Intelligent microgrids

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Abstract:	

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What are microgrids?

Microgrids are electrically- and geographically-small electric power systems capable of operating connected to or islanded from a larger terrestrial grid. Electrically small refers to the amount of installed generation capacity (typically less than 50 MW) and its voltage level (kV or less). Geographically small refers to the spatial dimensions of a microgrid, which can range from a personal office to an entire residential community.

There are a variety of reasons for the establishment of microgrids. For example, a facility with a very large set of dc loads may find it more reliable and efficient to establish a dc microgrid to service those loads rather than serving each independently from an ac source. A second reason for a microgrid may be provided by the difficulty in finding appropriate locations for large power plants and or transmission grids like those that exist today. A microgrid can facilitate either putting the appropriately sized generation near loads or locating loads closer to existing generation plants, reducing the need for the more extensive infrastructure and possibly enhancing energy security.

By far the most flexible trait of microgrids is their islanding capability, which allows them to separate from their larger (parent) power system and convert to an independent "micro" power system. This flexible trait is also an inflexible exigency that requires microgrids to be energy independent to support their loads for an intended period—from hours to months—depending on the microgrid type. Although microgrids can be as small as a single generator connected to a load, today they are commonly incorporated into facilities such as data centers, office buildings, hospitals, submarines, ships, university campuses, and military installations.

Introduction

Microgrids are considered intelligent when their operation is computer controlled so they can adapt to changing conditions autonomously. This requires significant intelligent control, sensors, and automation. Examples of intelligent control include fault mitigation and automatic topology reconfiguration. Faults are detrimental and unintentional interruptions in electrical supply. Intelligent microgrids not only detect and isolate faults on their own, but also reroute power from an alternate source to maintain service continuity. Topology reconfiguration can be used to reduce distribution losses, but also to reduce vulnerability to external attacks. These control actions are automated, but may also need occasional human intervention. For example, outages that cannot be fixed automatically must be repaired by a maintenance crew.

The distribution of electric power in grids is changing. An emerging trait is the penetration of renewable energy at distribution-level voltages (typically below 35 kV). One important factor stimulating this change is distributed generation such as solar panels. This type of generation produces desirable bidirectional power flows in a microgrid, but also provides challenges and new incentives to the design of electrical power distribution.

Due to the islanding capability of microgrids, an important aspect in electric power distribution is a high level of redundancy. Microgrids near 50 MW can have between two and 10 turbine-generators of various sizes to provide power. This redundancy permits choosing a correct set of generators to efficiently power and support large dynamic loads.

The distribution system may be configured so that important loads (e.g., hospitals, defense systems) can be supplied by either of two paths. This is critical to achieve maximum functionality during unintended outages. In addition, this reconfiguration provides opportunities for routine use of smart optimal control. The same control system, if well designed, can provide a power system configuration that provides maximum efficiency during routine operation and maximum flexibility during emergencies.

Another attribute of intelligent microgrids is that the power system does not have to be designed to supply the maximum of all possible loads. Under a "fiat" control, a microgrid operator can dictate which loads are served to extend survivability. This decision is normally in accordance with a prior determination of which loads are critical for each period of time.

Following are select ongoing research topics in the realm of intelligent microgrids. While the breadth of topics on this subject is large, the topics that follow highlight common automation and self-healing aspects of intelligent microgrids.

Dynamic Balancing

Microgrids are power systems with finite inertia, which makes them susceptible to destabilization and overloads following disturbances. ("Finite inertia" is jargon to indicate that islanded power systems have limited generation and significantly less ability to respond gracefully to abrupt changes in load than interconnected terrestrial power systems do.)

Dynamic balancing is an intelligent control strategy that ensures generation output and controllable-load demand match, while satisfying operational constraints in real time. (The real-time decision time step for finite inertia systems is commonly 10-100 milliseconds.)

Microgrids can incorporate a large number of intermittent energy resources, such as wind and solar. In this configuration, generation capacity varies according to both the weather and the time of day. Moreover, a plug-in electric vehicles (PEVs) are proliferating. When this occurs in an isolated microgrid, charging events risk causing frequency and voltage oscillations.

In addition to these potential sources of destabilization, the transition of a microgrid from grid-connected mode to islanded mode may overload or underload a microgrid's generators. Thus, dynamic balancing is a critical aspect of intelligent microgrids to match generation and load in a system with renewable energy intermittency, high penetration of PEVs, and finite inertia.

When sudden load or generation changes occur in microgrids, dynamic balancing regulates the setpoints of generators or loads to reduce the mismatch during the transient state. This mitigates frequency and voltage oscillations in the system. However, combustion generation units, such as diesel generators and microturbine generators, cannot respond quickly to sudden changes in load. A delayed response can result in significant frequency and voltage oscillations. In this situation, energy storage or additional controllable loads are used to compensate for the generation and load changes in microgrids due to their response times. Energy storage devices commonly used for dynamic balancing include batteries, ultra-capacitors, flywheels, and others. Controllable loads typically used for dynamic balancing include service loads such as washing machines, dryers, air conditioners, heaters, and other large load (PEVs included).

Short Circuit Fault Protection

Short circuits are unwanted contacts between an energized conductor and a return path (e.g., ground, neutral wire, etc.). This condition can produce large currents in a system, be a source of fire, and damage costly equipment. Microgrids operating in island mode have their sources synchronously coupled by electronic power converters, which can limit short-circuit fault currents.

Microgrids with ac and dc power distribution can be supplied from different types of power sources located apart from each another (e.g., solar arrays, fuel cells, wind turbines, etc.). Moreover, energy storage units (e.g., batteries, super capacitors) can also be connected to the distribution grid through electronic power converters. Although these sources can, in principle, source short circuit fault currents, their power electronic converters limit the fault current when compared to the case of conventional all-machine-based power systems.

While microgrids fed from multiple sources provide higher reliability, it can be difficult to isolate the faulted part of the system. However, the tradeoff is that controllable converters can limit fault currents by changing their output setpoints. These considerations bring about innovative fault protection methods to eliminate disruptive currents and provide rapid system reconfiguration.

Notwithstanding the presence of ground returns, terrestrial microgrids depend on a ground (i.e., "earth") path as a return conductor for fault currents. These solidly grounded systems dominate for safety reasons and result in relatively high line-to-ground fault currents which must be interrupted quickly to limit damage to equipment.

Nonetheless, there are certain microgrids that are meant to operate in islanded mode most of the time. Such microgrids can be designed to (intelligently) operate with a single line-to-ground fault, where "ground" in this context refers to an "accidental" common structure (e.g., a chassis) of the power system. This type of operation requires fully ungrounded or high-resistance ground systems, which pose significant challenges with respect to the grounding design and the identification of fault locations.

Load Re-Energization

Reclosers are protective devices that automatically open and reclose a line when a disturbance is sensed. In the case of high-impedance faults on distribution lines (e.g., foreign objects in contact with conductors), many times a reclosing action eliminates the source of the fault.

Reclosers operate in a "single shot" mode across a live and a dead line. If the fault is cleared, the recloser retains its closed position. If not, additional attempts follow until, if the fault does not clear in a preset number of tries, the recloser latches to its open position. This operation, while useful, reduces system reliability and degrades power apparatus due to the high inrush currents pulled by motors and transformers. (The degradation of power apparatus includes domestic electronics such as garage door openers, televisions, and furnace circuit boards to name a few.)

For microgrids in general, switching transients due to asynchronous reclosing on motor residual flux spurs the failure of protective devices and often causes nuisance trips resulting in a failure of the restoration process. Associated with this conventional reclosing action is a delayed voltage-level recovery which complicates the restoration process and may lead to under voltage load shedding. A surrogate example is the restoration of a downstream de-energized load section. Reclosing action from a live to dead wire poses issues such as large inrush currents, downstream motor-torque oscillations, speed droops, and low voltage conditions until the system reaches equilibrium.

Intelligent microgrids favor a more adaptive restoration process such as "soft reclosing". This approach involves load-side energy storage equipped with a ramp-up inverter tied to the distribution lines. Upon detection of grid outage, the inverter starts its operation in islanded mode and supplies the de-energized network portion with a voltage and frequency ramp. Before the ramping action settles, the inverter's output voltage and frequency are matched to a grid voltage-and-frequency reference signal that is available via a remote communication link. After the ramping settles, the energy storage system supports the load for a certain length of time, but expects the utility to recover or supplementary power sources within the microgrid to come online before the stored energy is fully consumed.

When the grid recovers from the disturbance, reconnection of the disconnected network (powered from the stored energy source) and the grid takes place. During this live-to-live wire reconnection, the aforementioned issues are not present because the grid voltage is synchronously stepped on to an energized load section. This soft reclosing approach increases service quality and preserves proper functioning of power apparatus.

This load restoration solution applies to microgrids of different sizes. For microgrids limited to small areas, the opportunities for this technology are favorable due to the reduced transmission distances of the communication link (i.e., grid reference and coordination signals). However, challenges arise in microgrids that have redundant power sources where more complex coordination is required between multiple generation and load-side energy storage units.

Communication and Control

Intelligent microgrids commonly rely on a centralized controller to assume overall supervisory control and energy management responsibilities. This controller communicates command action to other dispersed controllers local to diverse load and distributed generation points. Data collected from local points is also communicated back to the central controller, processed, and commands re issued across the communications network. This control and communication infrastructure is commonly used to maintain system stability, balance load and generation, or achieve energy management goals as initiated by the operator or automatically by the system.

Due to the small spatial dimensions of islanded microgrids, as compared to terrestrial transmission systems, controller communication propagation delays are not typically a significant issue; however, the overall communication latency does require examination for proper real-time control and energy management. The latency includes delays in communication nodes, delays due to congestion, and propagation delays.

The timing associated with the communication is particularly important in islanded mode and during the transition between grid and islanded modes, where the decision-time windows are much shorter than when there is grid support for maintaining stability and voltage-and-frequency regulation. (It is commonly assumed that large terrestrial grids have *infinite*.) Since the impact of communication issues in microgrids are minor, intelligent microgrid designs, operation, and real-time control rely on integrated control strategies considering the reliability and redundancy of the measurement and communications infrastructure.

Certain intelligent microgrids have more stringent measurement and communication requirements than others. (A driver of this stringency is vital loads such as defense systems.) In such cases, reconfiguration in response to a fault, or predictive reconfiguration in response to anticipated damage or loss of generation, requires synchronized measurements, millisecond decision making, and communication to local actuators.

Emerging computer simulation technology for faster than real-time state estimation plays an important role in mitigating system failures. Computer simulations running faster than real-time allow operators to "fast forward" in time and play "what if" scenarios to anticipate system behavior. These simulation tools are indispensible for reliable operation of intelligent microgrids.

Autonomous Operation

Autonomous operation combines passive and active control schemes to reach certain levels of reliability and security. Commonly, intelligent microgrid designs are based on an autonomous operating approach (i.e., little or no human intervention) where several aspects of the control and operation can be performed locally using communication-less controls for power balancing and voltage/frequency regulation. There are also microgrids that use coordinated and remotely-controlled schemes. There is a design tradeoff, however, to establish a balance between centralized schemes and distributed (passive or active) controls. Nevertheless, regardless of where the balance is, the possibility of communication system failure must be accounted for when considering line-loss contingencies to provide backup schemes.

Voltage and/or frequency droop-based schemes are commonly used as part of the power management systems within a microgrid. Autonomous droop-based controls integrate a wide range of generation technologies that are geographically dispersed and may connect or disconnect at any time during islanded operation. Droop control enables power sharing among various sources without the need for a fast and wide-spread communication infrastructure. Hence, communication requirements among various devices in a microgrid become a secondary issue to access only supervisory control information as part of the overall energy management controller of a microgrid. This aspect expands the horizon of applicable communication methods to also include low-speed (low-bandwidth) and intermittent communication schemes based on satellite or radio frequency media.

Certain microgrids are divided in predefined operating zones that are autonomously independent, but may operate in a coordinated manner. Each zone of operation is locally controlled and protected against system transients and contingencies. The local zones may be defined according to the power quality and reliability or established as part of the protection coordination methodology to provide proper protection coverage and fast fault detection and clearing. These types of microgrids are conventionally designed in a centralized fashion to achieve a high level of security and dependability. The power house and control room are established areas and integral parts of a supervisory control. Any change in the system operation and/or energy requirements is determined by the control room and communicated to the power sources. In this environment, the communication system also plays a critical role for control and remote status monitoring.

Protection methods may also be designed using teleprotection schemes. Recent designs use internet-based communication using DNP3 or IEC 61850 GOOSE. With the advent of renewable energy and energy storage as part of the heterogeneous generation found on microgrids, the need for autonomous and decentralized control methods are being re-visited.

Summary and Conclusions

Microgrids are of growing technical significance. The constraints found over different microgrids, the appropriate focus on extreme levels of reliability, and the need to be efficient over a wide range of operating conditions show that intelligent microgrids lead the development over traditional (i.e., older, non-intelligent) microgrids.

The wide range of electrical and geographical microgrids presents commonalities as well as challenges in their design and operation. Large microgrids can be expanded as their physical footprints are of less concern. In smaller, confined microgrids, sizing may be fixed *a priori*.

Most microgrids are geographically confined and feature relatively short communications distances. Although this inherently reduces the communication network's propagation delays, the overall latency requirements remain stringent due to the finite inertia, fast dynamics, and proliferation of power electronics controls in microgrids. (Wireless communication is a good option for certain microgrids, but it may not be suitable for other microgrid types.)

Protection, stability, and power electronics are important to the future of all microgrids. Different microgrids have unique attributes that will likely lead to somewhat different solutions. The possibility of cross-fertilization in these areas is large, however. Because microgrids can operate connected to a larger power system, it is essential that protection schemes warrant reliable and safe operation by using predefined setting groups, advanced settings computed online, and operational adaptation of settings of relays or reclosers.

Modern microgrids include a variety of power sources, renewable sources, and energy storage systems. These elements interface the distribution bus through controllable electronic power converters in dc and hybrid ac-dc systems. This controlled multisource system configuration introduces higher reliability, survivability, and brings about new options and challenges in terms of protection against short-circuit faults.

Maintaining reliability of supply during normal and emergency conditions (e.g., natural disaster) requires an integrated approach to the design and reliability analyses where the intertwined physical and cyber aspects are simulated and studied concurrently. From an operational view, both the electrical and control systems can benefit from faster than real-time modeling and simulations that enable predictive decision making and control in anticipation of a material event, such as sudden variability in supply or unanticipated system failures.

Advances in communication technology provide secure and economically viable media choices for the control and protection design of microgrids. Experience gained from pilot-based (i.e., classic) protection schemes is invaluable to the selection of operating modes and protection zones to achieve autonomy and visibility in the overall power and energy management of the system. Passive protection may indeed provide the ultimate backup, but over the next decade, more embedded processing power will be presented to provide additional operational intelligence and efficiencies.

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Biographies

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