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Building Resilient Integrated Grids

One neighborhood at a time.

THE MICROGRID, AS DEFINED BY THE U.S. Department of Energy, is "a group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the electric utility grid." DERs consist of distributed generation (DG) and distributed energy storage (DES) installed at utility facilities, e.g., distribution substations, DG sites, or consumer premises. A microgrid must have three distinct characteristics: 1) the electrical boundaries must be clearly defined, 2) there must be control systems in place to dispatch DERs in a coordinated fashion and maintain voltage and frequency within acceptable limits, and 3) the aggregated installed capacity of DERs and controllable loads must be adequate to reliably supply the critical demand. The microgrids may be operated in two modes:

1) *Interconnected to the grid*: under this mode, the microgrid can import, export, or have zero power exchange with the grid. This type of operation is generally designed for normal conditions (no system contingencies), and its objective is to improve grid performance and efficiency by using local DERs, e.g., to defer capacity investments, reduce system losses, and improve local reliability.
2) *Disconnected from the grid*: under this mode, the microgrid is allowed to operate islanded from the grid; this is also commonly known as intentional islanding. This type of operation requires the DERs within the microgrid to be dispatched in a coordinated fashion to provide voltage and frequency regulation. Successful islanded operation may also entail the implementation of energy demand management, e.g., demand response or curtailment, to achieve generation-load balance. This type of operation is generally intended to provide service to remote locations (permanent islanded operation) or to provide continuous supply during contingencies (temporary islanded operation). In the latter case, the microgrid is expected to return to interconnected operation once the contingency has been addressed.

A variety of applications have been identified for microgrids. The very first modern microgrids were deployed in university campuses, conceivably due to the availability of funding for research initiatives and internal expertise in engineering and science. Microgrid deployment is becoming an increasingly attractive solution for commercial and industrial consumers who require premium reliability and power quality levels and/or are interested in pursuing economic benefits from the strategic dispatch of their DERs, e.g., consumers who want to take advantage of available incentives and use idle capacity from backup generation to export power to the grid.

Moreover, there are growing numbers of microgrid deployments in remote locations since they can be a more efficient and viable solution to provide electric service than upgrading or building transmission and distribution (T&D) facilities. For instance, the microgrids can be operated in interconnected mode to provide peak shaving and defer capacity investments otherwise needed in remote locations, or they can be operated in islanded mode and used to supply service to isolated areas. The latter approach has been used extensively to provide service to remote rural areas, traditionally via conventional generation (e.g., reciprocating engines and small hydrogeneration), and more recently via combined dispatch of conventional and renewable DGs. Military

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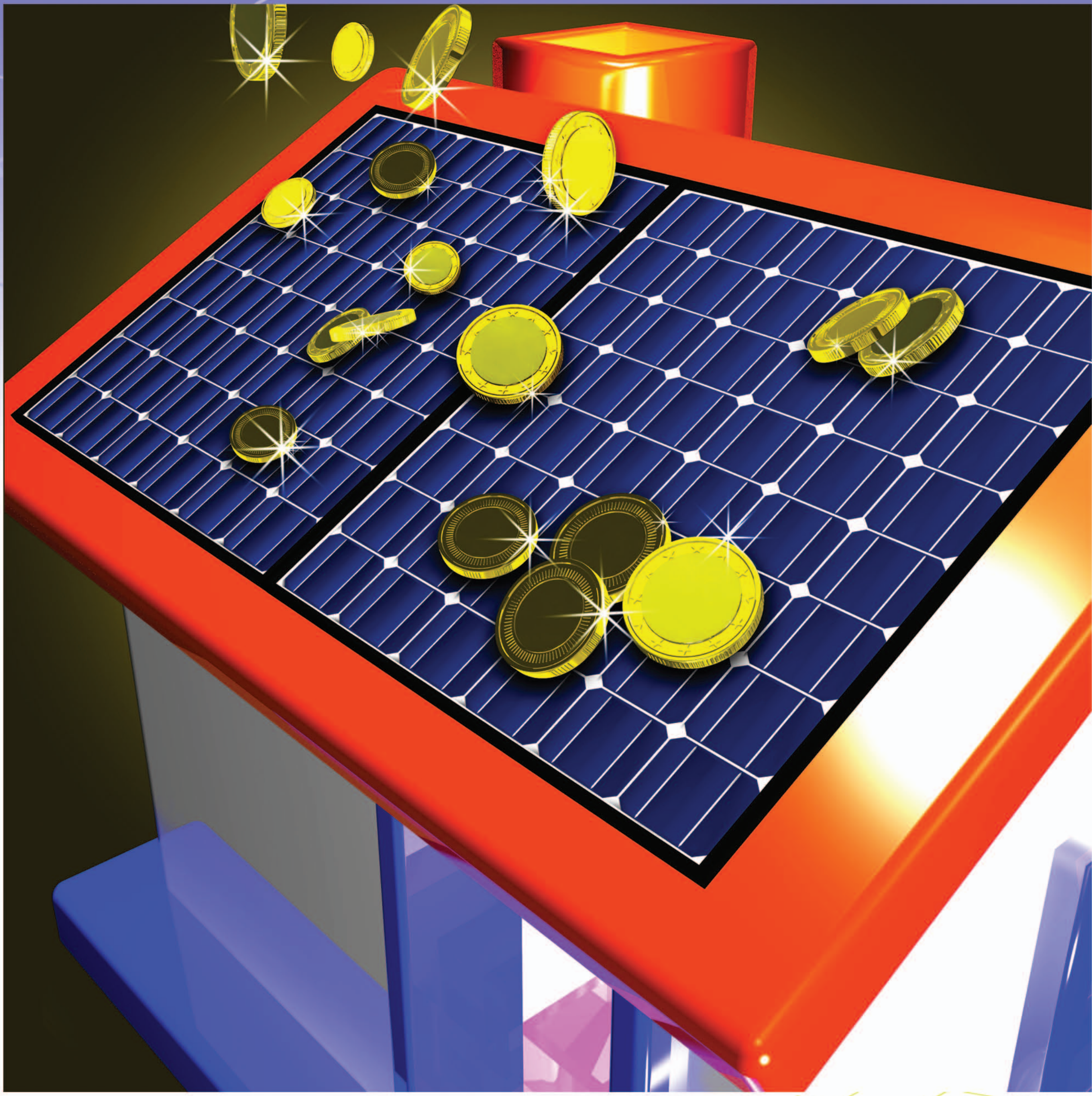

IMAGE LICENSED BY GRAPHIC STOCK

microgrids have also received increased attention in recent years, primarily due to support provided by the U.S. Department of Defense. Military microgrids consist of self-sustaining small power grids, which are required to address the mission-critical energy needs of military bases.

More recently, community microgrids have emerged as an alternative to address the rising societal demands for electric infrastructures that are able to provide premium reliability and power quality levels while being economical and environmentally friendly. Community microgrids aim primarily at supplying electricity to a group of consumers in a neighborhood or several connected neighborhoods in close proximity (Figure 1). Despite extensive studies on microgrids, very little literature is dedicated to community microgrids. This article discusses community microgrids and elaborates on the different components and anticipated outcomes of these viable deployments.

Why Community Microgrids?

Community microgrids are emerging as a potential solution to address the following trends: 1) residential consumers, who use more than one third of the electric energy produced in the United States, are demanding higher levels of reliability and power quality, 2) the utility grids are experiencing an unprecedented proliferation of intermittent renewable DG, which is motivated by the availability of attractive incentives and regulations

Figure 1. Community microgrids aim primarily at supplying electricity to a group of consumers in a neighborhood or several connected neighborhoods in close proximity.

designed to address socioeconomic and environmental concerns, 3) the commercial and industrial consumers' needs for high reliability and quality premium power is growing due to dependence on sensitive loads, and 4) society is demanding more resilient power delivery infrastructures due to the growing dependence on electric service for vital activities such as transportation, e.g., the emergence of plug-in electric vehicles, and the well-documented grid vulnerability issues exposed by recent natural phenomena such as Hurricane Sandy.

The transition from the conventional utility grid to the smart community microgrids and the enhanced utilization of DER and controllable loads are anticipated to extensively change the way the communities use electricity by increasing energy efficiency, enhancing conservation levels, and reducing greenhouse gas emissions, while lowering the stress level on congested T&D lines. Several obstacles, however, exist in the rapid and widespread deployment of community microgrids, including the high capital cost of microgrid deployment, the lack of consumer knowledge on potential impacts of DG and load scheduling strategies, and particularly ownership and regulatory issues.

Figure 2. Smart metering is one of the major enablers of energy management for buildings.

Microgrid developers must convince consumers that the benefits of the microgrid exceed the capital costs. The microgrid benefits must be scrutinized and compared with the microgrid capital cost for ensuring a complete return on investment to further justify the microgrid deployments. An accurate assessment of the microgrid's economic benefits is a challenging task because of the significant data uncertainty involved in the assessment. Moreover, some of the assessment results such as reliability improvements are difficult to comprehend for consumers when represented in supply availability terms. Thus, efficient planning models are required to ensure the economic viability of microgrid deployments and further justify investments based on cost-benefit analyses under uncertain conditions.

The second obstacle persists as long as consumers do not have a keen knowledge of load scheduling strategies or are not willing to contribute to energy management efforts in the microgrids. This obstacle could be removed by educating the microgrid consumers about the anticipated benefits. The financial incentives offered to consumers, who would consider load scheduling strategies, is the most powerful driver for performing load scheduling. Furthermore, the emergence of smart metering as well as state-of-the-art devices and building management systems have helped reduce this barrier (Figure 2). Proper scheduling and data acquisition tools are available to advise consumers and perform load scheduling autonomously with minimal consumer intervention. These tools may be used by a building energy management system to optimally schedule and coordinate loads.

Regulatory issues must be solved before planning a community microgrid deployment. Currently, there are several regulatory aspects that are still unresolved, including microgrid ownership, third-party generation participation, investment recovery, and inclusion in the utility rate case. As these challenges are being addressed, a more widespread deployment of community microgrids will be witnessed in power systems to the point that these smart communities may act as a core component of future power systems.

Benefits of Community Microgrids

Community microgrids introduce unique opportunities for consumers and for the operation and planning of the power system, as outlined in the following sections.

Security

Perhaps the most prominent benefit of community microgrids is the improved security as they could potentially mitigate the impacts of physical and cyberthreats. The community microgrids increase security of power delivery to critical facilities, such as hospitals, emergency response centers, water stations, transportation systems, food banks, and shelters within the electrical boundaries. These facilities can provide secure oases in the event of catastrophic disturbances to the utility grid. The secured electric supply is enabled by operation in the islanded mode in case of physical damage to the utility grid. The islanded operation, enabled by on-site generation, allows for the microgrid to maintain continuous supply to mission-critical loads during major grid disturbances (Figure 3). In addition to physical security, microgrids enhance the cybersecurity aspects of the distribution system. By sectionalizing power delivery into smaller segments and localized distributed control, microgrids can limit the impacts of cyberattacks. The impacts could be experienced in specific areas instead of causing a widespread circulation to all grid operations. Community microgrids also provide protection in numbers. As the microgrids are distributed throughout the power grid, they are not likely to be targeted at once, hence improving cybersecurity.

Resiliency

Resiliency improvement is observed as a complementary value proposition of microgrids. Resiliency refers to the capability of power systems to withstand low-probability, high-impact events by minimizing possible power outages and quickly returning to normal operating state. These events typically include extreme weather events and natural disasters such as hurricanes, tornados, earthquakes, snowstorms, floods, and cyber- and physical security attacks, and terrorism. Recurring and seemingly increasing intense seasonal storms, which many utilities are facing every year, could also be included among these events. The recent hurricanes in the United States as well as a documented attack on a California substation and the potentially significant social disruptions have spawned a great deal of discussion in the power and energy industry about the value and application of microgrids. If the power system is impacted by these events and critical components are severely damaged, e.g., generating facilities and/or T&D infrastructures, service may be disrupted for days or even weeks. The impact of these events on consumers could be minimized by the deployment of community microgrids, which allow the local supply of loads even when the supply of power from the utility grid is not available.

Reliability

One of the most important benefits of community microgrids is to improve consumers' supply reliability. Electric utilities constantly monitor consumers' reliability levels and perform required system upgrades to improve supply availability and to reach or maintain desired performance. Consumer reliability is typically evaluated in terms of system/customer average interruption frequency/duration indices (e.g., SAIFI, SAIDI, CAIDI, CAIFI, etc.—see IEEE 1366–2012, *IEEE Guide for Electric Power Distribution Reliability Indices*). Outage causes, such as storms and equipment failure, impact reliability levels by increasing the average frequency and duration of interruptions; however, when a community microgrid is deployed, these metrics can be significantly improved. This is due to the intrinsic intelligence (control and automation systems) of community microgrids and the utilization of DERs that allow islanded operation from the grid. Since generation in community microgrids is located in close proximity to consumer loads, it is less prone to being affected by T&D grid disturbances and infrastructure issues. Additional flexibility to provide service under these conditions is provided by the ability to adjust loads (e.g., demand response) via building and/or microgrid master controllers. Improved reliability can be translated into economic benefits for consumers and utility due to a reduction in interruptions, costs, and energy not supplied. The magnitude of these benefits is dependent upon load criticality and the value of lost load as well as the availability of other alternatives such as backup generation or automatic load transfer trips.

Emission Reduction

Community microgrids could be accredited as rapid enablers of renewable energy integration to distribution networks. Renewable energy resources may cause significant

Figure 3. Community microgrids improve security by mitigating the impacts of physical and cyberthreats.

technical challenges when integrated to a distribution network as they produce a variable amount of energy. Seamless integration of these resources may only be accomplished through the implementation of mitigation measures. Utilities may need to upgrade their distribution network, use advanced volt-var control practices, smart inverters, or energy storage to address the rapid deployment of renewable energy resources. Community microgrids use the coordinated control of a combination of dispatchable DGs, DES, and controllable loads to "smooth down" the intermittent output of renewable energy resources. This allows for increased penetration of renewable energy and diversification of resources, enables utilities to meet the goals set by the Renewable Portfolio Standards, and helps reduce greenhouse gas emissions (Figure 4).

Reduced Costs of Recurring System Upgrades

As the demand for electricity increases, today's power system must be reinforced by the addition of new generation, transmission, and distribution facilities. Community microgrids deploy DERs to supply local loads, including conventional and renewable DGs and DES, and implement load control to facilitate local grid management. Therefore, while operating in interconnected mode, the additional generating capacity from community microgrids decreases the average and peak T&D system loading, effectively deferring capacity increase or generation investments. This benefit, however, is contingent upon a large penetration of microgrids in distribution networks, which could accordingly contribute to mitigate T&D congestion issues. Community microgrids can also provide utilities with additional operational flexibility (increased reserve) to handle load transfers during restoration or system reconfiguration. These technical and economic aspects need to be carefully evaluated when considering microgrid deployment as part of system expansion plans, along with investments in conventional T&D and generation infrastructures.

Energy Efficiency

Community microgrids could help improve overall energy efficiency by reducing T&D losses and allowing the implementation of optimal load control and resource dispatch. The former is a direct consequence of supplying consumer loads with local generating facilities, and the latter can be accomplished by intelligent control and dispatch of consumer loads. For instance, the microgrid controller could interact with consumer controllers to curtail or dispatch loads to accomplish the overall system efficiency goals. Similarly, this objective could be adjusted to respond to the real-time price, operational security, power quality, or reliability signals. Evidently, this requires having the adequate regulatory framework and consumer incentives in place.

Figure 4. Community microgrids enable the integration of renewable energy resources to distribution networks for reaching environmental targets.

Power Quality

Consumers' needs for higher power quality have significantly increased during the past decade due to the growing application of voltage-sensitive loads, including a large number and variety of electronic loads and light-emitting diodes. Utilities are always seeking efficient ways of improving power quality issues by addressing prevailing concerns stemmed from harmonics and voltage. Community microgrids provide a quick and efficient answer for addressing power quality needs by enabling local control of the frequency, voltage, and load, and a rapid response from the DES.

Lowered Energy Costs

Financial incentives offered to consumers within a community microgrid who would consider load scheduling strategies according to electricity prices and benefit from locally generated power is a significant driver in the economic deployment of a microgrid. Although it is still more economical to purchase power from the utility, microgrids could provide benefits by reducing T&D costs. The reduced energy costs would impact each individual consumer within the community microgrid. However, the microgrid local generation not only has the potential to lower energy costs for local consumers (which will be more significant as DG technologies become less expensive) but it could also potentially benefit the entire system by reducing the T&D networks' congestion levels (when the community microgrids penetration is high) and enabling a more economic dispatch of available energy resources in the utility grid.

Community Microgrid Deployment

Components

The main microgrid components include loads, local DGs, DES, smart switches and protective devices, communication, control and automation systems, and a master controller.

Microgrid loads are categorized into two types—fixed and adjustable. The fixed loads cannot be altered and must be satisfied under normal operating conditions. The adjustable loads, however, are responsive to controlling signals from a local controller or the microgrid master controller. The adjustable loads could be curtailed (i.e., curtailable loads) or deferred (i.e., shiftable loads) in response to economic incentives or islanding requirements. Community microgrid loads could also be categorized into two types—individual loads and communal (shared) loads, such as street lights. The total load is defined as the community-aggregated load. The DGs in a community microgrid are either dispatchable or nondispatchable. The dispatchable units can be controlled by the microgrid master controller and are subject to technical constraints depending on the type of unit, such as capacity limits, ramping limits, minimum on/off time limits, and fuel and emission limits. The nondispatchable units, on the contrary, cannot be controlled by the microgrid master controller since the input source is uncontrollable. The nondispatchable units are mainly renewable energy resources, typically solar and wind, which produce a volatile and intermittent output power. The intermittency indicates that the generation is not always available and the volatility indicates that the generation is fluctuating in different timescales. These characteristics negatively impact the nondispatchable unit generation and increase the forecast error; therefore, these units are commonly reinforced with DES. The primary application of DES is to coordinate with DGs to guarantee the microgrid generation adequacy. They can also be used for energy arbitrage, where the stored energy at low-price hours is generated back to the microgrid when the market price is high. This action is analogous to shifting the load from high-price hours to low-price hours. The DES also plays a major role in microgrid islanding applications. The microgrid community-aggregated load minus the local generation from DGs and DES could be identified as the utility load, i.e., the amount of load that should be supplied by the utility grid.

Smart switches and protective devices manage the connection between DERs and loads in the microgrid by connecting/disconnecting line flows. When there is a fault in part of the microgrid, smart switches and protective devices disconnect the problem area and reroute the power to other loads, preventing the fault from propagating in the microgrid. The switch at the point of common coupling performs microgrid islanding by disconnecting the microgrid from the utility grid.

The microgrid scheduling in interconnected and islanded modes is performed by the microgrid master controller based on economic and security considerations. The master controller determines the microgrid interaction with the utility grid, the decision to switch between interconnected and islanded modes, and the optimal operation of local resources. It also controls and maintains the frequency and voltages within permissible ranges. Communications, control, and automation systems are used to implement these control actions and to ensure constant, effective, and reliable interaction among microgrid components.

Architecture

The common microgrid control architectures are either centralized or distributed. The centralized model collects all of the required information for the microgrid operation and performs centralized control. In the distributed model, however, each component is considered an agent with the ability for discrete decision making. The optimal schedule is obtained using iterative data transfers among the agents. Both control schemes offer benefits and drawbacks, but the centralized model is emerging as a more desirable approach as it ensures a secure microgrid operation and is more suitable for the application of optimization techniques. The main drawbacks of the centralized scheme are reduced flexibility in adding new components and extensive computational requirements.

In community microgrids, a hybrid model, which benefits from both centralized and distributed models, is expected to be adopted. Three levels of control can be identified for the microgrid, i.e., the device level, the building (or consumer) level, and the microgrid level. Adjustable loads would provide the first level of control. These loads would receive real-time electricity prices from the building controller as well as scheduling time interval, including operation start and end times, from the consumer. Once the time interval is set, the adjustable load would autonomously start and complete the operation cycle. Adjustable loads are important components of a community microgrid, which will offer load management capabilities. Examples of these loads for residential consumers are washers, dryers, dishwashers, and pool pumps.

The second level of control will be performed in the building. The building controller would coordinate the schedule of adjustable loads and the DES. If the building already includes backup generation, which is the case for critical loads, the building controller would also control and operate the backup generation. A building controller is an intermediate controller between adjustable loads and the microgrid master controller. Building controllers act as agents that schedule their own loads while at the same time communicating with the microgrid master controller to reach the overall community microgrid goals. (Facilities with several buildings that are themselves part of a larger community microgrid may include an additional control layer between the master and individual building controllers. The objective of this facility controller is to coordinate the dispatch of loads and DERs within its own service boundaries.)

The last level of control, which monitors and controls the entire microgrid, is the microgrid master controller. As mentioned, the microgrid interaction with the utility grid (i.e., the amount of power to be purchased/sold to the utility grid), the decision to switch to islanded mode (in the case of upstream network faults or voltage variations), and optimal operation of local resources (including load schedules received from the buildings, dispatchable DGs, and DES) will be performed by the microgrid master controller. It also controls and maintains the frequency and voltages within permissible ranges. The ultimate operational objective of the controller is to optimally schedule loads to maximize the utilization of local resources, manage power transfer with the utility grid, and minimize the community-aggregated electricity payment considering the convenience of individual consumers and hourly community load characteristics, which will be done through interactions among these three control levels.

Community Microgrid Deployment Phases

To build a community microgrid, several steps need to be performed. The following is a high-level plan including the major steps for deploying a community microgrid.

Site Selection

Site selection is perhaps the most important step in building a community microgrid. Although any neighborhood could be considered for a microgrid deployment, some offer additional benefits or appear as more critical than others. The important factors in site selection are electrical location, load criticality, existing generation resources or availability of primary (renewable) resources, available footprint, condition of T&D assets and available system capacity, and availability of communications, control, and automation systems. The electrical location of a microgrid within a power system would determine the impact of the microgrid on the utility grid by supplying additional generation to the network and enabling a reliable supply of loads in connected neighborhoods. Moreover, if properly located, a high penetration of community microgrids could potentially impact T&D network congestion levels, by reducing load at congested hours, and benefit the entire power system by enabling the flow of power from more economical units. Load criticality is another important factor in the microgrid site selection. Different loads in a neighborhood are associated with different importance levels, in which load curtailments for extended amounts of time are not acceptable for some of the loads. The examples include police stations, gas stations, hospitals, and nursing homes. Although these loads are typically reinforced by a backup DG to supply loads in case of utility grid power interruptions, the backup power cannot be employed for an extended period of time and also would partially supply the critical loads. The available footprint determines the DER generation mix, which could be deployed in the microgrid. If the community microgrid is planned to be built in a densely populated area where there is not enough space available to build combined heat and power plants or wind turbines, the planner must seek other alternatives with smaller footprints such as fuel cells and rooftop solar photovoltaics (Figure 5). The change in the DER generation mix could significantly impact the microgrid deployment capital cost and alter the rate of return on investment.

Figure 5. Rooftop solar photovoltaic panels are viable DG candidates for community microgrids.

Integration of the Building Management System

Buildings play a major role in community microgrids by controlling local loads and trading information with the master controller for a better management of the microgrid. Buildings, however, must be equipped with building management systems. Adjustable loads within a building would respond to price signals and autonomously operate. The schedule of these loads, however, is coordinated by the building DERs via a building master controller and based on the signals from the microgrid master controller. In other words, the building controller provides an intermediate controller between the microgrid controller and the loads. The interaction among multiple building controllers is performed via a centralized control by the master controller. Consumers would define their criteria for operating specific loads by considering the cycle duration and other characteristics of individual loads.

Determination of DER Generation Mix

A major obstacle in a rapid deployment of community microgrids is the high capital investment cost of DERs. DERs could provide a low-cost supply of energy, particularly at times of T&D network congestion when real-time electricity prices are high. The high capital cost, however, may prevent planners from deploying a microgrid. To determine the economic viability of microgrid deployment, and accordingly determine the optimal DER generation mix, a long-term microgrid planning study should be performed. The planning study must capture all value streams, such as cost, reliability, environmental impacts, and ancillary service payments, to justify the microgrid investment cost. Uncertain data must be considered in this study, including but not limited to forecast errors in loads, variable renewable generation, and market prices. Islanding incidents could be further considered as uncertain data with a high impact on deployment decisions.

Distribution Network Upgrade

Many distribution systems provide a radial supply of loads, i.e., loads are supplied only from one distribution line. In microgrids, however, to improve the reliability of the distribution network and prevent undesired supply interruption, the distribution network is upgraded to create a loop. In this fashion, each load is supplied from more than one direction. If the supply of power is interrupted from one side, it would be available from the other side. It would be left to the microgrid planner's discretion what loads would be provided with a loop supply based on the load criticality. Moreover, the switches in the distribution network are replaced with fast-response, high-reliability, communication-enabled switches. These switches talk to each other in case of system faults and intelligently disconnect the faulted area and reroute the power to minimize fault impacts on other parts of the microgrid. The interconnection to the utility grid should also be provided with a switch at the point of common coupling to receive islanding commands from the master controller and disconnect the microgrid from the utility grid if necessary.

Master Controller Deployment

The master controller is the brain of the microgrid. The microgrid scheduling in interconnected and islanded modes is performed by the microgrid master controller based on economic and security considerations. The master controller determines the microgrid's interaction with the utility grid, the decision to switch between interconnected and islanded modes, and optimal operation of DERs and loads. The microgrid master controller receives information from the building controllers and accordingly schedules available resources. It also sends price signals to buildings for load management purposes. The primary operational objective of the microgrid master controller is to maximize consumer benefits, i.e., minimize electricity payments, without any consumer interactions or compromising adjustable loads performances. The microgrid master controller could use a centralized control of loads via a direct load control, in which loads are directly controlled by the master controller, or a decentralized control of loads, in which loads are scheduled within each building and the resultant aggregated consumption pattern is sent to the master controller.

Communication System Deployment

Under the concept of smart grids, communication systems are being integrated with power systems more than ever. It is not different for community microgrids. Community microgrids need to install proper communication systems across the microgrid to connect a variety of microgrid players together and enable rapid and reliable data transfer among adjustable loads, building controllers, and microgrid controllers. Moreover, DERs must be equipped with communication systems to enable real-time monitoring and control and facilitate load management plans.

Conclusion

Community microgrids, which aim primarily at supplying electricity for a group of consumers in a neighborhood or several connected neighborhoods in close proximity, have emerged as an alternative to address the rising societal demands for electric infrastructures that are able to provide premium reliability and power quality levels while being economical and environmentally friendly. Community microgrids were discussed in this article, and different components and anticipated outcomes were elaborated upon. The studies advocated that community microgrids be deliberated as viable solutions to the pressing challenges of economy, reliability, and environment while providing unprecedented benefits for local consumers as well as the power system as a whole. Community microgrids would be built upon the existing utility distribution network; hence, these deployments would not be successful unless fully supported by utility companies. As this technology becomes more viable and advantageous, greater involvement of utility companies would be needed to ensure sustainable deployment to the point that utilities could ensure the benefits and become promoters of community microgrids. Commonwealth Edison (ComEd), the electric utility company in the greater Chicago area, was recently awarded a grant from the U.S. Department of Energy to develop a microgrid master controller with applications to community microgrids. A selected group of leading authorities from manufacturers, consulting firms, software developers, universities, and national labs active in the power and energy industry will be led by ComEd in this effort. This effort not only provides ComEd with an invaluable experience in transforming the traditional way of electricity supply and delivery and gaining first-hand knowledge on future integrated grids but also paves the way for other utilities that understand the urge to adopt new business models and are ready to embrace changes.

Disclaimer

The opinions expressed are solely those of the authors and do not necessarily reflect the positions or opinions of any entity or organization with which any of the authors may be affiliated.

For Further Reading

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