How New Microgrid Technologies Enable Optimal Cooperation Among Distributed Energy Resources

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Executive summary

Microgrids are local, interconnected energy systems and may become the keystone of the new energy transition. In the electrical domain, they are defined within boundaries, incorporating loads, distributed energy resources (including storage), and specific control capabilities.

Their implementation requires new technologies to enable cooperation among distributed energy resources with a shared objective, analyze strategies to optimally operate and manage the interconnected system, or relieve design constraints regarding bidirectional power systems.
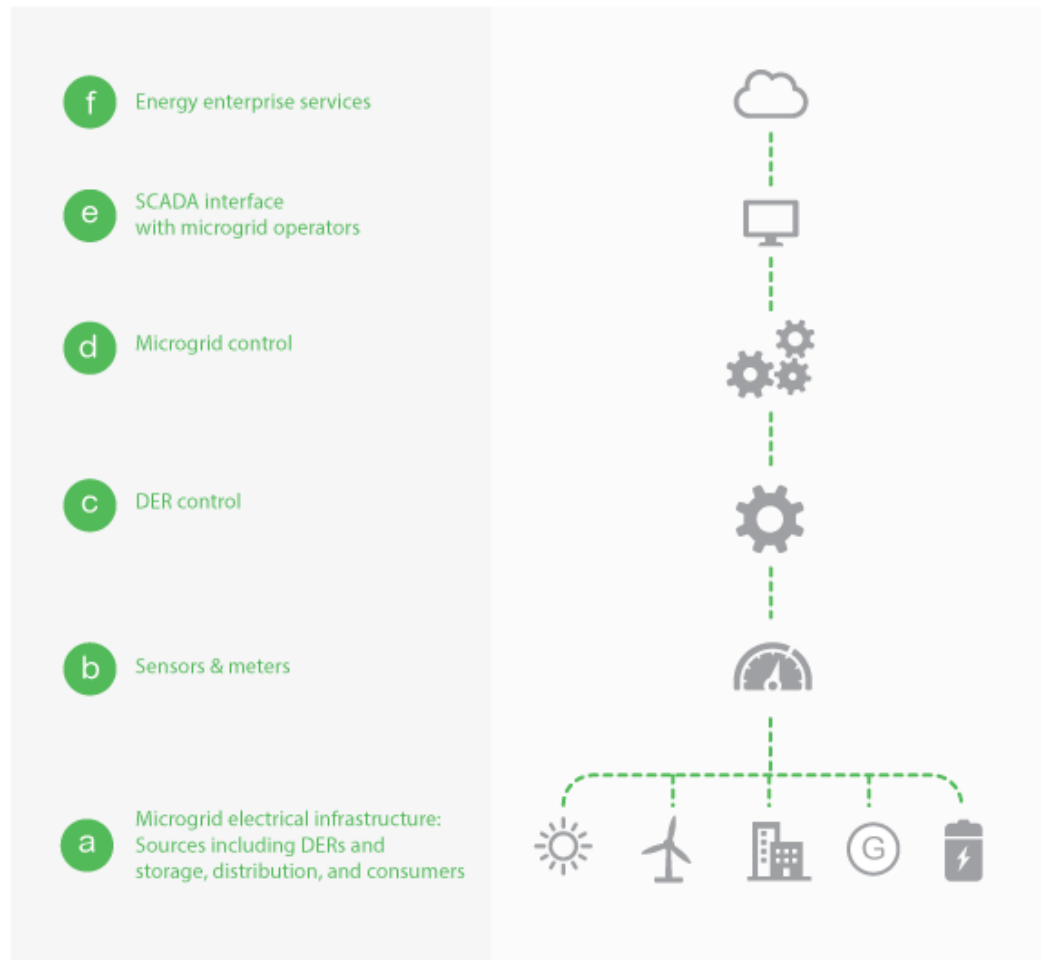
Current and future technologies

Microgrids result from the association of subsystems acting in a coordinated manner, rather than from independent functional components. Practically, they are often composed of:

a) An energy network infrastructure that includes equipment for energy generation (usually multiple Distributed Energy Resources), an energy distribution network(s), and energy users/consumers of different criticality levels and profiles

b) Sensors, meters, and network protection

c) Controls at the Distributed Energy Resource (DER) level

d) Controls at the microgrid management level, aiming to optimize the entire system

e) Supervisory Control and Data Acquisition (SCADA) system to interface with microgrid operators

f) Cloud-based decision services such as tariff management, demand charge optimization, demand response, self-consumption, blackout management, carbon dioxide (CO_2) reduction, etc.

Figure 1

Microgrid functional architecture, from the grid to the cloud

f Energy enterprise services

e SCADA interface with microgrid operators

d Microgrid control

c DER control

b Sensors & meters

a Microgrid electrical infrastructure: Sources including DERs and storage, distribution, and consumers

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Microgrids are implemented to fulfill global energy expectations such as resiliency, economy, security, and CO_2 reduction. The relative importance of these expectations depends on the microgrid category and the related technical features whose components might differ accordingly. However, in every case, specific performance objectives have to be solved through technical advances in systems' control and protection innovation such that cooperation of distributed energy resources towards a shared objective can be fulfilled.

Ensuring safe and reliable operation

Specific constraints for the protection strategy

In microgrids, the association of local distributed generation and capability to island from the main grid brings new challenges for the protection system design.
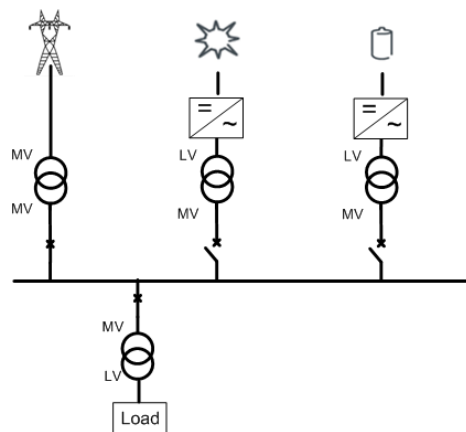
Microgrids are characterized by varying operating modes, according to the real-time production of distributed generation, the microgrid configuration (grid-connected or islanded), and the real-time power demand (load profiles), as shown in figures 2A, 2B, and 2C.
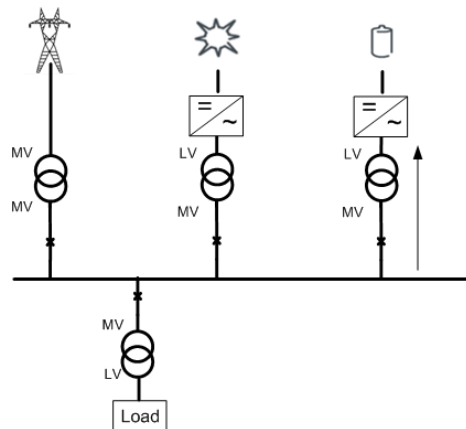
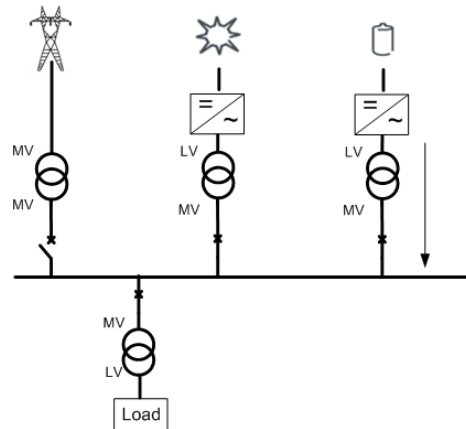**Figures 2A, 2B, 2C**

Examples of microgrid operating modes

A. *Supplied by the grid only*

Transformer

B. *Supplied by the grid and a local energy source in parallel, storage is recharged*

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C. *Supplied by a local energy source and storage (islanded mode)*

As microgrid operating conditions change, the network topology also changes. Consequently, the short-circuit current capacity may vary both in magnitude and direction. Protection systems have to be carefully designed in a way to secure people and equipment from all possible types of fault in each operating mode, while avoiding downtime due to errant protection discrimination.

Particular attention should be paid to the fact that microgrids are often multi-source systems with both rotating and power-electronics-based sources. Complication of the protection system design occurs because these sources can operate both in parallel and individually.

The first challenge is to deal with the low short-circuit capacity. Many DERs such as solar photovoltaic (PV) panels or wind turbines are coupled via inverters. The magnitude of the short-circuit current of these inverters is usually limited to values not much higher than the nominal current to protect the inverter itself. As a result, the short-circuit capacity is lower than from comparable rotating machines, which might present a problem in islanded mode with only inverter-based energy sources. Traditional overcurrent protection philosophies that rely on much higher available short circuit currents may be compromised, requiring alternative protection strategies to be established.

Another challenge for the protection system design is response to bidirectional energy flow. As the energy resources are distributed, the energy typically flows both top-down (from generators to consumers) and bottom-up (DERs and storage may contribute to a microgrid's main electricity supply or to the main grid)

For these reasons, project-specific electrical engineering studies are required to specify in detail the protection and metering devices to be used.
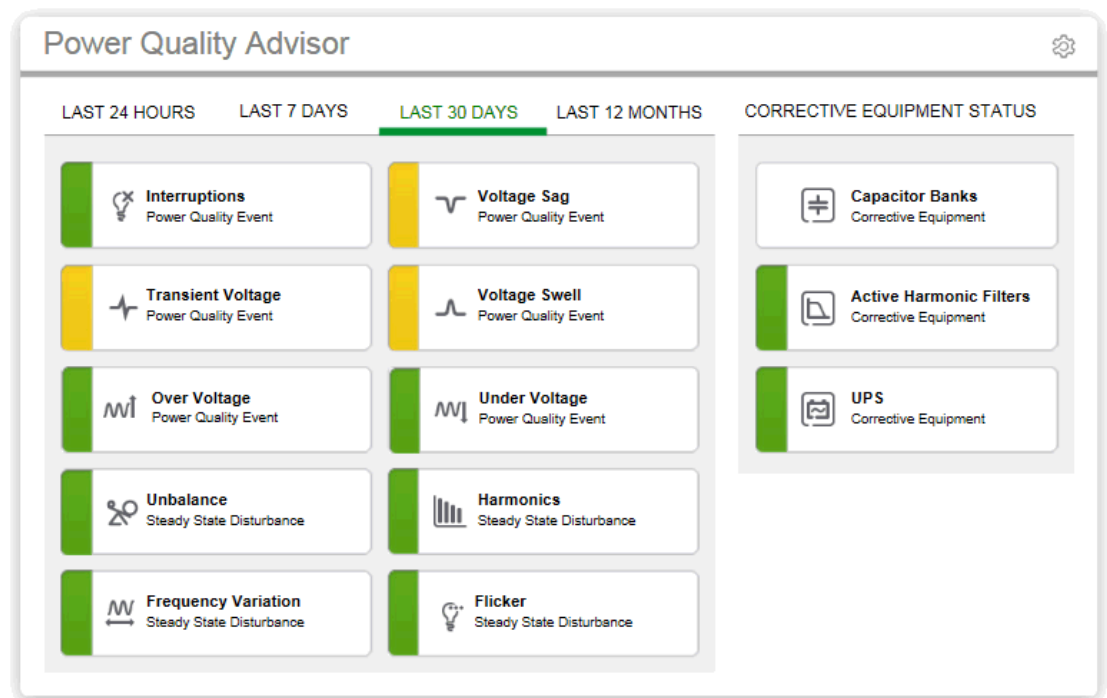
Specifics related to power quality

Microgrids balance energy generation and demand in real time. This requires fast and accurate measurements of active and reactive powers, frequency, current, and voltage levels in order to enable proper power quality control and automated operation.

Power quality measurements become even more important in microgrid applications. The following particular power quality issues should be monitored, analyzed, and kept within their normal operating range.

- Harmonics: Harmonics' presence and interactions are more important than in traditional networks where the major sources of harmonics are typically the electronic loads and equipment. In microgrids, inverter-based DERs generate additional harmonic pollution and the harmonic levels can potentially rise much higher if not monitored and treated properly.

- Frequency variations: Usually, when connected to the main grid, the microgrid frequency is stable and frequency variations are rare, especially in countries where the grid is strong and meshed. However, when a microgrid becomes islanded, frequency variations can become more critical due to less stiff generating sources in the system, and subsequently should be closely monitored.

- Transients: During configuration and operating mode changes, transients may occur. They should be captured and analyzed for any potential root cause analyses.

- Voltage sags and swells are major causes of unplanned downtime in both traditional networks and in microgrids. Sags and swells should be monitored, recorded, and localized through adequate monitoring functions, such as disturbance direction detection features.

Figure 3

Power quality measurements are key to assure microgrid control, reliability, and standard compliance

Power Quality Advisor

LAST 24 HOURS   LAST 7 DAYS   **LAST 30 DAYS**   LAST 12 MONTHS   CORRECTIVE EQUIPMENT STATUS

Interruptions — Power Quality Event	Voltage Sag — Power Quality Event	Capacitor Banks — Corrective Equipment
Transient Voltage — Power Quality Event	Voltage Swell — Power Quality Event	Active Harmonic Filters — Corrective Equipment
Over Voltage — Power Quality Event	Under Voltage — Power Quality Event	UPS — Corrective Equipment
Unbalance — Steady State Disturbance	Harmonics — Steady State Disturbance	
Frequency Variation — Steady State Disturbance	Flicker — Steady State Disturbance	

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Controlling DERs

Energy reliability is not primarily in the hands of DERs, but relies most of the time on the linkage between the energy sources, storage, and the grid. DERs need to cooperate in a reliable way to maintain stable frequency and voltage. This is inherent for islanded microgrids, and becomes a requirement for connected microgrids when supporting main grid stability.

Power control for stability

A stable power system has to be robust against non-controllable transients arising from short circuits, motor starts, load changes, or any distribution grid failures or outages. For this power system, it means a very fast response time. Maintaining microgrid stability therefore starts with understanding the way DERs interact naturally with each other, looking at their reflex behaviors resulting from fast internal controls.

Traditional generators made of synchronous machines are naturally grid-forming. It is a proven generation system to provide frequency and voltage stability, even during transients at the grid level. This is thanks to a mix of physical properties and control logic. Indeed, the rotating inertia and magnetic design of the synchronous machines offers them a natural ability to form the grid and share the effort properly (i.e., maintaining synchronism) with other parallel voltage sources when facing grid transients. This is accomplished through speed and voltage control loops that can automatically adjust the generators' power by using the droop function.

Most DERs use inverters to connect to the grid (solar PV, wind, batteries, fuel cells, etc.). Today, the most common internal control of those inverters is called "grid-tie," meaning that it relies on other generators to create the grid voltage and stabilize the frequency. This scheme is adopted to provide active and reactive power to the main grid, or in microgrids with low renewable penetration. But this grid-tie mode becomes insufficient if we want to create a power system using a majority of inverter-based generators, first and foremost, because they simply cannot rely on themselves to form the grid voltage.

Unlike with synchronous machines, we face new challenges when we want to use those inverters as "grid-forming" DERs, capable of operating in parallel with other grid-forming units. This becomes especially difficult when mixing inverter-based renewable generation with traditional generators. On top of the intermittency associated with renewable energies, inverters do not have the natural inertial link between rotational speed and grid frequency. Along with offering little overcurrent capability, inverter control loops are very fast as compared to rotating machines. This fast response time usually make them react before the rotating machine regulations, which may lead to issues like current saturation, loss of synchronism, and eventually disconnection. That is why robust IBG control loop design is one of the main challenges in order to ensure the stability of microgrids.

Recently introduced inverters are able to provide real DER grid-forming functionalities, capable of maintaining stable power systems while operating in a stand-alone mode or in a parallel mode with other sources, including traditional generators.

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Innovative concepts using Inverter-Based Generators (IBGs) can help overcome the previously mentioned stability challenges. Those inverter-based generators are usually composed of:

- A renewable DER (e.g., PV panel, wind or hydro turbine)
- An electronic-based inverter that embeds advanced voltage and frequency control loops
- An energy source called power storage, used to decouple the instantaneous renewable power generation from the actual load demand, and thus to smooth the renewable variability

Combining such IBGs alongside traditional generators will help tackle most of the issues related to microgrid transient stability.
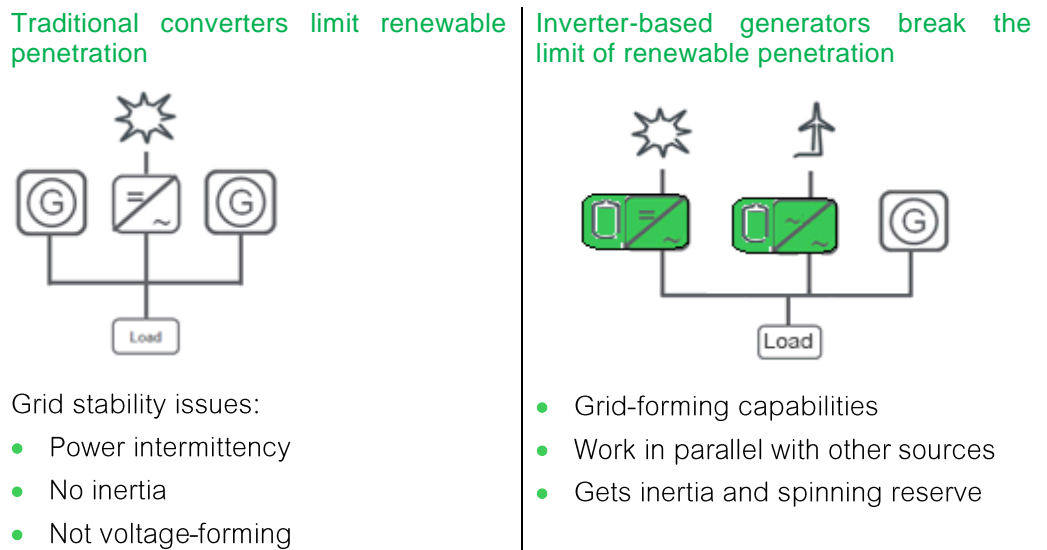
For example, the Virtual Synchronous Generator (VSG) concept uses a comprehensive model that mimics the physical behavior of a real machine and benefits from its natural grid-forming properties. Association with power storage enables VSGs to provide the "spinning-like" reserve necessary to ensure microgrid stability. Such VSGs could be implemented with an existing electrical architecture and existing control strategies.

To ensure long-term power stability and availability, IBGs also need to be controlled by specific power management algorithms. These "secondary" regulations are responsible for balancing power between DERs (such as the power sharing modules commonly used in traditional generator plants). Moreover, these regulations will be capable of maintaining adequate level of power storage while turning off some fuel-based generators.

This new capability allows for the wide adoption and increased integration of renewable energies, from basic "solar + PV-diesel" hybrid generation architectures offering lower fuel consumption, up to microgrids capable of zero emissions and based on storage-coupled, renewable DERs.

Figure 4

Traditional converters vs. inverter-based generators

Traditional converters limit renewable penetration

Grid stability issues:
- Power intermittency
- No inertia
- Not voltage-forming

Inverter-based generators break the limit of renewable penetration

- Grid-forming capabilities
- Work in parallel with other sources
- Gets inertia and spinning reserve

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Optimizing energy flows

Energy control for optimization

The microgrid controller is responsible for overall system operation. This coordination layer manages the local generation and storage capabilities, load management, and grid services in order to reach the expected goals related to energy costs, CO2 emissions, and reliability.

Consider one example that illustrates energy optimization and what it means in practice:

> A higher education campus building is supplied by a microgrid with solar PV, Combined Heat and Power (CHP) generation, and energy storage. The weather forecast predicts high sun radiance for the afternoon, the gas provider schedules an elevated tariff after 2 pm, and it's Friday, when people will typically leave work before 6pm. The microgrid controller can decide to use the CHP generator at max power to recharge the batteries and warm up the educational buildings until 2 pm. Then it will shut off the CHP and run on battery plus solar PV for the rest of the afternoon, having enough energy to supply the predicted average load and, according to the buildings' thermal behavior, slowly decrease the temperature to its acceptable minimum by 6:30 pm.

System optimization involves cloud-based analytics coordinated with an advanced microgrid controller. Data acquisition and situational intelligence are used to provide automatic forecasting and asset scheduling to meet operational objectives within defined constraints. The operating environment for microgrids can change based upon events such as severe weather, unresponsive equipment, unexpected islanding, system reconfiguration, or significant load changes. This is why microgrid analytics and control systems need to be dynamic and autonomous to reconfigure the system settings and algorithms to provide the most beneficial configuration.

There are several technical solutions to implement an effective microgrid controller:

- The most straightforward solution uses a central controller that gathers operating information, interacts directly with the SCADA or cloud services to run the optimization algorithms, and then deploys the selected strategy to the different connected assets. Today, this is typically accomplished with microgrid controllers, which have the advantage of being able to manage logical inputs/outputs and interface with the usual field networks such as Modbus. But this often ends up with a specifically engineered solution developed for a single project.

- A second solution is to implement a distributed microgrid controller. This means that every 'actor' participates in the system optimization and cooperates directly with its peers. Interestingly, this has become a typical solution for genset control manufacturers with distributed intelligence wherein each genset autonomously engages along with other actors according to the grid situation. Distributed control may be more challenging to implement, but offers several advantages:
  - o It provides natural redundancy and plug-and-play behavior, thus improving reliability and scalability
  - o It increases local operation performance thanks to edge optimization intelligence
  - o It drives the consolidation of data formats and exchange protocols used for system optimization.

- Alternatively, a mix of the two solutions above can be implemented. For example, in the case of a multi-facility microgrid, it makes sense to mix single-facility microgrid controllers (centralized operation) with a distributed approach for the multi-facility microgrid system coordination.

Figure 5

Centralized vs. distributed microgrid controller architectures
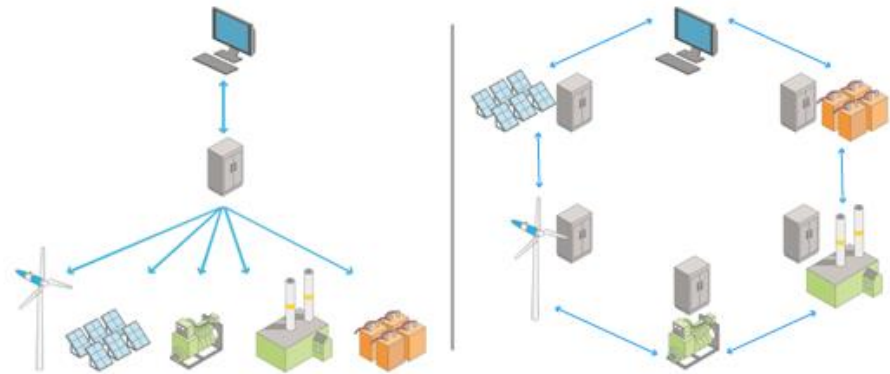
Conclusion

Major technical advances over the past decade have enabled the emergence of microgrids. Substantial progress in decentralized energy resources such as solar generation and deployable energy storage, along with an operational IoT environment, is providing new cooperation and optimization capabilities.

However, implementing these systems presents new and specific problems:

1. Ensuring the cooperation of distributed energy resources toward a shared objective requires multiple control layers.
2. Calculating strategies to optimally operate and manage the microgrid depends on data and monitoring systems throughout the network.
3. Technical constraints regarding bidirectional power flow demands improved renewable energy inverter performance and/or protection system design.

All these technical challenges are currently being solved by innovation and field-proven experience.

✎ About the authors

Véronique Boutin is an engineer from the Ecole Superieure d'Electricite. She wrote her PhD thesis on an experimental project with a thermodynamic solar power plant. At Schneider Electric, she designed numerous automated systems in various industrial contexts. She then focused on innovation and has been involved in several large, cooperative programs such as HOMES, dedicated to energy efficiency in buildings, and Arrowhead, dedicated to cooperative automation for industry, buildings, and infrastructures. She is part of the Analytics, Applications & Programs team, where she is in charge of Proof-of-Concept demonstrations.

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Yann Herriot leads an innovation project on microgrids at Schneider Electric's Corporate Research Center. He holds master's degrees in electrical engineering and automation from the ENSEEIHT school of engineering. His work experience has been focused on growing expertise in the power conversion domain, and is now extended to microgrid and distributed energy in general.

Andy Haun is Chief Technology Officer for the Microgrid Systems in North America. He is responsible for driving technology roadmaps necessary to create offer portfolios that simplify and enable the deployment of effective grid-edge solutions. Beginning with Square D Company in 1985, Andy has led a variety of key product development and technical innovations as well as R&D leadership positions during his 30+ year tenure with Schneider Electric. He has a Bachelor's Degree in Electrical Engineering from the University of Iowa and an MBA from Duke University.

Van Wagner, P.E. is a Power Systems Engineer for Schneider Electric Engineering Services, located in Troy, Michigan. He is responsible for power system design, analyses, troubleshooting, power quality studies and training nationally. Van received his MSEE and BSEE from the University of Michigan and Michigan State University, respectively. He is the former chair of IEEE 1346-1998, Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment. Van is Chapter Chair of the new industrial chapter of the IEEE 1100 "Emerald Book," Recommended Practice for Wiring and Grounding Electronic Equipment. He is a registered Professional Engineer in the State of Michigan.