 percent of the active power import limit for T_{DP}, T_{DM}, and T_{PF}
- Tolerance = 10 percent of the active power import limit for T_{VV} and T_{FkW}
- Settling time = 0.5 seconds

The microgrid controller had 30 seconds after a DMS disconnect request to initiate islanding. The utility grid would collapse 60 seconds after that request. Disconnect request violations were measured during a period when the microgrid was islanded and a main feeder was closed. The microgrid controller then had 60 seconds to reconnect to the grid once the disconnect request signal became inactive.

Figure 13 shows a frequency event handled by the SEL microgrid controller.

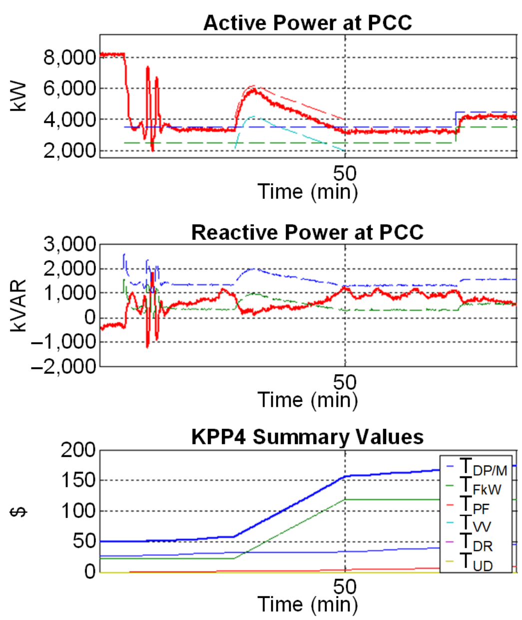

Figure 13—KPP4 Frequency Event Example and Summary Values

The bottom graph shows the microgrid controller testing results for KPP4; only the time period of the event is shown because other periods of the test sequence had no impact on this value.

KPP5: Power Quality

KPP5 measured violations of the clearing times defined in the IEEE 1547a-2014 standard based on the voltage and frequency on each bus. Every violation of the clearing times was counted.

Table 5 shows the KPP5 penalty values.

Table 5 KPP5 Price Factors

Description	Unit Price
Power quality voltage violations (N_{PQV})	P_{51} = \$4.88/(pu • s)
Power quality frequency violations (N_{PQF})	P_{52} = \$0.49/(Hz • s)

The final KPP5 value was calculated as:

$KPP5 = –N_{PQV}P_{51} – N_{PQF}P_{52}$

Figure 14 shows the SEL microgrid controller testing results for KPP5.

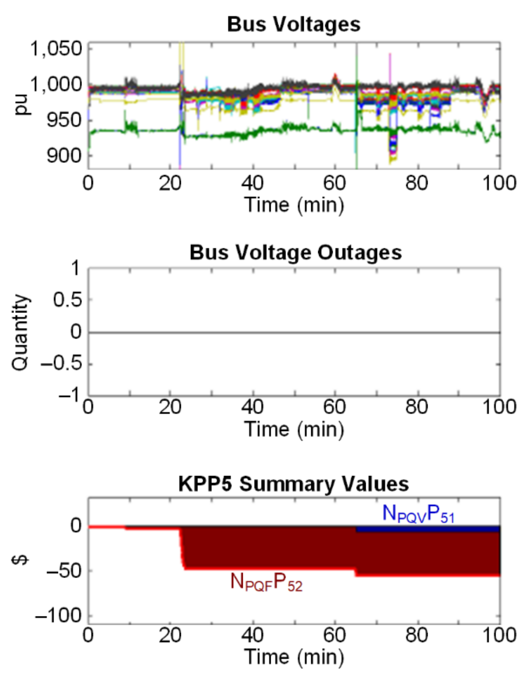

Figure 14—KPP5 Summary Charts

KPP6: Microgrid Survivability

KPP6 measured the microgrid controller's ability to optimize battery dispatch while maintaining a resiliency reserve of the battery's state of charge (SOC) in case of an unplanned islanding event. To ensure microgrid survivability, it is important to keep a minimum level of battery charge (e.g., 40 percent) during grid-connected operation. If the battery charge fell below this level during grid-connected conditions, a penalty was incurred.

KPP6 was calculated as the time below the requested SOC (T_{BRS}) in minutes multiplied by P_{61} ($1.87/min) as follows:

$$KPP6 = -T_{BRS}P_{61}$$

Figure 15 shows the SEL microgrid controller testing results for KPP6.

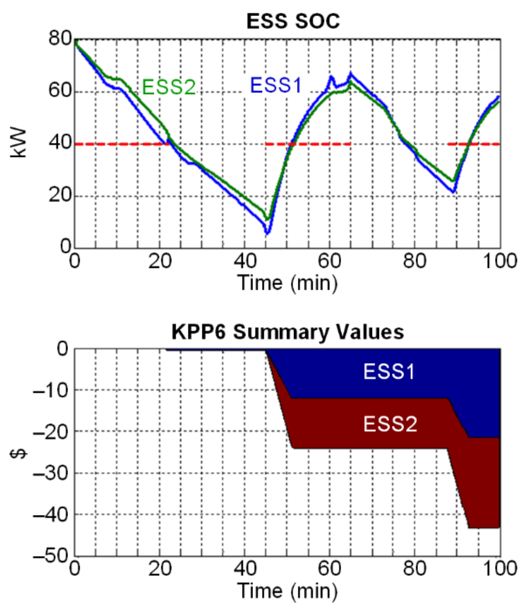

Figure 15—KPP6 Summary Charts

KPP7: Operation and Maintenance

The costs of operating and maintaining a microgrid depend on how its distributed energy resources and devices are managed. KPP7 captured the cost of activities that lead to asset degradation and failure.

Table 6 shows the KPP7 price factors. Operation costs are shown in red and italics.

Table 6 KPP7 Price Factors

Description	Unit Price
Number of diesel starts (N_D)	*P_{71} = $10.00*
Number of combined heat and power restarts (N_{CHP})	*P_{72} = $10.00*
Number of battery cycles (N_B)	*P_{73} = $10.00*
Number of circuit breaker switches (N_{CB})	*P_{74} = $0.40*
Generators over nominal current (O_G in A^2s)	*P_{75} = $1.00*
Transformers over nominal current (O_T in A^2s)	*P_{76} = $1.00*
Cables over nominal current (O_C in A^2s)	*P_{77} = $1.00*

The final KPP7 value was calculated as:

$$KPP7 = -N_DP_{71} - N_{CHP}P_{72} - N_BP_{73} - N_{CB}P_{74} - O_GP_{75} - O_TP_{76} - O_CP_{77}$$

Figure 16 shows the SEL microgrid controller testing results for KPP7.

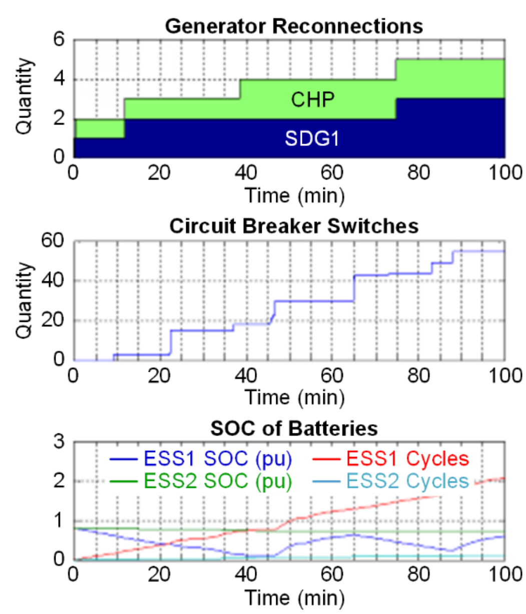

Figure 16—KPP7 Summary Charts

Tracking the number of breaker operations and the dispatch of the battery provided metrics for estimating maintenance and unit degradation costs.

KPP8: Economical Operation

KPP8 was the sum of all the other KPPs. A high result meant the microgrid operator obtained significant benefits from the microgrid controller. The selection of price parameters defined the aspects of microgrid control that most impacted the final results. By analyzing these results, operators can develop strategies for achieving the highest possible KPP8 value.

The final KPP8 value was calculated as:

KPP8 = SUM(KPP*n*, n = [1…7])

Results Summary

The NREL procurement process provided standardized performance metrics to evaluate microgrid controllers from various manufacturers. Each system was evaluated independently, and the manufacturers had no knowledge of the other manufacturers' results. This pushed each manufacturer to apply its maximum effort.

Ultimately, SEL achieved the best KPP results because the SEL microgrid controller features were robust from the start. SEL engineers did not have to spend time writing custom logic—features like intelligent high-speed load shedding, economically optimized generation control, automatic resynchronization, and battery management are off-the-shelf features in the SEL solution that were simply enabled for the NREL test system. This flexibility makes the SEL microgrid controller an ideal solution for accommodating the range of device types that will be tested at ESIF. Figure 17 summarizes the KPP results for the SEL microgrid controller.

The SEL system used a high-speed Ethernet network to rapidly detect disturbances at the utility or local generation sources, allowing the microgrid controller to react within milliseconds. The control philosophy was fine-tuned throughout the evaluation process to maximize the overall score (KPP8).

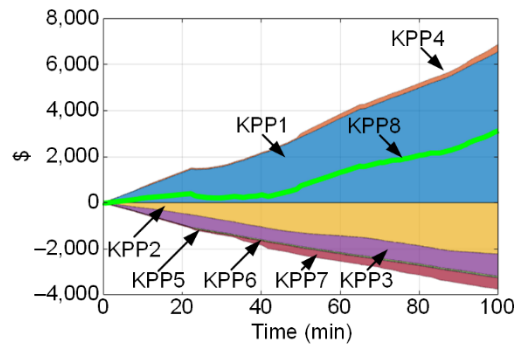

Figure 17—Summary of KPP Results

"When the SEL controller took over the microgrid and transitioned away from the utility, [it] proactively closed a lot of the tie breakers and the distribution lines between all the different areas," said Miller. "I think that allowed them to better serve some of those critical loads, regardless of which local generation assets were still available."

Conclusion

NREL now has a complete microgrid testbed available for research with a controller chosen by using the most comprehensive test sequence available for microgrid controller performance evaluation.

In addition to supporting NREL research, the SEL microgrid controller actively controls over 50 microgrid installations throughout the world.

ESIF User Program Manager Sarah Truitt summed up her experience with the NREL evaluation process by saying, "It's really exciting to be on the forefront of the energy systems transition and working with really smart people to develop our future energy systems."

Check out a video of this story at https://selinc.com/video/?vidId=123052.

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About NREL

NREL is the U.S. Department of Energy's primary national laboratory for renewable energy and energy efficiency research and development. NREL is operated for the Energy Department by The Alliance for Sustainable Energy, LLC.

About SEL

Schweitzer Engineering Laboratories, Inc. (SEL) has been making electric power safer, more reliable, and more economical since 1984. This ISO 9001-certified company serves the electric power industry worldwide through the design, manufacture, supply, and support of products and services for power system protection, control, and monitoring. For more information, please contact SEL at 2350 NE Hopkins Court, Pullman, WA 99163-5603; phone: +1.509.332.1890; fax: +1.509.332.7990; email: info@selinc.com; website: selinc.com.

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