Microgrids

Enhancing the Resilience of the European Megagrid

THE EUROPEAN ELECTRICITY SYSTEM of the future faces challenges of unprecedented proportions. By 2020, 20% of the European electricity demand will be met by renewable generation while, by 2030, a substantial proportion of the electricity generation would become largely decarbonized. Furthermore, beyond 2030, it is expected that significant segments of the heat and transport sectors will be electrified to meet the targets proposed by the EU governments for greenhouse gas emission reductions of at least 80% in 2050.

In addition to the climate change challenge, Europe has a growing interest in developing renewable generation to enhance its reliance on local energy resources and to reduce the import of conventional fuel (gas and coal) in response to growing concerns associated with the security of energy supplies. This comprises a very large resource of solar energy in southern Europe (which could be potentially further enhanced by renewable based contributions from North Africa and Middle East) and the very rich resource of wind power in northern Europe including a very significant offshore and marine energy potential.

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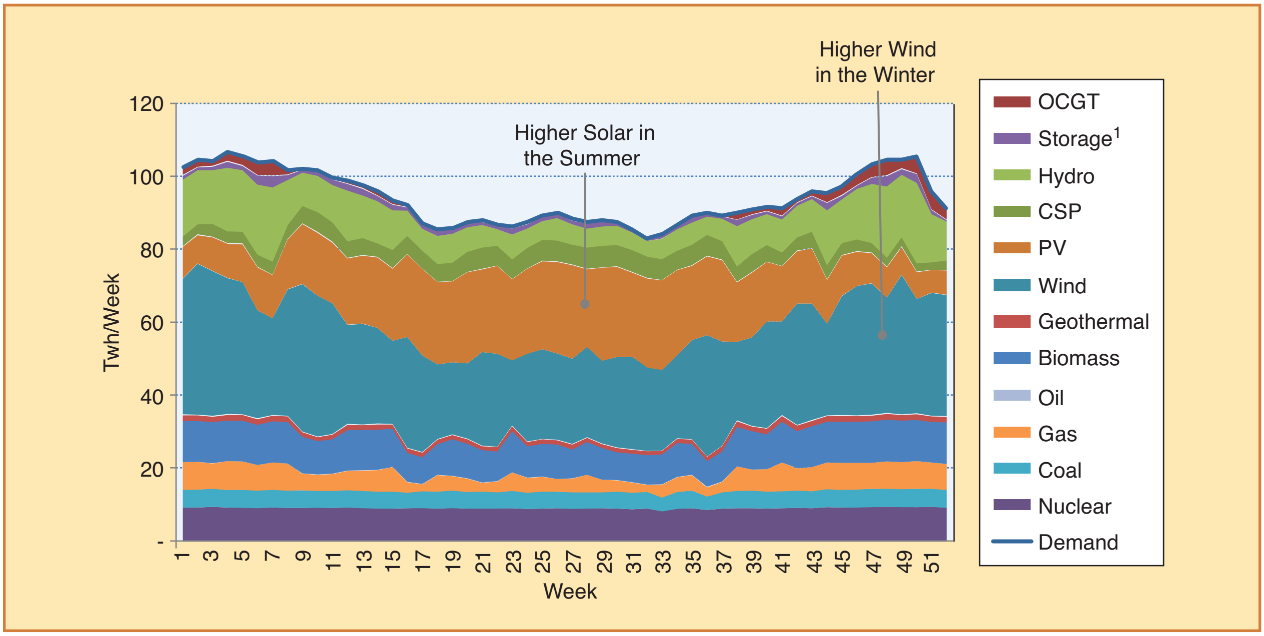

figure 1. Solar and wind are seasonally complementary.

Toward a European Megagrid: Facilitating the Decarbonization of the EU Energy System

To support this vision and facilitate the shift from the member-state centric to a EU-wide approach to decarbonization, a EU renewable energy directive was introduced to allow member states with lower renewable generation potential or higher costs to partially fulfill their renewables targets in or with other member states. This mechanism should provide incentives for investments in renewable power generation in locations with the most resources and a high renewable generation potential and therefore facilitates a cost-effective development of renewable energy generation in the European electricity system. (Although there are challenges in fully implementing the directive, the benefits of an EU-wide approach to deploying renewable generation are very significant, exceeding €200 billion by 2030.)

To deliver this EU-wide deployment of renewables, present interregional transmission must fundamentally change from a minor trading and reserve-sharing role to one that allows for very substantial energy exchanges between regions across the year, enabling a wider sharing of renewable generation resources and enhancing the ability of the system to integrate renewable energy sources (RES). The addition of significant new transmission capacity, with several thousand kilometers of new interregional transmission infrastructure, will be required to support a cost-effective integration of RESs. The analysis presented in *Roadmap 2050* suggests that the overall expansion would require a factor of three increase in interregional transmission capacity from today's levels. In some corridors, the expansion would be even greater, such as in Iberia to France, where capacity is currently under 1 GW and the required increase would range from 15 to 30 GW, depending on the level of RES penetration. This extended regional transmission network, the EU megagrid (supergrid), is not just about increased interconnection, it is also about integrating offshore renewable generation into the transmission system to optimize the output of technologies like offshore wind, marine, and tidal energy. The strategic development of an offshore network would integrate offshore grids and interconnection, significantly reducing costs and enabling more efficient resource sharing.

The EU megagrid would also enable the exploitation of counter-cyclicality among primary renewable energy sources, with solar in southern Europe and wind mostly in the north of Europe. The analysis clearly demonstrates the benefits of regional interconnection given the fact that wind is (seasonally) negatively correlated with solar; solar produces more in the summer, while the opposite is true for wind, as presented in Figure 1.

Furthermore, this additional interregional transmission would be particularly effective in enabling the system to benefit from diversity in demand and supply across the European Union, and it would allow sharing of geographically and technologically diverse energy resources across Europe. Without such interregional supply sharing, it would become far more challenging for individual regions to achieve the decarbonization and RES penetration targets. Clearly, in addition to facilitating the transport of renewable energy, significant interregional transmission infrastructure will allow for sharing of short- and long-term reserves across the European system. For example, wind output could be highly volatile on a very local level, but empirical data for Europe show that volatility dissipates substantially when measured across resource areas that are sufficiently dispersed; hence the need for balancing and backup generation would be significantly lower if multiple regions with sufficiently noncorrelated resource profiles are more effectively interconnected.

Smart Grid Technologies and Microgrids: Enhancing Cost-Effectiveness and Resilience

Although the shift from the member-state-centric to an EU-wide approach to a decarbonizing electricity system enabled by an EU megagrid would bring very significant benefits in integrating solar generation in the south and wind generation in the north of Europe, it is becoming clear that this vision should be supported and complemented by the application of smart grid concepts and technologies in distribution networks to enhance the cost-effectiveness and resilience of the future EU system.

Clearly, RESs will displace energy produced by conventional plants, but their ability to displace conventional generation capacity will be very limited. This would require maintaining a significant amount of conventional plant on the system, leading to asset utilization degradation. The analysis presented in "Benefits of an Integrated European Energy Market" suggests that the utilization of generation capacity would reduce from the present levels of 55% to 35% by 2025. Furthermore, incorporating the heat and transport sectors into the electricity system will lead to a very significant increase in peak demand disproportionately higher than the increase in energy. If the present, business as usual, or "predict and provide" network operation and design philosophy is maintained, massive electricity infrastructure reinforcements will be required, leading to high investments and low utilization of assets being less than 25%. Furthermore, massive increases in power transfers across the EU regions would potentially reduce system resilience by escalating the exposure of the system to large disturbances. The key concern is that outages of highly loaded transmission circuits on the EU megagrid would significantly increase system vulnerability and could potentially lead to large and prolonged blackouts.

If the asset utilization is not to degrade but rather potentially become enhanced, the system resilience and security that has been traditionally delivered through asset redundancy would need to be provided through more sophisticated control that incorporates advanced technologies (supported by appropriate communication and information technologies):

- ✔ network technologies, such as advanced measurement and network sensors, advanced power electronics technologies, and various novel control and protection schemes, that all enhance the utilization and resilience of network assets through facilitating a more sophisticated real-time control of the system
- ✔ demand-side response (DSR), through utilizing the inherent demand-side flexibility, particularly demand associated with heat and transport, that can be used for real-time system management while ensuring that the intended service quality is not adversely affected
- ✔ energy-storage technologies that can be used to support demand-supply balancing or control of network flows and hence increase the utilization of electricity infrastructure assets
- ✔ enhancing the flexibility of distributed and backup generation that can be used to facilitate more secure and cost-effective real-time demand-supply balance and control of network flows, hence enhancing the resilience of the local supply and the ability of the system to absorb intermittent generation and the regional level.

These technologies, through the appropriate information and communication technologies (ICT) infrastructure, will enable the cost-effective operation of the EU megagrid while enhancing the resilience of the electricity supply delivered to end consumers through active, real-time network control of the local microgrids, as indicated in Figure 2. In this context, microgrids, with appropriate enabling technologies, will facilitate the paradigm shift in delivering resilience and security of supply from redundancy in assets and preventive control to more intelligent operation through corrective control actions supported by a range of enabling technologies and ICT.

Microgrids can disconnect from the traditional grid, operate autonomously, help mitigate grid disturbances, serve as a grid resource for faster system response and recovery, and hence strengthen grid resilience. The proliferation of energy storage, distributed generation, solid-state equipment, and greater demand-side participation are, at present, not fully integrated for a variety of reasons (such as market, regulatory and policy barriers). Furthermore, information management, network measurements, disturbance recognition, and

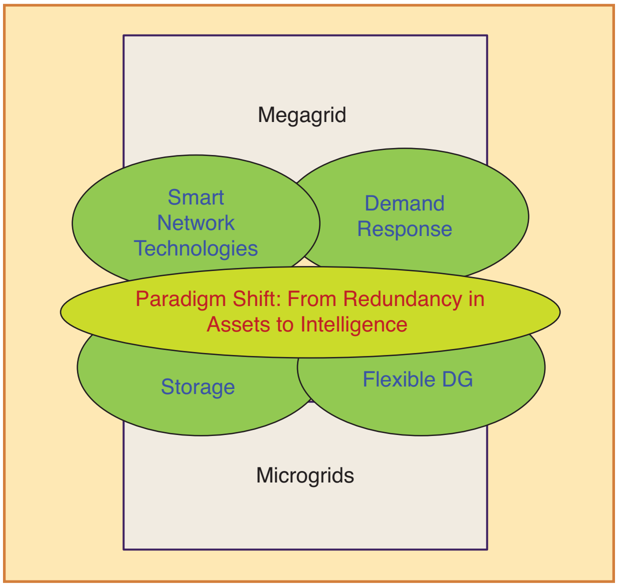

figure 2. The integration of mega- and microgrids to facilitate cost-effective and resilient evolution to an EU low-carbon future.

visualization tools are yet to be fully developed and implemented to enhance processing real-time information, accelerate response times to various system disturbances (such as power imbalances, network overloads, and inadequate voltages), and achieve compliance with reliability criteria at lower costs. This also includes the development of interface technologies and standards to enable a seamless integration of distributed energy and loads with the local distribution system. Although the major ingredients of most of these technologies do exist, the key unresolved challenge is in the development and demonstration of effective energy system integration and real-time control, showing that microgrids can deliver the functionality and enhance resilience of future low-carbon electricity systems.

It is important to stress that the development of resilient microgrids is in line with the concepts focused on the planning, construction, operation, and management of city energy infrastructure, systems, and services that have recently emerged as a distinctive and potent domain. This is driven by multiple challenges posed by rapid global urbanization, the massive demand for resilient urban energy infrastructure provision in response to growing concerns associated with vulnerability to energy supply interruptions. As a result, there is significant interest in making full use of various forms of local generation (backup generation) in large public or private institutions, combined with various forms of demand-side response and energy storage technologies, although integrating these resources within local microgrids would significantly enhance the security of supply delivered to local communities.

Control Challenges of Microgrids

The notion of control is central in microgrids. In fact, what distinguishes a microgrid from a distribution system with distributed energy resources (DERs) is their controllability so that they appear to the upstream network as a controlled, coordinated unit. DER elements include microgeneration units, responsive loads, and storage devices. The basic architecture of a microgrid is depicted in Figure 3 and comprises a hierarchically control distributed structure composed of a network of local controllers connected to each microgrid element and a higher control layer headed by the microgrid central controller (MGCC) installed at the medium-voltage (MV)/low voltage (LV) substation. Given the different characteristics of the DERs, the local can be distinguished in load

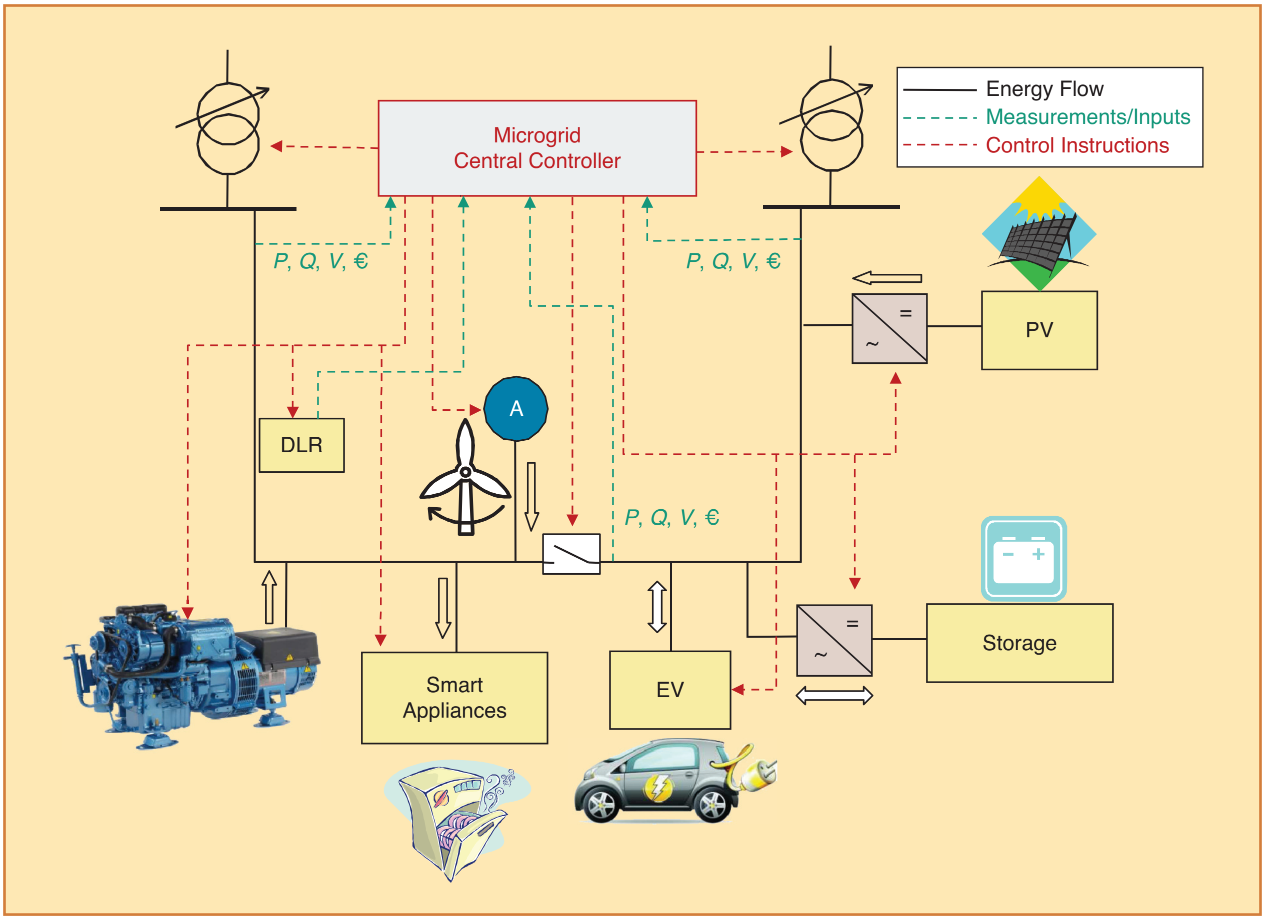

figure 3. An overview of a microgrid physical architecture.

controllers (LCs), microsource controllers (MCs) and electric vehicles (EVs) controllers (VCs).

Two basic problems need to be addressed in the operation of the microgrid: voltage control and frequency/load-generation balance. When in grid-connected mode, voltage control becomes the key issue and can be performed through a combined utilization of central decision that include control of MV/LV on load tap changing and control of the active power of the microgeneration units. Local control is affected through the use of a power/voltage (P/V) droop control solution. When in islanding mode, frequency control is the main concern.

Microgrids shifted to islanded mode require some form of energy buffering to ensure initial energy balance. The necessary energy storage can be provided by flywheels, supercapacitors, or batteries (static or mobile when associated with electric vehicles) and connected through appropriate power electronic interfaces. Microgeneration units and active loads can contribute to balance the system by responding locally using a droop control approach, as shown in Figure 4.

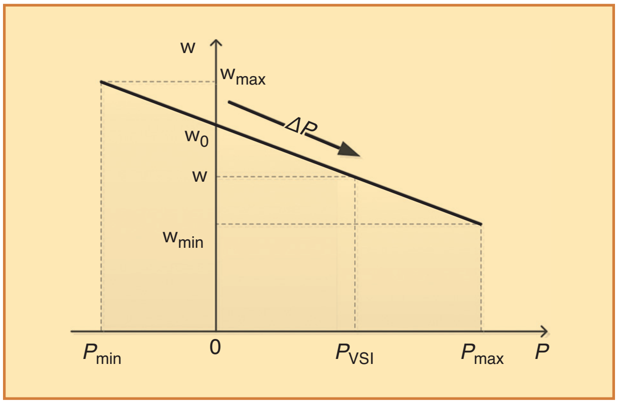

figure 4. The active power–frequency droop characteristic.

Figure 5 shows an example of recorded microgrid frequency response from a laboratory scale microgrid during islanding considering three cases, a base case without load shedding, case 1 considering a single load disconnection, and case 2 considering the shedding of two loads, followed by the reconnection of one of them to evidence the load following capability during autonomous operating conditions.

During islanding, the microgrid frequency will not reach its nominal value by the primary reaction of the droop controlled DER. The secondary control will dispatch controllable microsources to correct the frequency deviation. In general, secondary load-frequency control strategies can be identified: one implemented locally at each controllable microsources and another centralized and mastered centrally by the MGCC. Local secondary frequency control is added to the active power control of microsources to determine the new active power reference to compensate the power injected by the storage units. The main advantage of local secondary frequency control is that it only relies on local measurement to define the new reference power. However, the active power response of the microsources will also depend on the controller parameters. Centralized secondary control determines the new microsources set points based on the overall state of the microgrid. Controllable load shedding also plays an important role as an emergency functionality to aid frequency restoration to its nominal value after microgrid islanding.

The participation of the different elements of a microgrid controllable portfolio is based on a supporting communications infrastructure that ensures the exchange of control set points. Despite the fact that several technologies are available to ensure the necessary connectivity within microgrid control schemes, it will involve the interconnection of several data networks, where quality of service might not always be appropriate. Nevertheless, there are still uncertainties associated with the communications systems, namely the delay variation or the loss of control information, that needs to be accounted for to ensure the resilience of microgrid control systems. The severity of communications uncertainty is more relevant in demanding control applications like frequency control in islanding operating conditions, where a fast and coordinated action is mandatory in combining central and local control schemes. In Figure 6, the frequency variation in a microgrid resulting from different communication delays (jitter) of the set points exchanged with the MGCC is shown. The ideal response, represented with the full line, can have small variations as in the case where an average 2-s delay is considered or a more noticeable effect when the average delay is higher.

In Figure 7, the loss of frequency control set points on top of delay variation is depicted. Although the system frequency is able to recover, despite higher requests to the local control to immediately sustain the frequency value, with higher data losses the system is very likely to collapse. These examples show the importance of a communication infrastructure for demanding applications, like frequency control and the need to ensure the necessary coordination between

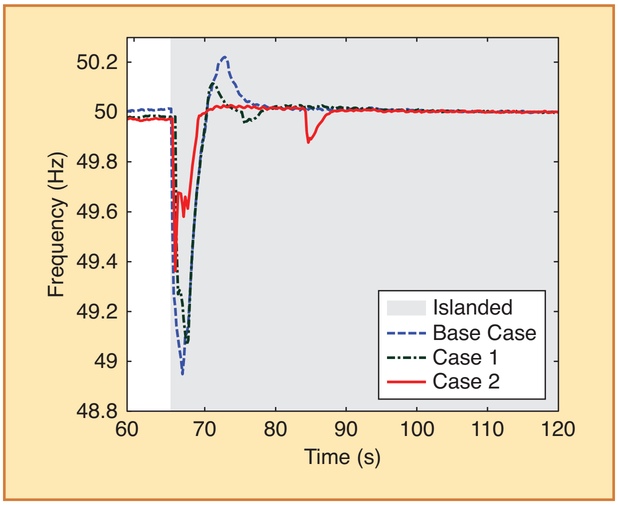

figure 5. Microgrid frequency during islanding (recordings were made at INESC's microgrid lab).

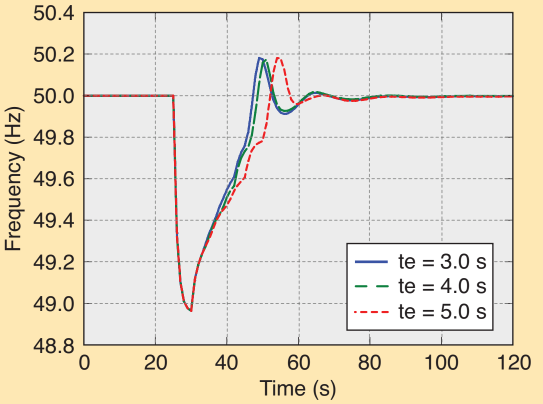

figure 6. The impacts of communications delays.

local and central control to overcome potential uncertainties in the communication systems.

Microgrid-Aided Restoration

The occurrence of general blackouts, resulting either from natural disasters or intrinsic events related to power system operation, is a rare event but has severe economic and social impacts, as a consequence of the long restoration times resulting from complex procedures followed by system operators. In such a catastrophic scenario, the microgrid operational flexibility and local generation capabilities can be coordinated to provide local restoration capabilities. The microgrid restoration procedure (black start, BS) is triggered by the MGCC when a general or local blackout occurs or when the MV network is not able to restore microgrid operation after a predefined time interval. Similar to conventional power systems, the microgrid restoration procedure can be technically regarded a sequence of actions to be checked and performed by microgrid LCs (and MCs) in coordination with the MGCC. However, the procedure should be fully

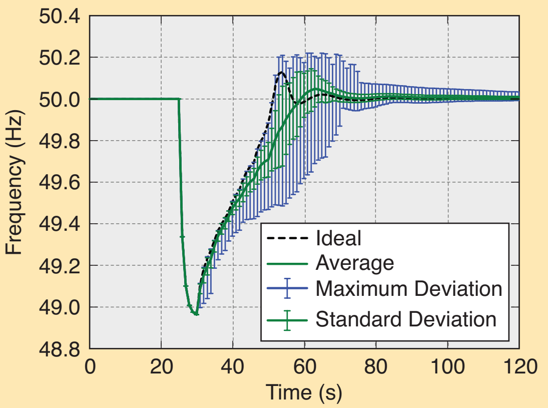

figure 7. The impacts of communications losses.

automated without requiring the intervention of distribution network operators.

To perform service restoration at the microgrid level, it is necessary that the microgrid includes the following:

- ✔ communicating their generation availability and operational status to the MGCC
- ✔ LV switches to disconnect the microgrid feeders, loads, and microsources in case a generalized fault occurs
- ✔ communication infrastructure powered by dedicated auxiliary power units to ensure the communication between the MGCC and the local controllers.
- ✔ adequate protection equipment to protect microsources and the LV grid from the fault currents and to isolate the faulted area. Since the BS procedure involves a step-by-step connection of microsources to the LV grid, the short-circuit power at the point where protection devices are installed will change. Thus, under such protection strategy, it is assumed that, during the restoration procedure, the MGCC has the ability to change protection devices settings to efficiently detect and isolate microgrid faults.

After a general blackout, the MGCC will trigger the BS procedure, being possible to organize the overall procedure in the following sequence of events:

- ✔ **Microgrid status determination**. The MGCC evaluates the network status both upstream and downstream:
  - Upstream network status: The MGCC only actives the restoration procedure if there is not any alternative to reconnect to the main grid. Before activating the procedure, the MGCC waits for a confirmation of a local or general blackout occurrence from the distribution system operator to eliminate the possibility of an interconnection switch malfunction or possible reconnection to the main grid through MV network reconfiguration.
  - Downstream network status: The MGCC evaluates the LV network status, analyzing switch status and alarms, to check the existence of local faults or equipment failures. At this stage, the MGCC also evaluates the generation and active load resources to ensure the successful microgrid service restoration. Historical data resulting from the microgrid operation can provide information about the priority loads to be restored.
- ✔ **Microgrid preparation to start the restoration procedure.** The MGCC should send a signal to the local controllers (MC, LC) to ensure the disconnection of loads and microsources from the LV network. Then microsources with local BS capability can be restarted and used to power some local loads. This procedure ensures that the microsources with storage capacity providing back power to their local loads are not energizing larger parts of the LV network.
- ✔ **Microgrid energization**, connecting the microgrid central storage unit at the MV/LV substation and

> Targets proposed by the EU governments for greenhouse gas emission reductions of at least 80% in 2050.

closing the substation LV feeder switches. The connection of the storage unit in no load/generation conditions ensures that the microgrid is operating at nominal frequency and voltage.

- ✔ **Synchronization of the running microsources to the microgrid**. The synchronization is enabled by the MGCC, with the necessary conditions, such as phase sequence, frequency, and voltage differences (both in phase and amplitude) checked by the MC, through synchrocheck relays.
- ✔ **Coordinated reconnection of loads and noncontrollable microsources**, considering the available storage capacity and local generation, to avoid large frequency and voltage deviations during load and noncontrollable generation connection.
- ✔ **Microgrid synchronization with the main grid**, when the service is restored at the MV network. The MGCC should receive a confirmation from the distribution network operator to start the synchronization with the upstream network. The synchronous conditions are checked locally through a synchrocheck relay.

Future Modeling Challenges

Further modeling development is needed for facilitating the application of such schemes at scale, while fully coordinating pre- and post-fault actions of demand-side, storage, distributed generation, and emerging advanced network technologies, particularly power electronics based, are yet to be developed.

In addition to real-time microgrid state estimation models using only a limited amount of real-time measurements, several key modeling tools are not yet fully investigated:

- ✔ models for the real-time computation of security and quality indicators including network steady-state and stability margin assessments
- ✔ models for the preventive optimization of microgrid configuration based on predicted load, generation, and line ratings including prefault optimization of

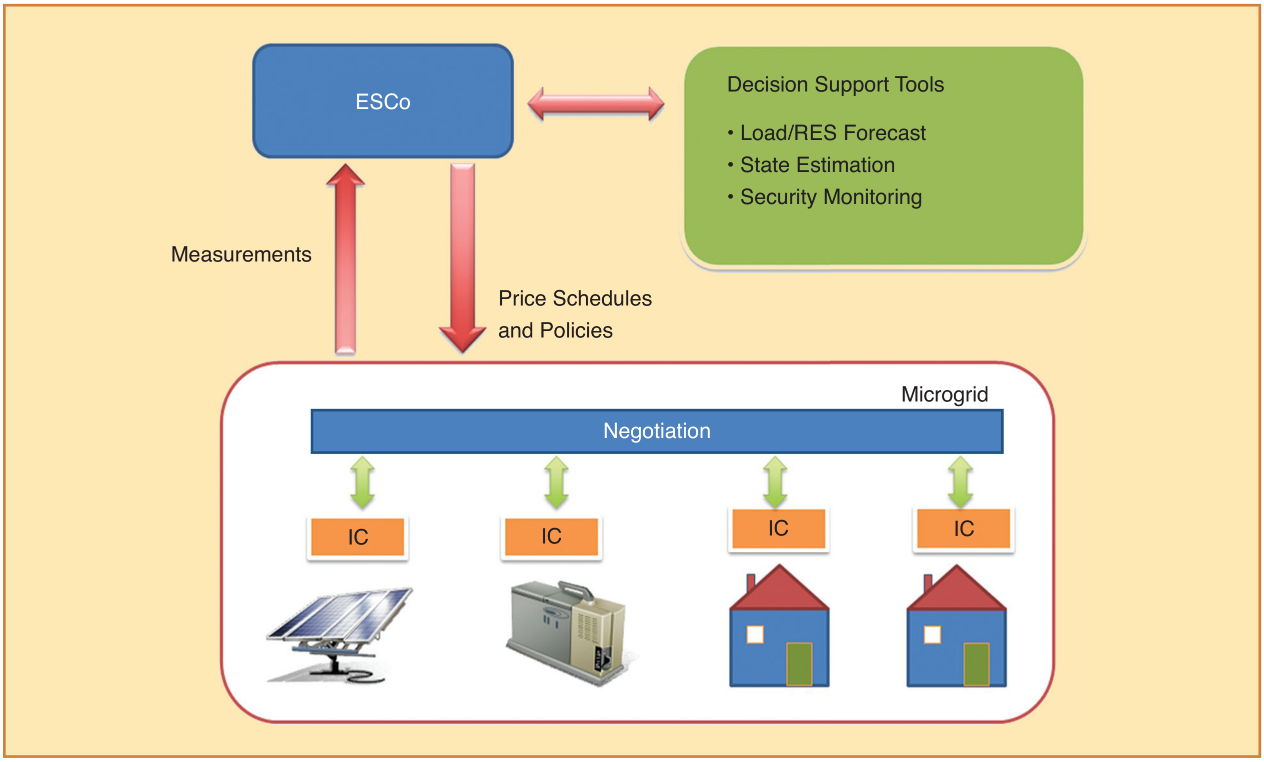

figure 8. The decentralized approach.

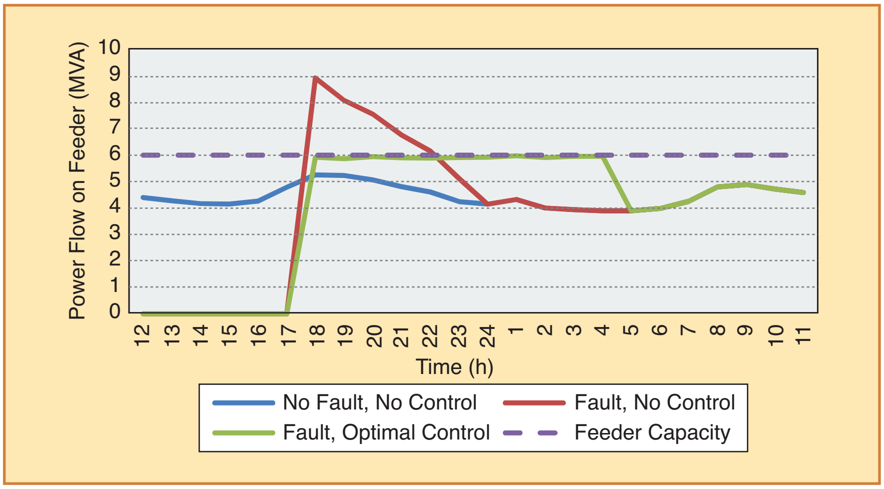

figure 9. Power flow on a feeder with electric heat pumps.

settings of network control devices while considering condition of distribution circuits and switching equipment; this would be a multiobjective optimization model that balances network security margin, distributed generation export levels, power quality, and power losses

- ✔ models to integrate the contribution that electric vehicles, either as controllable loads or storage elements, would bring to improve the operation of the microgrid and contribute to its autonomy when in islanding mode
- ✔ real-time, post-fault microgrid reconfiguration/restoration including optimizing settings of network control sources (active reactive power control, voltage control) the response of distributed generation, demand-side response, and distributed storage
- ✔ further enhancements should include risk-constrained approaches to directly deal with uncertainties associated with demand and generation predictions, including the impact of delays, inaccuracies, and losses of real-time measurements; there will be uncertainties associated with post-fault actions need to be taken into account.

figure 10. The Meltemi holiday camp in Greece with DERs and intelligent LCs has been used for implementing MAS technologies.

Shift from the Centralized to Distributed Control of Microgrids

Microgrids operating in a market environment might require that the competitive actions of each unit's controller have a certain degree of independence and intelligence. Furthermore, local DER owners might have different objectives, i.e., next to selling power to the network, they might produce heat for local installations, keep the voltage locally at a certain level, or provide backup for local critical loads in case of main system failure. Some microgrid customers might seek their own energy cost minimization and have diverse needs, although they all might benefit from the common objective of lowering feeder operating costs. Moreover, microgrids might have dozens of households with several installed DERs so the dimension of the problem can be very high. An approach that limits the amount of data transfer is essential. The availability of high computing facilities or dedicated operators in LV grids is also highly unlikely. These are factors that impose decentralized solutions to the overall operation problem of microgrids.

The shift from a centralized to a fully decentralized operation paradigm will open new opportunities for enhancing cost-effectiveness and security performance of future microgrids, with the objective of delivering truly integrated self-controlling, self-optimizing, self-protecting electricity and self-healing networks. In stark contrast to the present network control standard, control algorithms deployed within future microgrids will be meeting dynamically changing objectives while the network topology, network conditions, and control infrastructure are also changing. The key driver for enhancing real-time control of microgrids is the need to improve supply resilience and quality of service delivered to end consumers.

A significant paradigm for building such distributed systems is multiagent systems (MASs). The core idea is that an autonomous control process is assumed by each local intelligent controller, namely MCs and LCs. The MAS theory describes the coordination algorithms, the communication between the agents and the organization of the entire system including the energy service company. Agents are capable of acting in their environment, of which they have partial representation or none at all; they communicate with each other; they have a certain level of autonomy, meaning that they can make decisions without a central controller or commander; and they tend to satisfy certain objectives using their resources, skills, and services. (See Figure 8.)

A family of MAS algorithms to solve market problems are the auction algorithms, a type of combinatorial optimization algorithm that solves assignment and network optimization problems with linear and convex/nonlinear cost. The main principle is that the auctioneers submit bids to obtain goods or services. At the end of an iterative process, the highest bidder is the winner. For microgrids, goods can be an amount of energy traded.

Distributed control can also be applied for managing load recovery during supply restoration following interruptions. The key challenge is temporary load increase driven by the loss of diversity and the need for energy recovery. This effect is known as cold load pickup or payback effect that reduces the natural diversity of loads, leading to significant demand peaks that may violate network constraints. To maintain the resilience of the microgrid's supply, suitable control strategies are required to mitigate this effect. An example involving electric heat pumps (EHP) in domestic buildings is presented in Figure 9.

Under normal operating conditions, EHPs maintain the buildings' indoor temperature at the desired set points without violating network voltage and thermal constraints. Following supply interruption and without control of the EHP, however, a cold load pickup effect emerges at hour 18 when supply is restored, increasing significantly the demand level and breaching the network's thermal capacity limit. Distributed optimal control can avoid the violation of the network constraint, while achieving the minimum loss of comfort for the EHP users; this loss of comfort will be caused by the fact that the indoor temperature falls below the desired set point until the energy not supplied during the interruption is partially recovered. As observed in Figure 9, the application of optimal control approach results in prolonged energy recovery period, needed to maintain the power flow within the network capacity.

MAS-based decentralized control has been performed in several demonstration sites in the context of EU-funded research projects (Figure 10). Key findings are that Internet technologies will play a dominant role in the deployment of microgrids. Existing ICT infrastructure, as well the upcoming technologies, such as the smart/Wi-Fi-enabled home appliances can be used to actively control devices in the LV networks.

Another approach being investigated is the use of distributed constraint optimization, particularly for arbitration and negotiation within decentralized and distributed multi-agent control systems, where conflicting control decisions may arise. Significant further work, however, is required to develop comprehensive microgrid models and then carry out the analysis and comparison of distributed intelligent methods for applications such as voltage control, frequency control, thermal constraint management, reconfiguration, and control decision arbitration. Such models are needed to test the robustness and scalability of the self-organizing architecture and carry out a comparison with existing control philosophies to evaluate the advantages and disadvantages of the distributed control concept. This would also inform the operation and control of local community and smart cities energy systems and their integration within the national level system operation and control.

Summary

The EU megagrid is foreseen to exploit the very large resource of solar energy in southern Europe and of wind power in northern Europe. Microgrids with enhanced control capabilities can integrate and coordinate local distributed resources enhancing the resilience of the EU megagrid and providing local restoration capabilities. The future modeling challenges of microgrids and in particular the shift to distributed control, enhancing further the microgrids resilience, are highlighted.

For Further Reading

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