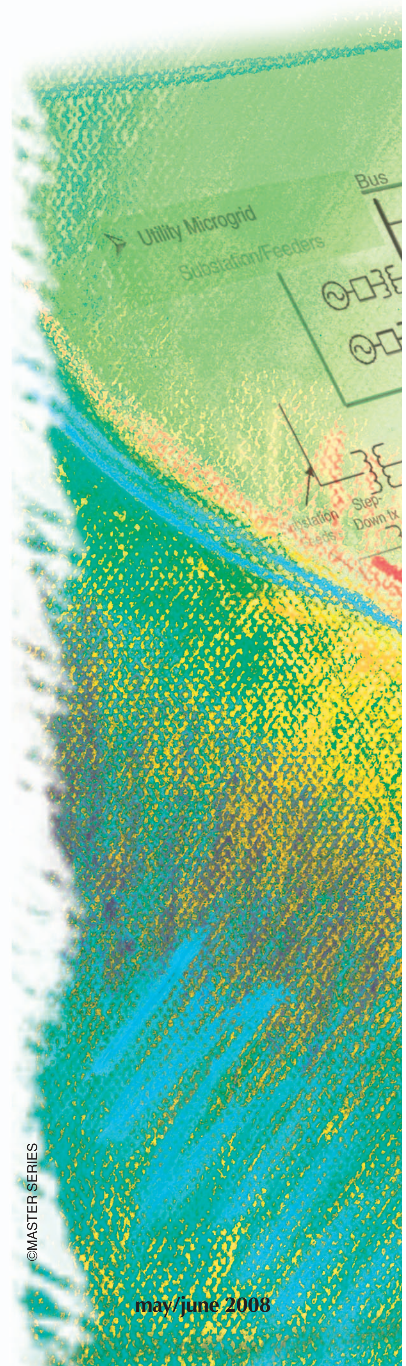
# Design for Distributed Energy Resources

THE RECENT BLACKOUT EXPERIENCES HAVE DEMONSTRATED THE vulnerability of the interconnected electric power system to grid failure caused by natural disasters and unexpected phenomena. Changes in customer needs, additional stress due to liberalized electricity markets, and a high degree of dependency of today's society on sophisticated technological services also intensify the burden on traditional electric systems and demand for a more reliable and resilient power delivery infrastructure. A restructured electric distribution network that employs a large number of small distributed energy resources (DER) units can improve the level of system reliability and provide service differentiations.

Table 1 represents major differences between conventional methods of distribution system planning and the emerging planning approaches based on decentralized energy generation and microgrid approaches. The conventional planning methods are designed based on electricity production in centralized power generation stations and delivery through passive distribution networks to end-users. In this structure, all customers, which are supplied from a distribution substation, are principally exposed to almost the same level of power quality. Although the current practice allows small-scale integration of DER at distribution levels, the overall penetration level is kept low to prevent adverse impact on system operation coordination and traditional control equipment actions. Hence, DER cannot provide any type of grid support including voltage regulation, reactive power control, and power frequency stabilization.

Interconnection of DER to the existing distribution systems may not provide utilities and DER owners with the support and benefits promised. The main concerns for the distribution network operators (DNOs) are adverse impacts on power quality of the main grid associated with a high level of DER penetration, especially issues related to power fluctuations caused by intermittency of renewable energy sources (RES). On the other hand, DER mainly rely on the backbone grid for power generation and voltage/frequency regulation. Hence, if the main grid is shut-down, principally the DER cannot deliver any power at the time that their output would be highly required.



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# Microgrid Planning and Architectures for Improved Reliability and Integration

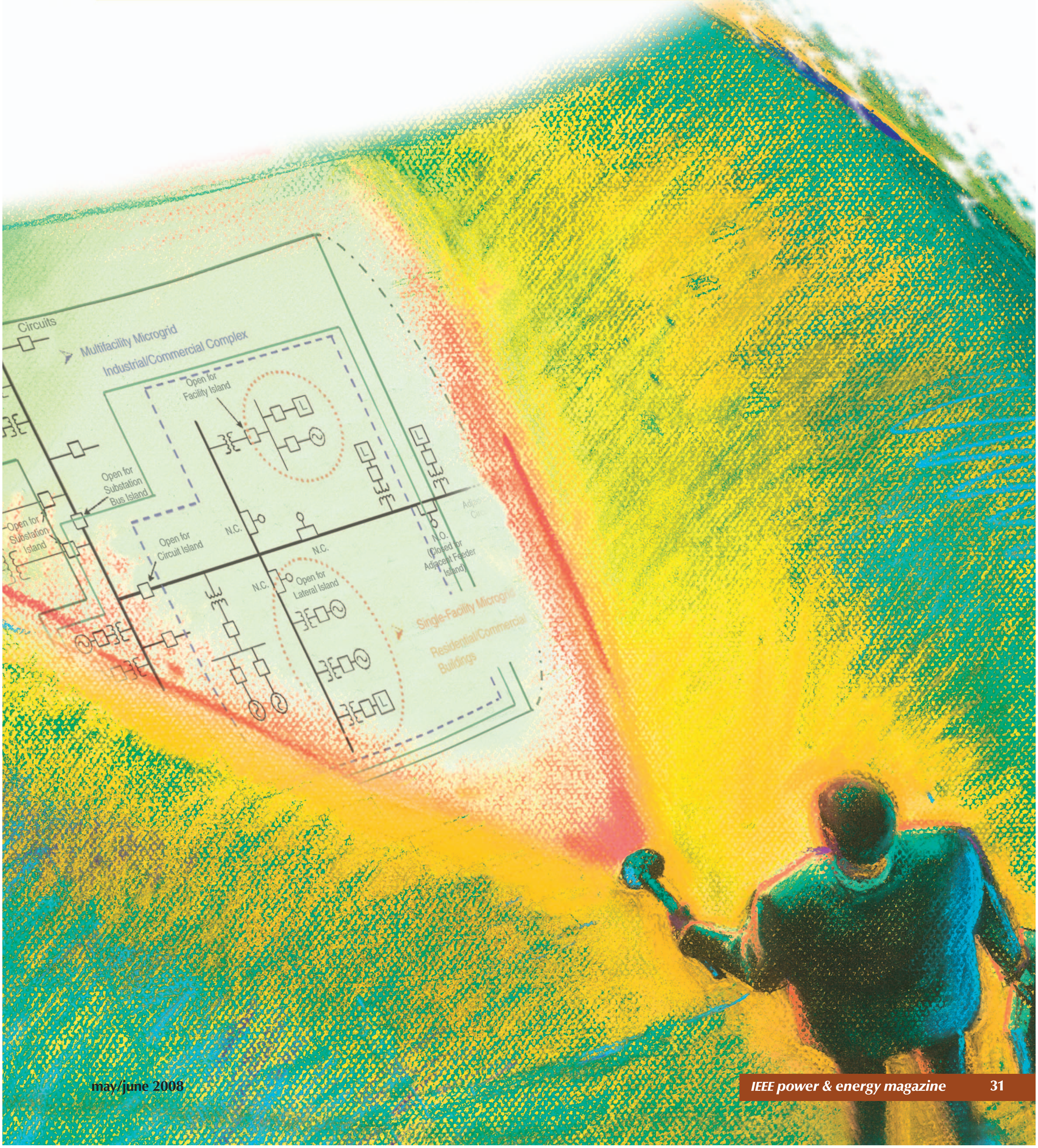

**table 1. Distribution system planning approaches.**

| Planning | Past<br>Conventional Approach | Present<br>Decentralized Energy Systems | Future<br>Microgrids |
|---|---|---|---|
| Generation Integration | Centralized<br>On-site, backup generation | Decentralized<br>Low/medium penetration DER | Decentralized<br>Medium/high penetration DER |
| Load | No differentiation | Load classification based on power quality requirements and controls (e.g., critical/noncritical, controllable/uncontrollable load) | |
| Distribution Network | Supplied from substation/passive network | Semi-active network | Active network/bi-directional power exchanges |
| Contingency Management | Frequency-based load shedding, forced power outage | Load shedding, disconnect DER | Islanding and autonomous operation, emergency DRM, power sharing, |

Under the current planning and engineering environment, the commonly used contingency management treatments for balancing generation and load are based on load shedding and forced power outages to manage shortage of power generation subsequent to faults on upstream feeders and disconnection of high-voltage lines and/or loss of a large generation station. Even though an adequate level of local generation sources may be available to serve part of the customers and prevent rolling blackouts, distribution system operation methodologies and lack of coordination between two levels of controls, namely DNOs and the independent power producers, do not permit isolated operation of part of the system.

The microgrid approach promotes 1) a highly efficient energy delivery and supply system based on co-locating DER and loads, 2) a secure and reliable power supply configuration with service differentiations based on customer technology preference and power quality desires, and 3) an energy delivery structure that has sufficient power generation and balancing sources to operate independent from the main grid in an autonomous manner during power outages or an energy crisis.

Restructuring the electricity network based on microgrid architectures can facilitate large-scale DER interconnection into medium/low voltage (MV/LV) distribution systems and provides a mechanism to fully utilize benefits of DER. The microgrid design methodology also offers a systematic approach for planning, large-scale deployment, and autonomous control of DER/RES rather than dealing with individual generation sources with diverse technologies. Furthermore, microgrids utilize three

**table 2. Microgrid architecture.**

| | | Utility Microgrids | | Industrial/Commercial Microgrids | | Remote Microgrids |
|---|---|---|---|---|---|---|
| | | Urban Networks | Rural Feeders | Multifacility | Single Facility | |
| Application | | Downtown areas | Planned islanding | Industrial parks, university campus, and shopping centers | A commercial or residential building | Remote communities and geographical islands |
| Main Drivers | | Outage management, RES integration | | Power quality enhancement, reliability and energy efficiency | | Electrification of remote areas and reduction in fuel consumption |
| Benefits | | • GHG reduction<br>• Supply mix<br>• Congestion management<br>• Upgrade deferral<br>• Ancillary services | | • Premium power quality<br>• Service differentiation (reliability levels)<br>• CHP integration<br>• Demand response management | | • Supply availability<br>• RES integration<br>• GHG reduction<br>• DRM |
| Operating modes: Grid dependent (GD), grid independent and autonomous operation (GI), isolated Grid (IG) | | GD, GI, IG | | GD, GI, IG | | IG |
| Transition to GI and IG Mode | Accidental | Faults (on adjacent feeders or substation) | | Main grid failure, power quality issues | | — |
| | Prescheduled | Maintenance | | Energy price (peak time), utility maintenance | | — |

sets of resources for power balancing and energy management including dispatchable DER controls (distributed generation and optional storage), demand response management (DRM), and control of power exchange with the main grid.

## Microgrid Architectures

A microgrid may comprise part of MV/LV distribution systems and clustered loads that are served by single or multiple DERs. From the operation perspective, a microgrid may operate with a point of common connection (PCC) to the rest of the area's electric power system and/or seamlessly transfer between two states of the grid-connected and an isolated grid (IG) mode. While physically connected to the main grid, the operating and control mode of the microgrid may shift between a grid-dependent (GD) mode or a grid-independent (GI) mode (autonomous mode) depending on power exchange and interaction of the microgrid with the backbone system.

Table 2 provides a general classification of possible microgrid architectures and their characteristics based on applications, ownership structure, and type of loads served by the microgrid. The three categories introduced in Table 2 are a utility microgrid, a single or multifacility industrial/commercial microgrid, and a remote microgrid. Typical representations of microgrid topologies that can be implemented on part of a distribution substation to serve industrial, commercial, and/or residential customers of the substation are shown in Figure 1.

### *Utility Microgrids*

The microgrid approach can facilitate large-scale deployment of RES or combined heat and power (CHP) generation in distribution networks by alleviating intermittency issues and power fluctuation impacts on the main grid. Microgrids can be implemented on part of or entire feeders of a distribution substation that is managed by a DNO. Utilizing a large number of DER located close to the center of the load, a utility microgrid can locally meet load growth and manage congestion on distribution feeders and medium-voltage subtransmission networks. At the utility level, small hydro, medium-size wind/photovoltaic (PV) generation farms, biomass, and biogas fuelled power generation plants are some of the alternative renewable energy sources that can be deployed along with low-emission gas-turbine generators to provide adequate levels of supply mix. A utility microgrid may be disconnected from the main grid during prescheduled maintenance periods on high-voltage feeders and substations in a coordinated manner. Planned islanding of the microgrid prevents load service interruption and extended periods of power outages.

A utility microgrid can offer ancillary services including local supply of reactive power and premium power quality.

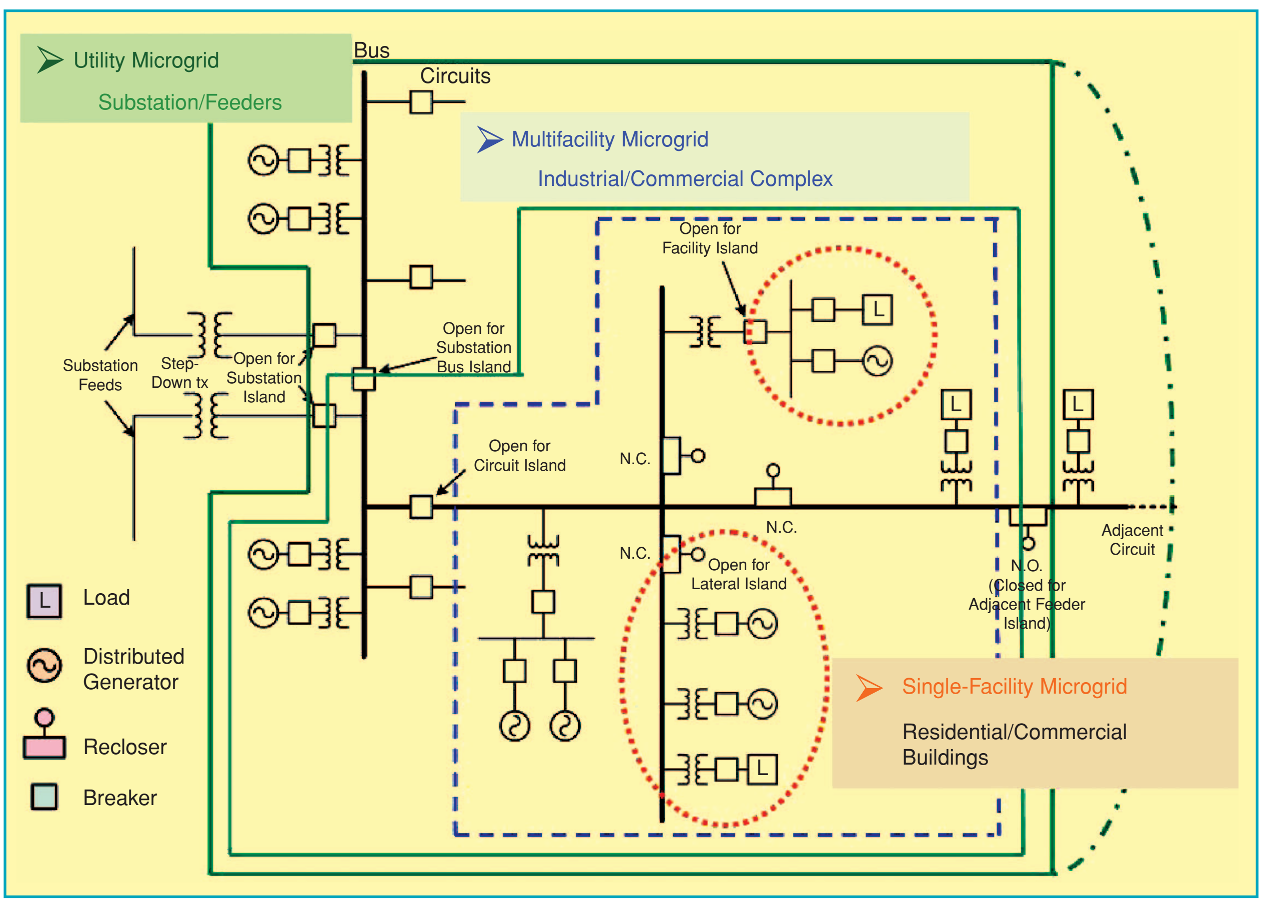


**figure 1.** Typical microgrid topologies (source: IEEE P1547.4).

Some DER technologies can supply dispatchable reactive power to compensate the reactive power of local loads and maintain voltage profile. Employing CHP sources, the utility microgrid can supply thermal energy from the electricity generation process in the form of heat and hot water (or steam) for domestic use. The CHP concept, in a microgrid environment, is applied through optimal placement of CHP sources where aggregation of thermal/electrical load increases overall efficiency of the plant and reduces fuel consumption.

## Commercial and Industrial Microgrids

Commercial and industrial electricity users are normally defined as critical and/or sensitive load classes demanding a high degree of power quality and reliability. A critical load may not tolerate momentary power outages and the level of power quality typically found on most grids. A microgrid can be adopted to serve load demand of a multiple industrial/commercial facility; e.g., a university campus, a shopping center, or an industrial installation. The advanced power management strategies of the microgrid supported by distributed control and automation prevent instantaneous power interruptions and improve quality of supply by limiting the influence of the main grid or adjacent users.

Using the microgrid approach, a distinctive level of reliability and power quality can be defined based on load classification and service differentiation for multiple users of the microgrid. Load classification and demand response control aspects of a microgrid can also help manage generation and demand for peak shaving and during the grid-isolated and independent mode of operation. A commercial or industrial microgrid may be islanded when power quality of the grid supply does not meet load requirements and may adversely deteriorate power quality of the microgrid. Grid-independent operation of a commercial/industrial microgrid can also be planned, for instance, during peak times of the utility system when the energy price is high to reduce power export from the grid.

A microgrid can also supply a small multifacility residential customer; e.g., a set of town houses or high/low-rise condominiums in urban and/or suburban areas. The residential microgrid offers a convenient and reliable energy delivery system that is customized based on customer electricity supply desires provided that multiple DER units are employed. Solar PV generation and microturbine-based CHP generation plants are attractive small-scale DER technologies for residential and commercial building applications. PV source can be integrated into building structure. The building owners can benefit from good correlation between the daytime peak load and solar power generation. Modular small-scale microturbine DER provide reliable and controllable cogeneration sources of electricity and thermal energy with very low noise to be installed inside individual apartments or offices to locally meet load demand at higher overall efficiency. Based on the microgrid approach, overall thermal/electrical energy consumption of the residential microgrid is controlled through appropriate power and demand-side management strategies to customize the energy cost and to also mitigate impact of power fluctuations of the intermittent generation sources and/or sudden changes in load demand on the utility grid. A commercial/industrial microgrid with integrated energy and power management strategies for real-time control of power generation and consumption represents a constant or controllable load with a prespecified power consumption profile from the main grid perspective.

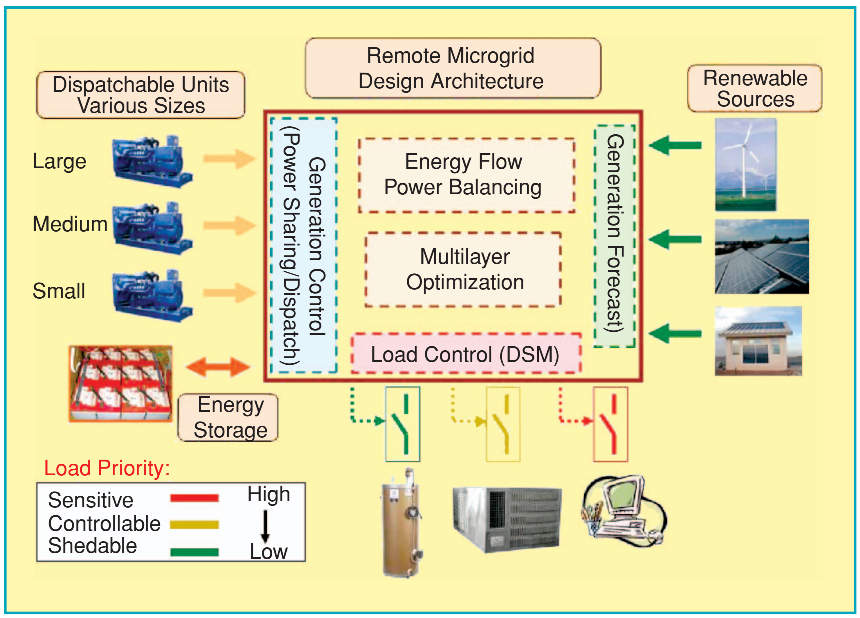


**figure 2.** Remote microgrid architecture (source: F. Katiraei).

## Remote Microgrids

Historically, the major drivers for small/modular DER technology development were distributed generation applications as stand-alone power generation systems for electrification of single remote premises, isolated communities, and as backup generation sources for critical loads. Electrification of remote communities and nonintegrated areas in developing countries and geographical islands has been a high priority mandate for utility companies around the world. Some countries have investigated adoption of the decentralized energy generation concept, in general, and the microgrid approach, in particular, for remote power supply applications. Energy requirements of nonintegrated areas can be supplied by installing renewable and alternative DER to form isolated grids and autonomous microgrids that supply electricity and possibly heat or hot water to residential and commercial customers.

> Future protection systems for microgrids will be different from the current types that operate on a philosophy originating from the days of electromechanical relays.

Depending on the geographical characteristics of a remote area and resource availability, diverse types of generation sources such as small-hydro, wind-turbine, solar PV, and low-emission gas-turbine sources can be used. A major distinction in remote microgrid design is that the generation sources in a remote microgrid have to be sized to serve the entire load along with an adequate level of reserve capacity for contingency management. In addition, load dispersion and large differences between the minimum and maximum load of the microgrid make the technology selection, sizing, and sitting of DER a challenging task. The following methods are normally suggested to achieve short-term and long-term energy/power balancing of the remote microgrid and to overcome power fluctuations introduced by intermittent generation and variable load (Figure 2):

- ✔ advance power sharing and unit commitment among a set of multiple-size generation sources to select appropriate combination of DER based on variations in load
- ✔ utilization of optimal-sized energy storage units
- ✔ prioritization and advanced control of load.

The remote microgrid design approach offers a self-healing system with sufficient emergency supply to achieve a reasonable level of supply availability and reliability.

Note that in isolated grids or in grid-connected microgrids with a back-to-back power electronic coupling, the grid voltage characteristics can totally differ from the main grid. It may not only be a different set of power quality parameters; a variable frequency or a dc-voltage-based distribution network is part of the possibilities (Figure 3).

## Optimal Deployment of Microgrids: Redefine DER Planning

The transition toward a microgrid-based planning approach will be a different process in a vertically integrated system compared to a fully unbundled environment where DNOs and generating parties no longer are linked. In an integrated system, the utility has full power over siting and connecting DER units and will aim for a global system benefit, whereas in unbundled systems each stakeholder tries to optimize on its own according to market rules. In this perspective, a DER stakeholder (Figure 4) and a DNO may even have potentially conflicting objectives. Whereas a DER owner sees revenues in terms of aggregated energy exchanges, the DNO analyzes grid operation and grid investment in terms of (peak) power flows.

Incentives can be given directly by means of special charges or through implementing a balancing market, but specific localized signals based on a combined vision of load dynamics, DER production, and grid operation issues are not obvious. Regulators have to watch over costs and benefits of DER connection, which will indirectly have an impact on all tariffs. In this respect it is useful to find out what the global optimum microgrid design would be, to serve as a benchmark or best practice. In the microgrid architectures discussed above, the boundaries between a DNO and DER operator begin to fade as the functions to implement on both sides of the PCC become quite similar.

The economic aspects of microgrid planning and design will be the focus of the article by Marnay et al. that also appears in this issue of *IEEE Power and Energy Magazine*; this article will concentrate further on the technical optima. Nevertheless, the multiobjective nature inherent to unbundled systems is kept, even in technical matters. Many policy tools exist to promote dispersed and renewable energy production (e.g., greenhouse gas (GHG)-emission reduction benefits, exemption of transmission and distribution tariffs, feed-in tariffs, renewable obligation certificates, etc.). These are global incentives that do not take grid performance improvements into account. Localized incentives are specifically given in active networks in which DER units contribute to frequency control, voltage support, local balance, and power quality enhancement. Note that this requires, in many cases, a revision of market rules that are traditionally set up for large power systems with central generation. New integration

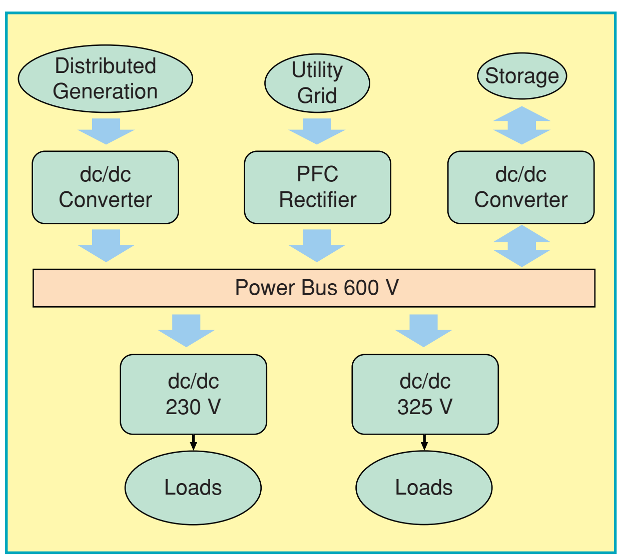


**figure 3.** Schematic of a dc-based microgrid architecture.

planning schemes are needed to connect the dots of local investment, real-time operation, and ancillary service remuneration.

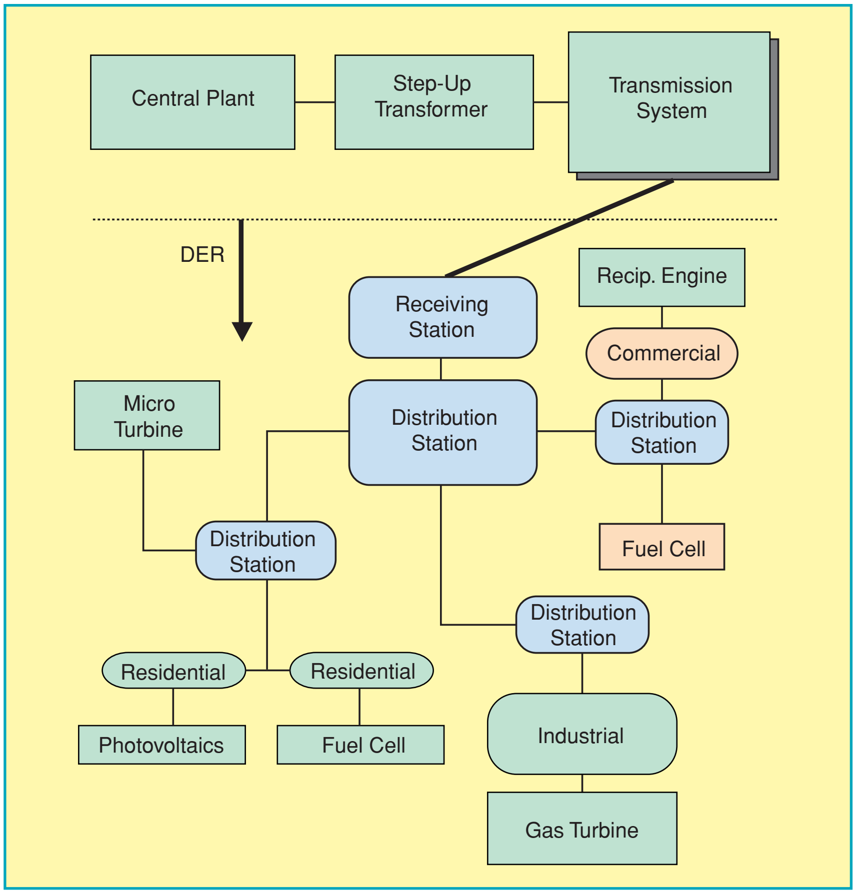


**figure 4.** Example of DER stakeholders connected on the grid of the same DNO.

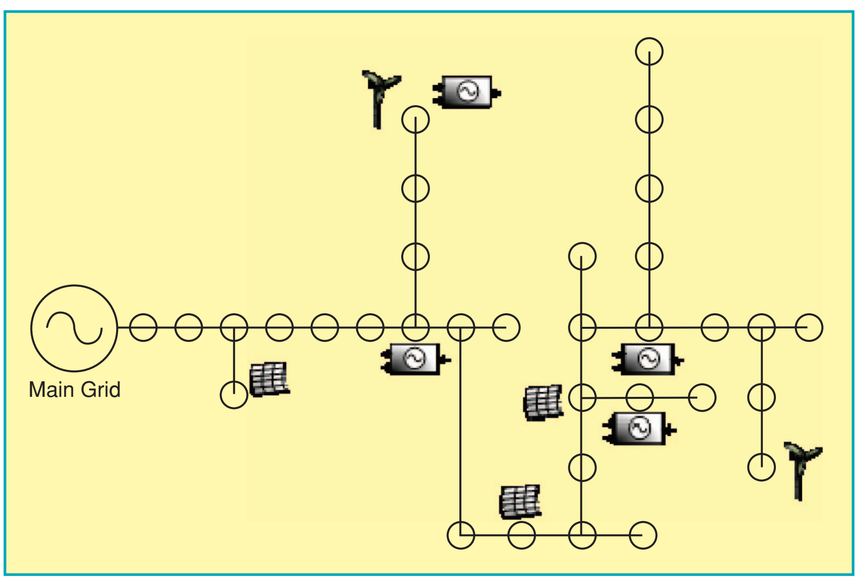


**figure 5.** Benchmark example of optimal deployment of DER units in a given distribution grid.

## *Microgrid Design Benchmark*

It is clear that to fully benefit from the advantages of microgrids, such as energy efficiency, power quality enhancement, and investment deferral, an optimal placement benchmark of the DER units within the microgrid is to be considered. Key is the local matching of energy production (heat and electricity) and loads along with the overall reliability improvement of the microgrid, while maintaining the secure operation of the grid as a constraint. The approach can be applied to nonelectrical networks such as a gas-grid supply utility.

A typical microgrid design practice and benchmarking can be described as follows (Figure 5).

a) First, the DER specifications have to be determined including:
   - what is the suitable type of distributed generation in the given circumstances: wind, PV, CHP, diesel, and/or micro-hydro?
   - what is the appropriate size of the unit?
   - where is the best location for DER siting in the grid?
   - is there any requirement to include a storage unit and with which power and energy characteristics?
   - what are the other DER technology-specific issues?

b) Secondly, the operational aspects of the microgrid for every operating mode need to be determined, including:
   - GD operation: import/export, peak shaving, arbitrage in a free market in coordination with optional storage, etc.
   - GI operation: limited internal power balancing and load control to reduce power exchange with the main grid, but ancillary services may be acquired
   - IG operation: full internal power/load balancing and provision of ancillary services.

There are always multiple objectives and constraints to take into account, even in a simple case. This is mainly because the microgrid cannot

> To make the most out of the emerging microgrid planning and architectural approach, a coordinated, market-compatible deployment has to be applied using advanced tools.

be considered as gold plated and, hence, technical constraints are to be accounted for. The main technical constraints are:

- ✔ overall system losses
- ✔ voltage stability, including feeder voltage profile
- ✔ unbalance conditions and other power quality parameters.

In addition, the following economical objectives need to be considered:

- ✔ investment
- ✔ revenues
- ✔ income generated with ancillary services
- ✔ loss-of-load probability
- ✔ operation and maintenance costs.

A complication comes from the stochastic uncertainty: deviations due to uncertain future fuel prices, weather conditions, load growth, and the like. The optimization strategy will be different for various stakeholders: customers, who want to improve self-sustainability; power producers, who want to diversify their production park; grid operators, who have to plan grid investments; and, last but not least, regulators and governments, who need to have a benchmark and a tool to assess the impact of support mechanisms. As an example, Figure 6 shows a comparison among several DER planning scenarios for which the coordinated deployment and/or investments, based on utilizing localized signals, yield a significant benefit over random connection. Note that this is a mixed discrete/continuous problem that requires solving complex optimization functions. In practice, evolutionary algorithms (e.g., genetic algorithms) are used to obtain a robust solution on a "Pareto front," representing different objectives. Taking into account controllability of the sources is an added complexity.

The tools to support microgrid design and planning are diverse. Adequate static and dynamic simulations are to be made, thereby considering the specificities of microgrids, such as single-phase units, mixed fast and slow dynamics introduced by the DER power electronic interfaces, and the stochastic modeling of the input sources. Large data sets have to be reduced to usable models and/or well-chosen samples. For instance, Figure 7 illustrates how year-long monitoring data can be reduced by sampling a set of representative days and consecutively deriving a simplified power-output curve.

### *Microgrids Safety and Protection: Protecting Grids with DER*

Introducing local generators or energy storage units into a distribution grid changes its properties significantly; for instance, the feeder voltage profiles and dynamic behavior are altered. With more sources present, the short-circuit capacity increases at first sight and short-circuit current paths become more complicated and even bi-directional. It is important that the safety of microgrids stays at the same level as and/or is improved beyond the characteristics of the existing electricity grid in order to guarantee the power quality and reliability enhancement.

In case of occasional autonomous microgrid operation, in between periods of connection to a strong grid, the short-circuit capacity will be altered significantly. As a consequence, classical protection techniques may become inadequate and have to be revisited in transitions toward microgrids. Additionally, DER units are dynamic in operation and often unpredictable in nature. Because of this, the behavior of a grid when a fault occurs changes constantly.

In general, three types of DER interfaces have to be considered: synchronous and induction generators and power electronic-interfaced generation, all with very different

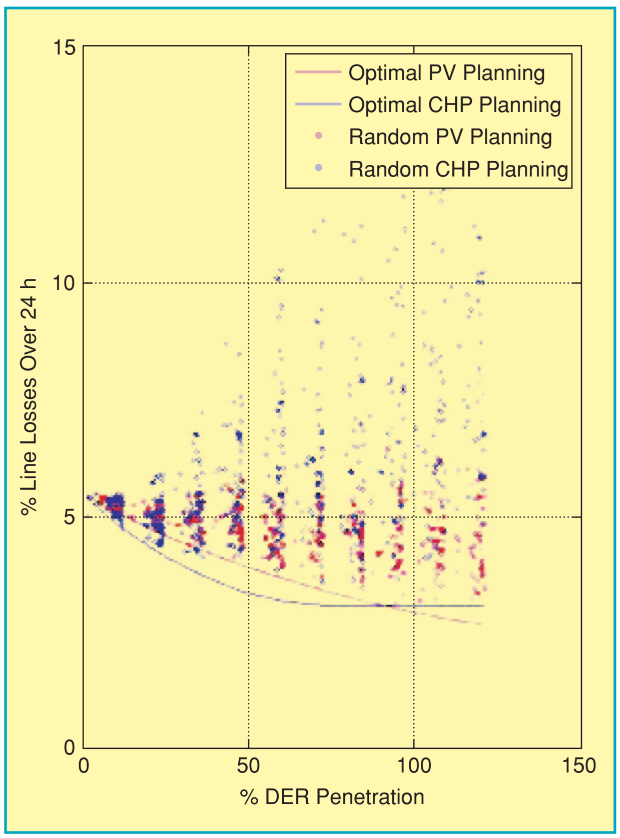


**figure 6.** Illustration of possible benefits of coordinated deployment of a microgrid (source: C. Marnay).

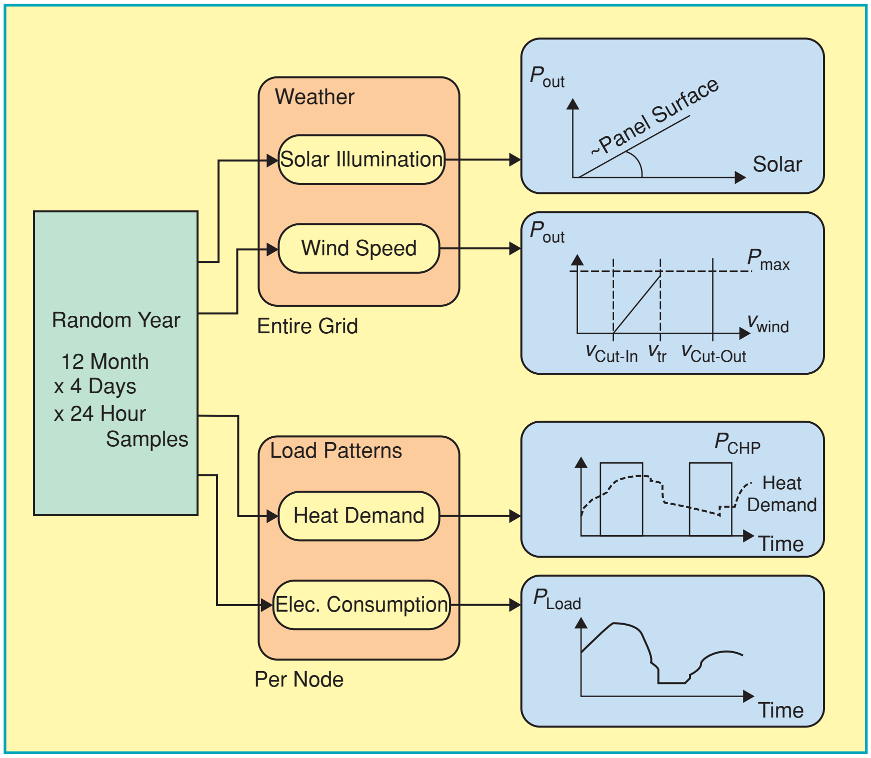


**figure 7.** Simplified modeling of power exchange patterns of DER units (source: E. Haesen et al.)

or Stirling engines). This affects the balance of the three-phase current and fault behavior.

### *Loss of Protection Coordination: Selectivity and Sensitivity*

System protection is selective if only the protection device closest to the fault is triggered to remove or isolate the fault. If the primary protection fails to operate or it takes too long to act, a secondary protection (backup protection) at a higher level takes over. This restricts interruptions to only those components that are faulty. Without DER, power flows go in one direction during normal operation as well as when faults occur in radial distribution grids. This allows for the creation of a relatively simple selective system by applying time grading to downstream overcurrent relays. The tripping current of protective devices has to be situated between the maximum load current and the minimal fault current. Both current levels depend on the state of the (micro)grid, including the state of the generators.

When local sources emerge, a hierarchical organization of the protection devices, even in a radial network, is insufficient. A possible scenario is the disconnection of a healthy feeder by its own protective relay because it contributes to the short-circuit current flowing (upstream) through a fault in a neighboring feeder: "sympathetic tripping" (Figure 8).

properties. The power electronic-based DER units cannot deliver a large short-circuit current as they are current limited. The impact is that a nearby short-circuit fault would rather cause a severe voltage distortion than a high current injection, making fault detection a complicated task. However, since the dynamic behavior of such units is controllable up to a certain level, a sort of "virtual synchronous generator" short-circuit behavior can be implemented when enough energy storage is locally available to draw the sustained short-circuit current from those units. Certain DER units inject single-phase power into the distribution grid (e.g., small PV systems

### *Anti-Islanding: To Redefine?*

Disconnection of DER units is currently required to prevent unintentional islanding. The main concern is safety of utility personnel and out-of-phase reclosing. In case of a quasi-match between the local electricity production and consumption, no matter how small the chance is, the separated system lives on, thereby energizing the grid. The workforce coming in to repair the faults may be exposed to unexpected voltages. Special protective devices are required to detect the loss of the main grid and to shut down the source.

When intentional islanding and autonomous operation of a microgrid is considered, such protection

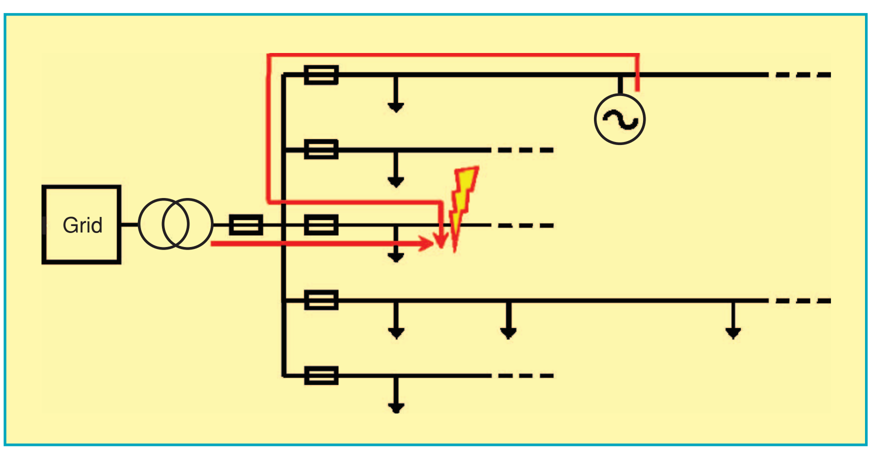


**figure 8.** Protection problem due to bidirectional short-circuit current: the DER feeder risks being disconnected without fault.

> Many future visions of the electricity system foresee a great potential for microgrid concepts.

provisions become obsolete; however, fast islanding detection is still required to trigger the change in control mode.

### *Grounding a Multigenerator Environment*

When rotating machines or power electronic inverters are used as loads, they are in general not grounded locally. Nevertheless, as with generators in a microgrid, it may be necessary to provide appropriate grounding; for instance, to connect the neutral conductor. Rotating machines most likely have such a terminal, but power electronic interfaces in general create this artificially and/or through an external connection (e.g., through a local transformer neutral). Four-leg inverters and dc-link capacitor center points can be used as well. Note that these issues are not new and are well studied as they arise in (parallellised) uninterruptible power systems (UPS) as well.

In the case of microgrids, when the grid layout is dynamically changed by separation of part of a distribution system, selecting the location of the grounding may become a problem. Often the neutral points of distribution transformers are used for this purpose. However, in case of a hard-switched separation, it may not be entirely clear where to ground. Grounding every interface may lead to a risk for exaggerated neutral currents. Especially with power-electronic based interfaces, filtering common-mode currents can cause distortion in ground current detection. These issues have to be taken into account in the microgrid design.

### *Future Protection Systems*

Future protection systems for microgrids will be different from the current types that operate on a philosophy originating from the days of electromechanical relays. The step forward with (separating) microgrids means, from a protection point of view, a dynamic reconfiguration of short-circuit current sources and the introduction of nonlinearly behaving power electronic interfaced generators. Gradually, the protection difficulties of the meshed networks will be showing up in radial but bi-directional distribution grids. The key to maintaining a safe grid operation will lie in, on the one hand, introducing a higher level of intelligence in the protection devices and, on the other hand, guaranteeing a communication channel between the grid protection and detection devices. In addition, it is expected that protection systems will become integrated with distributed controls.

## Conclusions

Many future visions of the electricity system foresee a great potential for microgrid concepts. Although many variations in architecture and design exist, depending on their level of "hard" (dis)connection or "soft" control-wise link to the central system operation, the common perspective and focus of all approaches lies in the optimal integration of DER units and the associated potential technical and economical benefits.

To make the most out of the emerging microgrid planning and architectural approach, a coordinated, market-compatible deployment has to be applied using advanced tools. In the practical transition from the current centrally supplied grids toward microgrid-oriented system designs, the key requirements are development and utilization of safe and dependable communication infrastructure and control strategies.

## For Further Reading

*Draft Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, IEEE Standard P1547.4, 2008.

G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'Haeseleer, "Distributed generation: definition, benefits and issues," *Energy Policy*, vol. 33, no. 6, pp. 787–798, Apr. 2005.

F. Katiraei and C. Abbey, "Diesel plant sizing and performance analysis of a remote wind-diesel microgrid," in *Proc. IEEE Power Engineering Society General Meeting*, Tampa, FL, pp. 1–8, June 2007.

European Technology SmartGrids Platform, "SmartGrids: Vision and strategy for European electricity networks of the future," [Online]. Available http://www.smartgrids.eu/documents/vision.pdf

Electricity Networks Analysis, Research and Development (ENARD), IEA implementing agreement on electricity networks analysis, research and development. [Online]. Available: http://www.iea-enard.org.

E. Haesen, J. Driesen, and R. Belmans, "Robust planning methodology for integration of stochastic generators in distribution grids," *IET J. Renew. Power Gen.*, vol. 1, no. 1, pp. 25–32, Mar. 2007.

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