The Illinois Institute of Technology campus uses H&L Instruments fiber optic transceivers, and the company’s SCADA networking technology, to ensure a resilient, self-healing, and economical microgrid distribution system that represents a model design for replication in both campus and urban communities scenarios.

This photo shows a typical Model 570 Fiberoptic Transceiver installation at the IIT campus beside the S&C Electric Vista Switch and SEL 351 Protection System equipment. The IIT campus system reliability is ensured in great part by the H&L Instruments redundant, self-healing fiber optic transceiver technology, which automatically switches to a secondary fiber in half a power cycle (~6 milliseconds) if the primary fiber cable breaks or a node failure occurs.

H&L Instruments newest product is the Model 570X Fiberoptic Gateway, which further enhances SCADA networks by providing serial-DNP3 transmission via TCP or UDP over the fiber network. The 570X Fiberoptic Gateway technology eliminates the need for multi-serial conversion equipment, thereby improving reliability and performance.

The following IEEE Electrification article, published in September of 2013, explains the IIT campus design objectives, and the economic benefits of the microgrid comprised of conventional, wind, and solar power sources. The reference on page 44 to communication via fiber-optic cables facilitates the coordination between Vista switches emphasizes the important role played by H&L Instruments redundant, self-healing fiberoptic technology in the design of reliable and economical power distribution systems.
Cutting Campus Energy Costs with Hierarchical Control

The economical and reliable operation of a microgrid.

With the introduction of the smart grid, there is an intense interest in the integration of intelligent and flexible microgrids in large-scale power systems. Microgrids would be operated locally in grid-connected and island modes and can provide black start operation, frequency and voltage support, active and reactive power control, and better energy management through storage technologies. The proximity of power generation to microgrid consumptions could result in improved power quality, lower power losses, better voltage stability, and higher reliability (fewer customer outages) by engaging fewer components and eliminating additional transmission services. Distributed energy resources (DERs), which include distributed generation (DG), distributed storage, and adjustable load, are a key component in microgrid operations.
Microgrids could be clustered at distribution levels to enhance the economics and the reliability of small DGs such as microturbines and wind-generation turbines as well as DGs with power electronic (PE) interfaces such as photovoltaic (PV) arrays and fuel cells. PE interfaces are fast, enabling full control of transients by introducing virtual inertia implemented through control loops known as droops. The implementation of droops would enable adjustments in frequency and voltage, which are in proportion to real and reactive power at converter terminals. Microgrids use small generators with low or no inertia, which are mostly equipped with PE interfaces in resistive networks, whereas the utility grid includes large synchronous machines with high inertias and an inductive network.

The microgrid control architectures are offered in grid-connected and island modes. Microgrids use two control architectures: multiagent system control and hierarchical control. The multiagent control system provides generation unit autonomy, reduces large data manipulation, and increases the control system reliability; however, the implementation would require a more complicated control infrastructure, which is not recommended for industrial applications. The hierarchical control of microgrids includes primary-, secondary-, and tertiary-level operations. The primary control would share the load among DER units using droops while eliminating circulating currents. The secondary control would eliminate steady-state errors imposed by primary control. The tertiary control would ensure the economical and secure operation of the microgrid and manage the microgrid's energy imports/exports with the utility grid. The hierarchical control of microgrids would minimize operation costs and increase the microgrid reliability and enhance the dynamic performance of a highly nonlinear system through various control strategies. The hierarchical control of islanded microgrids would use existing DERs for regulating the system frequency in different time spans. In addition, using microgrids would reduce communication requirements among local DER units.

In this article, we discuss microgrid objectives and present options for microgrid operations and their monitoring and control in the context of a functional system at the Illinois Institute of Technology (IIT) in Chicago. The microgrid represents a multilevel hierarchical control of self-sustaining energy infrastructure with islanding and resynchronization, self-healing, and demand response capabilities. The intelligent high-reliability distribution system (HRDS) at IIT is equipped with phasor measurement units (PMUs) for real-time monitoring, nondispatchable renewable energy production, as well as conventional and dispatchable energy resources.

**Status of a Typical Distribution Network at a University Campus**

IIT is located approximately 2.5 mi south of downtown Chicago, bounded by 35th Street on the south, Michigan Avenue on the east, 29th/30th Street on the north, and the Metra Rock Island train line on the west. Starting with the campus substations, IIT owns, manages, and operates its underground electricity distribution system. A cross-tie feeder between the substations allows for the seamless operation of the microgrid in the case of a utility grid failure in the shared feeder or one of the individual feeders in the North or the South Substation. The on-site generation can also feed the northern part of the campus through the cross-tie between the North and the South Substations.

In the decade preceding the implementation of the IIT microgrid, the university experienced several outages within the campus infrastructure and the utility feeders, which resulted in partial or complete loss of loads in buildings and research facilities. Several campus buildings lost power, including laboratories, resulting in the loss of experimental data and subjects. The substantial annual loss of revenue as a result of the outages included the replacement costs of damaged equipment due to undervoltage or unbalanced voltages (campus facilities as well as laboratories), the personnel and administrative costs of restoring and sustaining research and educational experiments, and the cost and aggravation associated with disrupted academic classes and laboratories and any other major campus events such as open houses and conferences that were interrupted by the outages.

The IIT microgrid, funded mostly by a grant from the U.S. Department of Energy, empowers the campus consumers with the objective of establishing a microgrid that is economically viable, environmentally friendly, fuel efficient, robust, and resilient with a self-healing capability. The IIT microgrid enhances its operation reliability by applying a real-time reconfiguration of power distribution assets, real-time islanding of critical loads, and real-time optimization of power supply resources.

**Objectives for Establishing a Microgrid**

The IIT microgrid is powered by a master controller, which offers the opportunity to eliminate costly outages and power disturbances, supply the hourly campus load profile, reduce daily peak loads, and mitigate greenhouse gas production. The distribution system topology consists of several loops, which provide redundant electricity supply to the end consumers. The IIT microgrid would specifically:

- Demonstrate the higher reliability introduced by the microgrid system at IIT
- Demonstrate the economics of microgrid operations
- Allow for a decrease of 50% of the grid electricity load
- Create a permanent 20% decrease in the peak load from the 2007 level
- Defer a planned substation through load reduction
- Offer a distributed system design that can be replicated in urban communities

The criteria for achieving these objectives are short-term reliability and economical operation. Figure 1 shows the microgrid elements, functions, and control tasks associated.
with each criterion. To achieve the optimal economics, microgrids apply coordination with the utility grid and economical demand response in island mode. The short-term reliability at load points would consider microgrid islanding and resynchronization and apply emergency demand response and self-healing in case of outages.

Campus Microgrid Components
In this section, the components of the IIT microgrid, including DERs, HRDS switches, meters and PMUs, and building controllers, are introduced. DER units include dispatchable units such as natural-gas turbine generator and battery storage units, and nondispatchable units such as solar PV and wind turbine units. The storage unit includes a flow battery and several lead-acid batteries. Building controllers would provide control and monitoring functions for building loads on campus. Figure 2 depicts the seven-loop configuration established at IIT in which three loops are connected to the North Substation and four loops are connected to the South Substation. The components of the IIT microgrid are described in the remainder of this section.

Natural-Gas Turbine Synchronous Generation
The IIT microgrid is equipped with an 8-MW natural-gas-fired power plant with two 4-MW Rolls Royce gas turbines. The natural-gas turbine consists of five sections, including air intake, compressor, combustor, turbine, and exhaust. The air sucked into the inlet is compressed by the compressor and mixed with the fuel (natural gas) to form an air-fuel mixture. The mixture is burned in the combustor to form a high-pressure air, which drives the turbine. The synchronous generator installed on the turbine shaft will convert the mechanical energy into electrical energy.

Figure 3 shows the full-scale model of the natural-gas turbine generator located at the IIT campus.

Solar PV Generation
A total of 140 kW of solar PV cells are installed on three building rooftops, including a 20-kW solar canopy (shown in Figure 4) installed at the electric vehicle charging station to supply portions of the IIT campus load. The solar PV units are not dispatchable and use the maximum power point tracking (MPPT) control system shown in Figure 5 to maximize the solar power output for a given insolation. A solar PV cell is a controlled-current source with a nonlinear current-voltage relationship corresponding to a given insolation and temperature. Generally, as the solar PV cell voltage increases, its output current will decrease. To achieve the highest efficiency and capture maximum solar energy, a solar PV array voltage-control mechanism is developed for a given insolation. Here, the inverter output voltage $V_o$ of solar PV units is determined by the microgrid. The dc/ac inverter uses an angle control to stabilize the dc bus voltage $V_b$, based on the fixed $V_r$. and also used a magnitude control to regulate the reactive power output at a reference value (typically zero). Based on the stabilized $V_b$, the dc/dc converter adopts MPPT control to regulate the solar PV array voltage $V_o$ and reach the maximum real power output. The objective of solar PV generation control is to withdraw maximum real power without injecting any reactive power to the microgrid.

Wind Turbine Unit
An 8-kW wind turbine unit is installed on the north side of the campus in the Stuart soccer field, connected to Loop 1, as shown in Figure 6. The wind turbine unit on the IIT campus
uses a Viryd wind turbine unit. The wind turbine features continuous variable transmission (CVT) technology, which provides automatic and continuous variable ratio change that maintains stable rotor speed for the generator as wind speed changes. This would enable the generator to maintain high efficiency at all wind speeds. The CVT can also precisely slow the rotor in high wind speed, curtailing the excess wind power. Figure 7 shows the structure of the CVT-based wind turbine unit. The role of the variable gear ratio is to regulate the power output close to the rated value when the wind speed is within the acceptable range. The cut-in and cut-off wind speeds for this turbine are 4.5 and 25 m/s, respectively, and the turbine has an 8-m diameter and 50-m² sweep area. Figure 8 shows the hourly power output and the wind speed for the wind turbine unit on 20 May 2013. Here, the wind turbine unit would spin when the wind speed is higher than 10 m/s (4.47 m/s).

Battery Storage
The IIT microgrid is equipped with a 500-kWh battery storage system (including ten 50-kWh battery cells) with 250-kW power capacity, which is connected to Loop 1. Figure 9 shows a stack of the flow battery and the battery inverter, which can regulate the real and reactive power output.

HRDS Switches
The HRDS at IIT uses underground closed-loop fault-clearing Vista switchgear with SEL-351 directional overcurrent protection relays. The fault isolation takes place in a quarter of a cycle by automatic breakers. The communication via fiber-optic cables facilitates the coordination between Vista switches. Figure 10 shows the underground installation of a HRDS switch at IIT. In HRDS, at least two simultaneous failures in the cable segments feeding a building from both paths will lead to a complete outage in the building. As the chances of two coincident failures are far less than single failures in cables feeding, the interruption indices of the buildings are improved significantly by the installation of HRDS. Figure 11 shows a loop configuration in distribution system at IIT. Here, in Loop 1, any cable failure between Vista switches 1C and 1D will be cleared, and the Stuart and Life Sciences Buildings fed by the switches will not face any interruptions.

Meters and PMUs
The IIT microgrid is equipped with building meters and PMUs, which report building electricity consumptions to the master controller. The master controller will receive an energy consumption update every 15 min. The load data recorded on 17 July 2012 at the McCormick Tribune Campus Center (MTCC) at the IIT microgrid are shown in Figure 12. Approximately 30% of building consumptions at IIT are shiftable loads, which can be served when the electricity price is lower. The IIT microgrid is equipped with 12 PMUs that monitor and record the real and reactive generation and consumption in real time and provide the information on instantaneous voltage and current of DER units (including the magnitude and phase angle) at a sampling rate of one signal per cycle to the master controller. Figure 13 shows a PMU installed at the North Substation. Figure 14 shows the real and reactive power of critical loads and DER units, which are calculated by master controller based on the instantaneous values.

Building Controllers
Building controllers facilitate the building consumption manage-
ment in the IIT microgrid. The reduction in building consumption is accomplished by defining several operating modes representing consumption levels in each building. Once the operation mode for each building is set by the master controller, the building controller will send a signal to the sub-building controllers to set the requested load level associated with the selected mode and feed back the confirmation signal to the master controller to acknowledge the mode change. Figure 15 shows the buildings equipped with building controllers in Loop 1, in which the blue squares represent command signals from the master controller, and the green squares represent acknowledgment signals originating from the building controllers. The building controllers are also able to monitor and control the energy flow within the buildings, including hot and cold water flow, heating and cooling loads, and monitoring the temperature of different spaces within the building.

**Microgrid Control**

Figure 11 shows the DER units (including DG and rechargeable storage) implemented in the IIT microgrid. The IIT microgrid integrates DG units, which are classified into conventional DGs and PE coupled DGs. Table 1 shows that the DER control schemes are categorized into grid-following and grid-forming control.

In grid-forming control, DER units maintain the microgrid voltage and frequency, while in the grid-following control, the units maintain their individual real and reactive power dispatch. In other words, DER units with grid-forming control would act as the swing bus in microgrids and should have adequate real, reactive, and reserve power capacity and fast response to control microgrid voltage and frequency. The DER unit using this control scheme can either collaborate with other microgrid units (interactive control) or operate autonomously (noninteractive control). Dispatchable DER units, which follow set points determined by their controllers, can interact with other DER units using a grid-forming interactive control scheme. DER units with load-sharing capability, which would collaborate in setting their output real and reactive power dispatch according to the microgrid frequency and voltage, are an example of grid-forming interactive controlled DER units. Dispatchable units can also use grid-forming noninteractive control to maintain a fixed set-point for microgrid voltage and frequency. This control scheme can be used in dispatchable units with sufficient real and reactive power capacity (such as microturbines) to maintain nominal microgrid voltage and frequency.

The grid-following control is used when the DER unit is not required to directly control the microgrid voltage and/or frequency. In this control scheme, the real and reactive power output of the DER is maintained within permissible limits, and the voltage and frequency is regulated by other DER units in the microgrid. Similar to the grid-forming control scheme, DER units using a grid-following control scheme can either collaborate with other DER units in the microgrid or operate autonomously. It shows a CVT-based wind turbine unit with a fixed-speed induction generator. Figure 7 shows the wind power generation on 20 May 2013 at IIT.
autonomously. Nondispatchable units in a microgrid (such as solar PV units with MPPTs or wind turbine units) often apply a noninteractive control, which maximizes their output power. Dispatchable units apply a grid-following interactive control in which the real and reactive power output is determined by the respective set points. This control scheme can be applied to PV units equipped with storage in microgrids, where the output real and reactive power is regulated irrespective of the control strategy for microgrid voltage and frequency.

Depending on the microgrid operating mode, a proper DER control scheme, shown in Table 1, is used. An interactive grid-forming control can be used either in island or grid-connected mode. In island mode, DERs apply this control scheme to share the load, while in the grid-connected mode, DERs apply this control scheme to regulate the power exchange between the microgrid and the utility grid. The noninteractive grid-forming control can be used only in island mode, as the frequency and voltage will be set by DER units in the island mode. In the grid-connected mode, if the utility frequency or voltage deviates from the DER set point, the DER real or reactive power may reach its physical limit once its controller apply the set point voltage or frequency. The DER unit with grid-following control follows the microgrid voltage and frequency, which is set by the utility grid in grid-connected mode and other DER units in island mode.

Table 1 shows that the natural-gas turbine and the battery storage at IIT are using interactive grid-forming control and the wind turbine and PV units are using noninteractive grid-following control. The interactive grid-forming control scheme on the natural-gas turbine and the battery storage units would enable the microgrid to operate in both island and grid-connected modes.

The proper monitoring and control of DERs at the IIT microgrid would satisfy the following objectives:

- load sharing among DERs
- voltage and frequency regulation in island mode
- islanding and resynchronization to the utility grid
- optimal generation and consumption at IIT microgrid
- real-time monitoring of the distribution system components.

Functionally, three control levels (shown in Figure 1) are applied to the IIT microgrid:

1) Primary control, which is based on droop control for sharing the microgrid load among DER units
2) Secondary control, which performs corrective action to mitigate steady-state errors introduced by droop control
3) Tertiary control, which procures the optimal dispatch of DER units in the microgrid and manages the power flow between the microgrid and the utility grid for optimizing the grid-connected and island operation schemes.

The control levels at the IIT microgrid are discussed next.

**Tertiary Control**

Tertiary control is the uppermost level of the control system in Figure 1; it ensures the optimal operation of the microgrid by determining the set points of generation and load entities at the IIT microgrid. The master controller, which is regarded as the most important control element of the IIT microgrid, is responsible for applying the tertiary control. The master controller uses the data supplied by the supervisory control and data acquisition (SCADA), which enables the real-time monitoring and control of microgrid elements including HRDS controllers, on-site generation, storage, and individual building controllers and meters. The master controller signals, which are relayed through SCADA, will adjust building loads and the generation dispatch for economical operation.

Figure 16 shows a hierarchical operation within the tertiary control that would provide generation and load management at normal and emergency conditions. The hierarchical tertiary control includes the following components:

- The master controller determines the optimal and reliable operation of the microgrid through optimal generation dispatch and load signals. The generation control...
dispatch signals are sent to dispatchable DER units on campus, and the load signals are sent to the building controllers.

The building controllers are responsible for setting the building loads according to the dispatch signal received from the master controller.

The sub-building controllers perform device-level load management by controlling the operation status of devices located in buildings.

The hierarchical tertiary control approach would receive the information from loads and power supply entities on campus as well as the information on the status of campus distribution network and procure the optimal solution via an hourly unit commitment and real-time economical dispatch for serving the campus load in the normal operation mode and contingencies. In Figure 16, the monitoring signals provided to the master controller indicate the status of DER and distribution components, while the master controller signals provide set points for DER units and building controllers. Building controllers will communicate with sub-building controllers through a ZigBee wireless control and monitoring system to achieve a device-level rapid load management.

Figure 11. The DER units and HRDS in the IIT microgrid.

Figure 12. The MTCC load on 17 July 2012.
Secondary Control
Secondary control in Figure 1 is the middle level control at the IIT microgrid. Secondary control is used to eliminate frequency and voltage deviations caused by lower control level (primary control). As illustrated in the Figure 17, once there is a sudden decrease in demand in microgrid, the frequency and voltage increases. Once the frequency or voltage increases, the operating point may slide from A to B with primary control to decrease the generation dispatch and match the generation with demand. As the frequency or voltage is above the rated value, the secondary control is used to lower the operating point from B to C, where the frequency or voltage is restored to the rated values. As shown in Figure 17, only the frequency or voltage is restored in secondary control, while the real or reactive power dispatch is not changed. Thus, with secondary control, dispatchable DER units would maintain the frequency and voltage at the rated value while adjusting their dispatch according to the tertiary control signal to serve the microgrid load. The secondary control is a centralized and performed by master controller. The master controller will set the microgrid voltage and frequency and send the set points to primary control at DER level. Restoration, load sharing, and management can be performed in secondary control.

Primary Control
The primary control, shown in Figure 1, is the lowest level of control in the IIT microgrid. The primary control is mainly used for load sharing among controllable and dispatchable fast-response DER units, which have adequate capacity to serve the microgrid load. The most widely used primary control strategy is droop control, which is shown in Figure 18. DER units equipped with droop control, which are connected in parallel, would not need to communicate with each other to perform load sharing; instead, individual dispatch levels are calculated based on predefined droop characteristics and microgrid frequency and voltage.
Figure 18, the DER dispatch $P$ is at its rated value $P_{\text{nom}}$ at the rated frequency $f_{\text{nom}}$, which are determined by the master controller through tertiary control level. As the frequency increases, there will be a slight decrease in power dispatch to compensate the frequency deviation. Similarly, as the microgrid voltage increases, the injected reactive power decreases to compensate the voltage drop. In Figure 18(a) and (b), $m_\omega$ and $m_v$, respectively, represent the slopes of the $f-P$ and $v-Q$ curves. The DER units at the IIT microgrid, which are equipped with primary and secondary control, are the natural-gas turbine synchronous generator and the battery storage unit.

**Natural-Gas Turbine Synchronous Generator**

Figure 19 shows the control diagram for the natural-gas turbine synchronous generator. Here, $\omega$, $\omega_{\text{nom}}$, $V$, and $V_{\text{nom}}$ are the measured speed, rated speed, measured voltage, and rated voltage of the synchronous generator, respectively; $P$, $P_{\text{nom}}$, $Q$, and $Q_{\text{nom}}$ are the measured real power, rated real power, measured reactive power, and rated reactive power of the generator, respectively; $\omega_{\text{ref}}$ and $V_{\text{ref}}$ are the adjustment signals used for secondary control. As shown in Figure 19, the natural-gas turbine and exciter provide the input mechanical torque $T_m$ and excitation to the generator. The primary and secondary control modules for $\omega-P$ and $v-Q$ generate signals to the turbine and exciter, respectively, to regulate the real and reactive power output and maintain the microgrid frequency and voltage at the rated values. At steady state, if the generator dispatch is deviated from the rated value through primary droop control, the secondary control will generate a nonzero adjustment signal shown in (1) to restore the frequency or voltage back to the rated value. Thus, the natural-gas turbine synchronous generator would serve the campus load while maintaining the microgrid frequency and voltage at the rated value.

$$\omega_{\text{ref}} = m_\omega (P - P_{\text{nom}})$$

$$V_{\text{ref}} = m_v (Q - Q_{\text{nom}}).$$  

(1)

**Battery Storage Unit**

The control structure of the battery storage system is shown in Figure 20, where the battery storage is connected to the microgrid through a bidirectional dc/ac inverter, an ac filter, and a transformer. Here, the output real and reactive power denoted by $P$ and $Q$ is calculated by measuring the terminal voltage and current $V$ and $I$. The measured real and reactive power are used in the primary droop control to provide a reference voltage signal $V_{\text{ref}}$. The voltage loop is used to stabilize the inverter terminal voltage using the reference voltage signal and to ensure that the DER output impedance is inductive at
TABLE 1. The Classification of DER Controls and Units at the IIT Microgrid.

<table>
<thead>
<tr>
<th>Control</th>
<th>Grid-Following Control</th>
<th>Grid-Forming Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noninteractive control</td>
<td>Power injection (wind turbine, solar PV)</td>
<td>Voltage and frequency control</td>
</tr>
<tr>
<td>Interactive control</td>
<td>Real and reactive power dispatch control</td>
<td>Load sharing (battery storage, natural-gas turbine)</td>
</tr>
</tbody>
</table>

Rated frequency, which is an important factor in implementing $f-P$ droop control. The current loop is used to obtain a fast response in a wide frequency band. The biloop block output (voltage and current loops) is the

pulselowidth modulation (PWM) ratio, which would trigger dc/ac inverter switches. If the microgrid frequency $f_{mg}$ or the microgrid voltage $V_{mg}$ deviates from the rated value, the secondary control module will generate secondary control signals $f_{mg}$ or $V_{mg}$ to restore the rated frequency or voltage. The inverter power output is limited between $-250$ and $250$ kW as enforced by primary control module. In Figure 20, the battery storage system would maintain the rated frequency and voltage of microgrid in case of any disturbances in the island mode. Moreover, the battery storage system would perform the following functions:

- contain abrupt load changes in island mode
- help mitigate frequency deviations in island mode
- participate in frequency regulation when the microgrid operates in grid-connected mode
- charge and discharge periodically for the economical operation of the IIT microgrid.

Economical and Reliable Operation of the Microgrid

The hierarchical tertiary control is used to ensure the economical and reliable operation of the microgrid. In Figure 1, the economical operation pertains to unit commitment and economical dispatch as well as economical demand response in grid-connected and island modes. Also, the short-term reliability of microgrid is satisfied through islanding and resynchronization, emergency demand response, and self-healing. In this section, the economical and reliable operations of microgrid performed by the hierarchical tertiary control are discussed.

Economical Operation

The cost of economical operation includes the cost of utility grid energy transactions (in both directions), cost of microgrid energy supply, and load curtailment costs (value of lost load.) Microgrid outages
could result in a loss of revenue estimated at US$80/kWh (value of lost load), which covers the replacement cost of damaged equipment, and personnel and administrative cost of restoring and sustaining research and education at IIT. Once the real-time price exceeds 6–8 cents/kWh (marginal cost of microgrid generation), the campus load is supplied by the local microgrid generation. The master controller uses a security-constrained unit commitment to calculate the day-ahead optimal operation of microgrid. The optimal hourly solution includes the dispatch of the microgrid generation and renewable energy resources, exchanges with the utility grid, charge/discharge schedule of the battery storage unit, and adjustments to set points of building loads.

To perform the tertiary control, the master controller procures the day-ahead forecasts for building loads and renewable energy resources. The forecasted price of electricity is procured by ComEd. The forecasted values are calculated based on the historical data and forecasted weather data using nonlinear regression methods. The integration of renewable energy generation in microgrids will reduce carbon footprints while decreasing the cost of supplying the campus load. The drawback of integrating renewable technologies is the variability of their generation portfolio. To overcome this challenge in the microgrid, several approaches are used including the coordination of dispatch with the utility grid and hourly demand response. The economical operation of microgrid is implemented by two master controller functions, which are discussed below.

Unit Commitment and Economical Dispatch
To ensure the economical operation of the microgrid, the master controller performs unit commitment and economical dispatch in island and grid-connected modes to procure the optimal generation scheduling of DER units as well as the utility grid dispatch. In grid-connected mode, the microgrid load is compensated by adjusting the power generation exchange with the utility grid. Here, the primary and secondary controls of DER units will not respond to disturbances, as the microgrid voltage and frequency are set by the utility grid. Figure 21 shows the day-ahead hourly control signals provided by the master controller for supplying the campus load on 17 July 2012. On this day, the campus reached its annual peak load of 11.263 MW at hour 15. The master controller dispatched the microgrid generation once the electricity price was higher than 6 cents/kWh. In Figure 21, the battery storage was charged when the electricity price was lowered to 2.8 and 2.7 cents/kWh at hours 4 and 5, respectively. In addition, the battery storage was discharged as the price of the electricity was increased to 22.4 and 24.5 cents/kWh at hours 16 and 17, respectively. The cost of supplying the campus energy on this day was US$15,524.

The real-time optimization is based on real-time information, such as the price of electricity, campus load, renewable energy generation, and the topology of the campus microgrid including the state of Vista switches and cables. The master controller will perform the campus energy management by procuring the optimal 15-min economical demand response and the dispatch and commitment of campus generation.

Economical Demand Response
The master controller will adjust shiftable building load schedules to calculate optimal generation schedules. Shiftable loads can often be served at delayed hours without jeopardizing the convenience of campus residents. Moreover, the tertiary control will schedule the charging/discharging sequence of battery storage to optimize the supply of campus load with respect to the utility price of electricity. In island mode, the microgrid load is supplied by dispatchable DER units, which respond according to their droop characteristics using primary and secondary control scheme. The tertiary control would also set the optimal operating point of dispatchable DER units. The nondispatchable DER units including solar PV and wind turbine units will not respond to deviations in real and reactive campus loads. In Figure 22, the master controller would apply demand response through tertiary control.

![Figure 17. The secondary control in DER units.](image)

![Figure 18. The (a) frequency and (b) voltage droop characteristics of a DER unit.](image)
signals when the price of electricity is high, which would lower the cost of supplying the campus load. Here, the building load is shifted from peak hours 16–18 to off-peak hours 4–6. The set points shown in Figure 22 are sent to DER units and building controllers to set the campus load and generation. The local microgrid generation is also used to supply the peak demand at the utility grid. Accordingly, the daily energy cost of the microgrid is reduced from US$15,524 to US$13,715. Figure 23 shows the economical load reduction at IIT on 19 August 2010, which was recorded by ComEd. Here, the campus load is reduced by 60% through curtailing building loads, shifting campus loads, and dispatching the natural-gas turbine at IIT.

**Short-Term Reliability**

The IIT microgrid connects to the utility grid through four 12.47-kV feeders located at the North and South Substations. The IIT microgrid can operate in both grid-connected and island (autonomous) modes. In the grid-connected mode, the microgrid frequency and voltage

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**Figure 19.** The natural-gas turbine synchronous generator control module.

**Figure 20.** The control structure of the battery storage system.
are regulated by the utility grid. In island mode, the natural-gas turbine and battery storage would maintain the microgrid frequency and voltage, while solar PV and wind turbine units serve portions of the campus load. The short-term microgrid reliability is enhanced by implementing three major functions at IIT: islanding and resynchronization, emergency demand response, and self-healing, which are discussed in this section.

Islanding and Resynchronization
The microgrid may increase its load point reliability indices by setting up its operation in island mode. Generally, there are two major reasons for setting up a microgrid in island mode: 1) poor power quality at the utility grid, such as frequency or voltage deviations, and 2) major faults at the utility grid. PMUs and voltage/current meters at the point of common coupling (PCC) would report the utility grid malfunction to the master controller, which will initiate the islanding process at the tertiary control level. The master controller will monitor building meters for supplying the local generation dispatch. At islanding, the master controller may reduce the campus load through emergency demand response to match the load with the local generation dispatch. The load reduction may entail shifting building loads and reducing curtailable building loads. Matching the load with generation at islanding will reduce transients and ensure a feasible microgrid operation considering the ramping limits of DER unit generation.

Figure 21 shows the campus load restoration in island mode at the Engineering 1 and Stuart Buildings located in Loop 1 on 19 July 2012. The load restoration started at 6:19 a.m. on both buildings and was fully restored at 6:29 a.m. Figure 21(b) shows the inrush current of a switched-on transformer located in the Stuart Building. In island mode, any abrupt changes in the local microgrid load are served by the battery storage through primary and secondary controls. Once the normal operation at the utility grid is restored, the microgrid will be resynchronized with the utility grid. In island mode, the microgrid could be operated at a frequency and a voltage magnitude that are different than those of the utility grid, which could cause transients during the resynchronization process and damage the substation equipment. The master controller will send synchro-

Figure 21. The day-ahead storage, microgrid, and utility grid supply on 17 July 2012.

ization signals to the campus DER units through secondary control for mitigating any possible transients.

The following criteria are to be satisfied for transition from island to grid-connected mode:
1) The voltage magnitude difference at the PCC would be small.
2) The frequency difference would be small to match the voltage phase angles at the switching instance.
3) The voltage angle with the lower frequency should lag behind that of the higher frequency. Figure 25 shows the voltage angle difference between the microgrid and the utility grid at resynchronization instance. Assuming that the microgrid frequency is slightly smaller than that of the utility grid if \( V_{\text{micro}} \) leads \( V_{\text{utility}} \), then the power flow will be from the microgrid to the utility grid and in the reverse direction at steady state. The flow from the microgrid to the utility grid at resynchronization may result in the overloading of the microgrid DER units.

The IIT microgrid resynchronization process is presented as follows. At first, the master controller will send the
frequency adjustment signal to the natural-gas turbine and the battery storage unit to adjust the microgrid frequency to less than nominal frequency (59.9 Hz). The secondary control will maintain a lower microgrid frequency than that of the utility grid before resynchronization. When the microgrid voltage angle lags behind that of the utility grid slightly (fewer than 10°), the PCC switch will be closed, and the IIT microgrid will be resynchronized with the utility.

Emergency Demand Response
The objective of emergency demand response is to maintain the microgrid voltage and frequency within acceptable levels in island mode or to supply the utility grid partially in grid-connected mode in case of an emergency. In either case, the IIT microgrid will perform emergency demand response. In island mode, the emergency demand response will match the load with the generation (e.g., dispatch the battery storage or curtail building loads), while in grid-connected mode, the microgrid would curtail loads as required. The master controller will communicate with building controllers to curtail or shift loads and monitor the updated load level through building meters.

Once the campus load is reduced, DER units on campus will be redispached through primary and secondary controls to maintain the nominal voltage and frequency. After the completion of emergency demand response, the tertiary control provided by master controller will procure the steady-state optimal generation dispatch of dispatchable DER units.

Self-Healing
Self-healing relies on robust HRDS protection and switching schemes as well as on-campus storage to supply the load

Figure 23. The load reduction test at the IIT microgrid on 19 August 2010.

Figure 24. The load restoration at the (a) Engineering 1 and (b) Stuart Buildings in Loop 1 in island mode on 19 July 2012.
during campus contingencies (e.g., component outages). The integration of HRDS provides a looped distribution network by integrating Vista switches to automatically detect and isolate microgrid faults while maintaining the service to buildings through redundant distribution paths. Moreover, the integration of battery storage will serve critical campus loads in case of generation deficiency or distribution cable contingencies. The interruption indices are calculated for load points on Loop 3 with and without Vista switches, which show that the integration of HRDS will result in a dramatic reduction in load interruption indices. Rapid fault detection and clearance will result in fewer transients in distribution systems.

Figure 26 shows two induction motors in non-HRDS and HRDS systems. The response of motor 1, located close to the Vista switch 1, to a nearby cable fault is shown in Figure 27. As shown in this figure, HRDS has cleared the fault in 0.1 s, which has retained the normal motor speed quickly. In Figure 26(a), without the HRDS system, the cable fault would lead to a dramatic drop in the motor 1 speed as the fault clearing time is longer and the fault clearance would lead to the loss of load downstream, i.e., motor 2.

Conclusions
This article discusses the hierarchical control of microgrids and the role of primary, secondary, and tertiary controls in enhancing the microgrid reliability and economics and introduced the control applications to a functional microgrid at IIT. The IIT microgrid is analyzed as a test bed, and the functions for implementing microgrid objectives are discussed. The functions include unit commitment and economical dispatch, economical demand response, islanding and resynchronization, emergency demand response, and self-healing. The master controller applies tertiary and secondary control to ensure the economical and reliable operation of the microgrid. Primary control is applied at the DER unit level to respond to disturbances in a short time, while the secondary and tertiary control signals eliminate errors introduced by primary control to regulate the voltage and frequency and maintain the optimal dispatch of DER units. The functions are performed by the master controller, DER units, building controllers, and meters, which can achieve economical and reliable operations of a microgrid. The effect of HRDS switches in reducing the transients that occur during distribution network faults and component failures in microgrids is discussed. Transients occur when switching a microgrid between island and grid-connected modes, and options such as emergency demand response, load restoration, and DER unit response are considered in this article to maintain steady-state operations in microgrids.

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Figure 25. The voltages at the microgrid and the utility grid.

Figure 26. Distribution networks (a) with and (b) without HRDS switches.
For Further Reading


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