6

On Site Generation and Microgrids

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Nowadays, the conventional electric power systems that rely on centralized power generation using fossil fuels face various challenges relating to secure energy supply with the required power quality, efficiency and environmental concern.

The fossil fuel resources exploited today are limited and capturing new ones may be expensive and technically difficult. Moreover, energy production from such sources causes the increasing emission of gases resulting in environmental pollution. Reducing emission means increased generation costs. Without expanding existing generation capacity it will be difficult to meet future energy needs.

Centralized energy generation needs bulk and complex power networks to transfer energy to distributed customers. Investment and maintenance costs are high and energy efficiency is reduced because of relatively high power losses in the networks. On the one hand the existing power system infrastructure (transmission networks) is becoming old and, on the other, there are environmental problems with constructing new components, mainly high voltage transmission lines (e.g. lack of space, public objections). The important issue on the distribution side of the system is maintaining the required quality of supply. Customer demands are still increasing, together with the increasing number of sensitive loads used by them. Utilities are under an obligation to provide customers with good quality energy in an effective and reliable manner. On the other hand, we can observe an increasing number of loads that are becoming the sources of electromagnetic disturbances.

In many European countries special support systems and mechanisms have been developed in recent years that, according to the EU policy [1], promote an increasing share of distributed generation (DG) in total energy production. Difficulties in the development of new high voltage transmission systems (so-called constraints) contribute to the development of distributed generation, which does not need a large power system to transfer electricity to consumers.

Electrical Energy Efficiency: Technologies and Applications, First Edition. Andreas Sumper and Angelo Baggini.

In these conditions one can expect that the number of distributed energy resources (DERs) installed in the network will grow continuously.

DERs produce power on a customer's site or at a local distribution utility and supply electrical energy to the local distribution network. Installing DERs may delay the need to upgrade distribution infrastructure in the case of network operation near its capacity limits. Individual electricity consumers can use DERs as backup sources to supply energy when the power from the grid is unavailable. In normal operation conditions DERs may deliver energy to the hosting grid for the benefit of the owner. DERs owned and operated by power utilities are located at specific sites in the distribution grid to supply the local power or power and heat demand. Their capacity may be relatively high from a hundred kW to MW. DERs owned by independent power providers are scattered within the grid. They have a capacity from a few kW to hundreds of kW.

The integration of a considerable number of DERs into the grid may lead to a stressed power grid operation and cause difficulties in maintaining the required power quality (PQ). DERs may generate disturbances such as voltage variations, asymmetry or harmonics. The problems may be heightened by disturbing loads if they are installed in the grid. For a specific network, one can determine so-called 'hosting capacity' [2], which is the highest amount of DG that can be integrated without the PQ limits being violated. In many practical cases, the network hosting capacity limits wide penetration of DG, unless some measures are applied that will facilitate the integration process and assure the required power quality. Such measures include additional compensating devices and management and control systems.

6.1 Technologies of Distributed Energy Resources

The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the losses, especially at the distribution level to make the system more efficient and reliable. The losses can be reduced in many ways. One technique is the use of DERs – energy sources and energy storage systems. Integration of DERs into an existing network can result in several benefits. These benefits, in addition to line loss reduction, also include reduced environmental impacts, peak shaving, increased overall energy efficiency, relieved transmission and distribution congestion, voltage support and deferred investments to upgrade existing generation, transmission and distribution systems. Furthermore, the electricity price in the spot market displays frequent fluctuations. DERs dispatched for the purpose of avoiding wholesale electricity purchases must be both dispatchable and flexible or be on-line at full capacity during the peak hours of highest electricity prices. Crucial factors in the applications of DERs for loss minimization are the size and location of DERs (see Section 6.3).

6.1.1 Energy Sources

Different types of DG technologies are in use today (e.g. Table 6.1). They can be classified into two categories depending on the prime fuel used. Micro-turbines, fuel cells and reciprocating engines are based on gas and are fully dispatchable. Photovoltaics, wind and hydro sources use renewable energy that is intermittent in nature, so they are non-dispatchable. Prime fuel local availability, investment and operating costs are the main factors influencing the selection of the source type (Table 6.1).

Table 6.1 Comparison of distributed energy sources [3]

	Combined cycle gas turbine	Gas turbine	Diesel engine	Micro-turbine	Gas engine	Fuel cell (high temperature)	Photovoltaic	Wind turbine	Small hydro power plant
Electrical efficiency [%]	35–55	25–42	35–45	27–42	25–43	40–60	6–19	25	
Overall efficiency [%]	73–90	65–87	65–90	90	70–92	90			
Typical power range [MW]	3–300	0.3–50	0.2–20	0.03 –1	0.003–6	0.00–100	20 W–few MW	200 W–5 MW	25 kW–100 MW
Heat	Medium-grade steam or high temperature hot water	High-grade steam or hot gas	Low-pressure steam and medium temperature water	Hot gas or hot water	Low and medium temperature hot water	Steam or hot water			
	CHP technologies (see Section 6.2.1.1)								

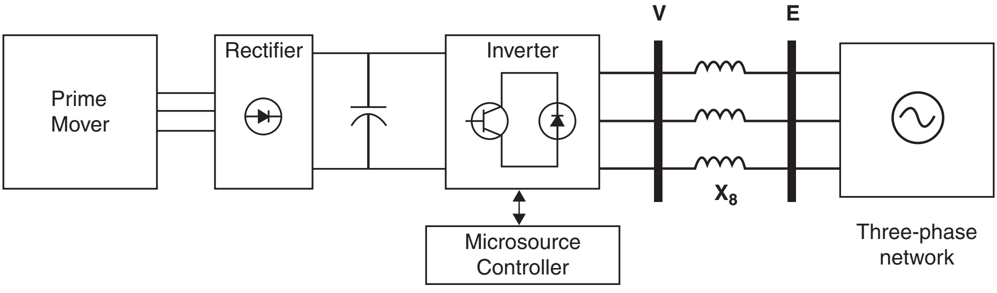

Figure 6.1 Typical structure of a microsource

Some of the DG technologies require a power electronics interface in order to convert the energy into grid-compatible AC power. The generic structure of the microsource that uses a power electronic inverter is shown in Figure 6.1.

For sources with AC output such as high speed micro-turbines the voltages are first rectified to produce a DC output and inverted to produce the desired AC voltage and frequency. The inverter is typically a voltage source converter and provides the necessary controls over the phase and magnitude of the bus voltage. Storage can be added at the DC bus to decouple the dynamics of the prime mover from the output. Sources such as fuel cells and PV panels produce DC directly and only an inverter is needed to produce AC output at the desired voltage and frequency. The power electronics interface can also contain protective functions for both the distributed energy system and the local electric power system, which allows paralleling and disconnection from the electric power system. A more detailed overview of DG technologies is reported in, for example, [4–6].

Some types of distributed generation can also provide combined heat and power by recovering some of the waste heat generated by the source – Combined Heat and Power (CHP).

6.1.1.1 CHP

Waste heat is produced in energy conversion processes. Through CHP generation (cogeneration) this heat is collected and used for spatial or process heating, which results in improving fuel-to-energy efficiency. Cogeneration means the simultaneous generation in one technological process of thermal and electrical energy. The overall efficiency of cogeneration is defined as the annual sum of electricity and useful heat production divided by the input fuel used to produce the sum of electricity and useful heat output. The efficiency is dependent on cogeneration technology, and the size of the unit (Table 6.1); an average value reaches 85%.

The comparison of cogeneration with separate production of electricity and heat is illustrated in Figure 6.2.

According to [3], the following efficiency is assumed for the comparison: for cogeneration an electrical efficiency of 35% and a thermal efficiency of 50% (based on a gas engine); for separate generation, a power plant with a typical efficiency of 43% and a boiler of 95% efficiency. Assuming that the same amount of electricity and heat is produced, the amount of fuel used in separate generation is 25% higher than in CHP systems, which means an energy efficiency improvement of 25%.

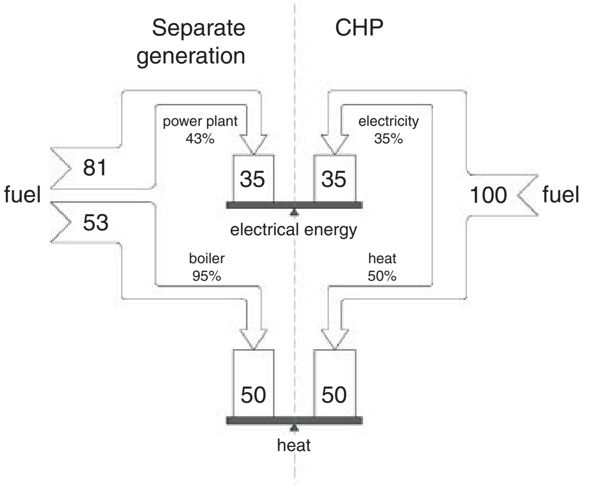

Figure 6.2 Comparison of a CHP system with separate electricity and heat production

A methodology for determining the efficiency of the cogeneration process is given in [7]. The amount of primary energy savings (PES) provided by cogeneration production can be calculated using the following:

$$PES = \left(1 - \frac{1}{\frac{\eta_{Q,CHP}}{\eta_{Q,Ref}} + \frac{\eta_{E,CHP}}{\eta_{E,Ref}}}\right) \cdot 100\%, \tag{6.1}$$

where $\eta_{Q,CHP}$ and $\eta_{E,CHP}$ are the thermal and electrical efficiency of the CHP calculated as the ratio of annual useful heat output and annual electricity, respectively, to the fuel input, and $\eta_{Q,Ref}$ and $\eta_{E,Ref}$ are the efficiency reference values for separate production of heat and electricity for which the cogeneration process is intended to substitute.

For the values from Figure 6.2, it yields:

$$PES = \left(1 - \frac{1}{\frac{0.5}{0.95} + \frac{0.35}{0.43}}\right) \cdot 100\% = 25.4\% \tag{6.2}$$

The efficiency reference values can be calculated taking into account the same fuel categories. Each CHP unit is compared with the best available and economically justifiable technology for the separate production of heat and electricity on the market in the year of construction of the cogeneration unit.

Cogeneration, which provides primary energy savings of at least 10% compared with the references for separate production of heat and electricity, is classified as high-efficiency cogeneration. Production from small scale and micro-cogeneration units providing primary energy savings may be regarded as high-efficiency co-generation.

The CHP systems provide consumers with both electricity and required heat simultaneously. Typically, CHP units are located close to heat loads because the transportation of heat is more difficult than the transportation of electricity. Different technologies of CHP systems are applied at different scales. CHP units with a maximum capacity below 50 kW are classified as 'micro-cogeneration', the units with an installed capacity below 1 MW are 'small scale cogeneration' [7]. The obvious application is in industry where heat demand usually accompanies energy demand. Small CHP units offer great flexibility in matching heat load demand, therefore in recent years cogeneration has also become attractive for commercial and residential customers. Heat used for spatial heating is used at a relatively low temperature, whereas for process heating a higher temperature is required.

From a utility point of view the benefit of domestic CHP is its contribution to the reduction of peak loads. Usually, the peak electricity demand occurs in the winter season when heat demand is the highest. However, in countries where the summers are hot the summer peak load may be comparable to or even larger than the winter peak load. Using CHP systems to provide building cooling may also contribute to the reduction of peak electricity loads [8].

Improved efficiency is the most important benefit that the CHP systems can offer. The development of this technology is supported and promoted by the European Commission [7] and one can expect that the share of electricity from cogeneration to overall power production will be increasing.

6.1.2 Energy Storage

Electric energy storage is one of the contemporary electrical engineering challenges. Its purposes are, *inter alia*, improvement of electric power generation effectiveness by levelling power demand, better management of transmission and distribution systems and improvement in electric power delivery. The key drivers for energy storage systems are the increasing popularity of distributed energy sources and their characteristic features: location, usually remote from public network, output power often not correlated with demand and varying over a wide range, low average power generating capacity utilization (0.2 wind generators, 0.1 photovoltaic sources), and still high energy cost, as well as, relatively low efficiency of centralized generation.

Depending on the unit power and required autonomy time, the energy storage issues can be divided into two groups concerning: power supply quality – chiefly consumer protection during voltage dips and short supply interruptions, the so-called *backup storage energy supply* (BSES), and energy management. The latter requires significantly larger power and longer autonomy times (Figure 6.3).

In utility applications, storage units should have large power capacity (to a few dozen MW) and storage time in a range from minutes to hours – depending on the task performed. In end-user applications, there is lower power capacity (from a few dozen to few hundred kW) but a larger storage time is needed.

The devices used in distribution networks can be also classified into three categories according to the energy discharge rate [9, 10]:

1. systems to supply energy within seconds or less to address ancillary services including PQ events compensation;

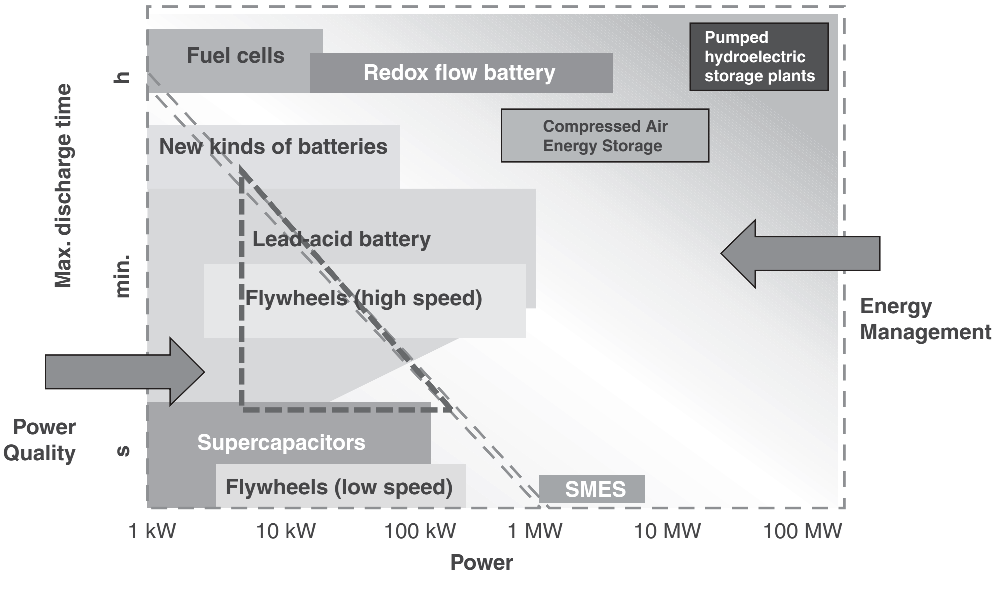

Figure 6.3 Classification of selected energy storage systems versus autonomy time and unit power (based on [6, 11])

2. systems to supply energy within minutes to address power shortages (uninterruptible power supply);
3. systems to supply energy for more than a few minutes to several hours for load levelling, peak shaving and energy management, including island operation.

There are many technologies that make energy storage possible [10]. The most commonly used are pumped hydro power plants due to the cost of storage and their effectiveness. Other technologies are nowadays used at a smaller scale, or in special cases such as flywheels, which are used when a large amount of power, but not necessary a large amount of energy, is needed (as in the emergency power supply to cover energy needs before a diesel generator becomes fully operational – no longer than 1 minute). The systems designated for long-term storage are pumped hydro, compressed air, hydrogen storage, batteries (including redox flow) and thermal storage. Flywheels, superconductive coils and supercapacitors (as well as some kinds of batteries) are generally meant to store lower amounts of energy; they are, however, capable of being ‘charged’/‘discharged’ with large power that, combined with their good dynamics (like reaction time), makes them perfect for power quality regulation, for example. A major challenge to the market in the near future comes from applications such as electric vehicles or plug-in hybrids and grid-coupled PV systems with batteries, which will be used to suit the application and not primarily to support the grid. Tables 6.2 and 6.3 sum up the energy storage methods.

There are some technologies that are typical for their areas of application. In energy management applications, for a discharge time of up to 1.25 h, lead–acid batteries are the most

Table 6.2 Comparison of direct energy storage systems [6, 11–13]

	Disadvantages	Advantages
In magnetic field – superconducting magnetic energy storage – SMES	• High capital cost and stringent safety requirements, danger of thermal stablity loss and threat of coil damage • High operating and maintenance costs, large auxiliaries, complex cooling system to maintain cryogenic temperature and resultant additional power losses • Low specific energy • Specific losses: *c*. 30–40 W/Wh • Possible hazard from a very strong magnetic field (to living organisms) • Charging time: min–h	• Maximum powers from 1 to 100 MW, 500 MJ • High power density W h/kg: 30–100 • In-service time up to 30 years • Discharge time at nominal power: s min • Environmentally friendly, recyclable • Fast response time (ms) • Very short charging time, less than 90 s from full discharge state • Requires less space than a battery bank of the same power • Efficiency (charge/discharge): 85–98% • Technology readiness level – prototype (at the research stage) • Very strong support for technology development, main areas of application: RESs, SR, T&D*
In electric field – supercapacitors (ultracapacitors or double-layer capacitors) – SC	• Expensive technology • Low specific energy: 1–10 W h/kg • Low cell voltages – a series connection is needed to achieve higher voltages, voltage balancing required where a larger number of capacitors are connected in series • Requires advanced power electronics • Voltage reduction during discharge	• High specific power (10 000 W/kg), nominal power: 0.01–100 kW, 10 MJ • Less weight than batteries • Very slow self-discharge process • Efficiency (charge/discharge): 85–98%, specific losses: 0.026 W/W h • Capability for operation at very low temperatures, even (−40°C) • Simple charge methods – no full-charge detection is needed; no danger of overcharge, very fast charging/discharging time 0.3–30 s • Low impedance – enhances load handling when put in parallel with a battery • Virtually unlimited cycle life, maintenance-free (over 500 000 charging/discharging cycles) • Very strong support for technology development, main areas of application: RESs, SR*

*RESs – Renewable energy sources; SR – Support for RESs; G&SR – Generation and system reserve; T&D – Support for transmission and distribution; UPS – Uninterruptible power supply systems

economical [9]. Other technologies such as nickel–cadmium, sodium–sulphur or Li–Ion can offer a better performance in terms of cycle life or efficiency, however their costs are higher or they are currently under development.

Supercapacitors and fly-wheel energy storages are appropriate solutions for applications where large power capacity is required. In PQ applications ultracapacitors have attracted the great attention [14, 15].

Table 6.3 Comparison of indirect energy storage systems [6, 11–13]

		Disadvantages	Advantages
Mechanical	Pumped hydroelectric storage plants	• Geographic and geological constrains on the location of the installation • High capital cost • Long construction period • Dedicated for very large powers (0.1–1 GW)	• Mature technology – employed in the power sector for a long time • Relatively cheep operation • Discharge time at nominal power: h–days • Efficiency (charging/discharging): 65–80% • In-service time: 30–50 years • Main application areas: RESs, G&SR*
Mechanical	Kinetic energy storage systems	• Low specific energy (2000–10 000 W h/kg) • High idling losses	• Mature technology – mass production • High specific power • Nominal power: 0.01–10 MW, 15 MJ • Discharge time at nominal power: s–min • Efficiency (charging/discharging): 90% • Specific losses low speed: 2000–10 000 rpm – 2.2 W/Wh; high speed: 10 000–1 000 000 rpm – 1.2 W/W h • In-service time: *c*. 20 years • Very strong support for technology development, considerable application potential, main areas of application: RESs, SR*
Mechanical	Compressed air energy storage (adiabatic CAES)	• Geographic and geologic constrains on the location of the installation • High capital cost • Long construction period • Dedicated for large installations • Long starting time, poor compatibility with distributed energy sources	• Mature technology • High specific energy and power • Nominal power: 0.1–1 GW • Discharge time at nominal power: hrs–days • Efficiency (charging/discharging): 60% • In-service time: 20–40 years • Strong support for technology development, area of application: RESs, G&SR[1]
Electrochemical	Fuel cells (various technologies)	• Expensive technology (expensive catalysts) • Difficult fuel production (hydrogen) • No current overload capability • Specific energy: *c*. 11 000 W h/kg	• Mature technology (mass production) with very strong support for further development • Nominal power: up to 5 MW • Efficiency (charging/discharging): 40–55% • Capability for cogeneration (high temperature fuel cells) • Discharge time at nominal power: min–h • In-service time: 20–30 years • Main application areas: RESs, SR, G&SR, T&D and UPS

(*continued overleaf*)

Table 6.3 (*Continued*)

			Disadvantages	Advantages
Electrochemical	Battery – SB	Lead–acid battery	• Specific power: 1000 W/kg • Specific energy *c*. 10–100 W h/kg • Limited number of charging/discharging cycles • Limited operating voltages and currents • Requires maintenance and technical surveillance • Battery capacity dependence on temperature • High deep-discharge voltage • Expensive recycling • Efficiency: *c*. 80%	• Mature, readily available technology, extensive production and operating experience • Long in-service time: 10–20 years • Low price • Easy production • Modular construction, suitable size • Possible large power installations, up to 10 MW, over 600 MJ • Suitable voltage characteristic • Charging time: h, discharge time: min–h • Specific losses 0.023 W/W h • Efficiency (charging/discharging): *c*. 70–85% (concerns all battery storage technologies) • Main application areas: RESs, SR, G&SR, T&D and UPS
		Sodium–sulphur (Na-S) or NaNiCl battery	• Expensive technology, sodium polysulphides are highly aggressive – a container must be chromium and molybdenum plated (both are very expensive) • High operating temperature, necessary thermal insulation and temperature monitoring necessary, ceramic electrolyte is sensitive to thermal cycles	• Mature technology • Powers up to 8 MW, 60 MW h • Large power and energy densities • Efficiency: 70–80% • Very cheep electrode material • Applications: RESs, SR, G&SR, T&D and UPS
		Redox flow battery (vanadium) (VRB)	• Expensive technology at the development level • Difficult standardization	• Intended for large applications (1 MW – 1 h; 3 MW – 1.5 s) • High power and energy densities • Efficiency: 60–75% • Very strong technology development support, considerable application potential
		Zinc–bromine battery (Zn-Br)	• Expensive technology at the development level • High operating costs • Contains corrosive and toxic materials	• High power and energy densities • Intended for large applications • Efficiency: 70–80%

Table 6.3 (*Continued*)

			Disadvantages	Advantages
Electrochemical	Battery – SB	Li–Ion battery	• Technology at the development level, expensive and 'difficult' operation, instability of lithium in the presence of air causes hazard of battery failure, particularly in portable equipment • Short in-service time	• High power and energy densities • Efficiency: 90–95% • Minimum maintenance required • Small dimensions and weight
		Nickel-cadmium battery (Ni-Cd)	• Expensive technology • Contains toxic materials (cadmium) • Fast self-discharge (particularly at high temperatures) • Limited capability for charging in high temperatures • Application to low power systems	• Mature technology • High mechanical robustness • High energy density • Efficiency: 60–70% • Permissible high charging currents d • Long in-service time (up to 25 years) • Insignificant influence of ambient temperature on the battery capacity • Large number of deep discharges • Possible and recommended battery storage in discharged state
		Nickel metal hydride (Ni-M-H)	• Expensive technology • Sensitive to high temperatures, similarly as Ni-Cd batteries • Difficult recycling process	• Mature technology • Efficiency: 80–90% • High mechanical robustness • High energy density • Long in-service time • Smaller number of toxic compounds as compared with Ni-Cd batteries

* RESs – Renewable energy sources; SR – Support for RESs; G&SR – Generation and system reserve; T&D – Support for transmission and distribution; UPS – Uninterruptible power supply systems

6.2 Impact of DG on Power Losses in Distribution Networks

Active power losses in distribution networks depend on both active and reactive power flow:

$$\Delta P = 3I^2R = 3\left(\frac{S}{\sqrt{3}U}\right)^2 R = \frac{P^2}{U^2}R + \frac{Q^2}{U^2}R \tag{6.3}$$

The source connected to the node k of the network presented in Figure 6.4 introduces active power P_k and reactive power Q_k. Then, power flow in the network is changed. The active power in a $(\alpha - 1, \alpha)$ branch is equal to:

$$P_{\alpha-i,\alpha} = \sum_{i=\alpha}^{k-1} P_i - P_k + P_{k+1} \tag{6.4}$$

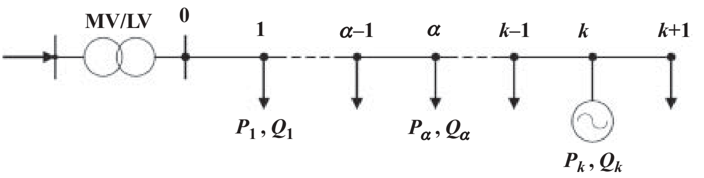

Figure 6.4 Connection of a source in an LV grid

and the reactive power to:

$$Q_{\alpha-1,\alpha} = \sum_{i=\alpha}^{k-1} Q_i \pm Q_k + Q_{k+1}. \tag{6.5}$$

The total losses in the network, after the source connection, are expressed as:

$$\Delta P_{T(s)} = \frac{1}{U_n^2} \cdot \sum_{\alpha=1}^{k+1} \left[R_{\alpha-1,\alpha} \left(P_{\alpha-1,\alpha}^2 + Q_{\alpha-1,\alpha}^2 \right) \right], \tag{6.6}$$

where

$$\begin{aligned} P_{\alpha-1,\alpha} &= \sum_{i=\alpha}^{k-1} P_i - P_k + P_{k+1} \qquad \text{for} \quad \alpha \leq k-1 \\ P_{k-1,k} &= P_{k+1} - P_k \\ P_{k,k+1} &= P_{k+1} \end{aligned}$$

and

$$\begin{aligned} Q_{\alpha-1,\alpha} &= \sum_{i=\alpha}^{k-1} Q_i \pm Q_k + Q_{k+1} \qquad \text{for} \quad \alpha \leq k-1 \\ Q_{k-1,k} &= Q_{k+1} \pm Q_k \\ Q_{k,k+1} &= Q_{k+1}. \end{aligned}$$

In general, a source can produce or consume the reactive power, however in most practical cases the source reactive power is equal to zero. Under such an assumption, connecting the source into the network will influence the active power component of the losses. The difference in active power losses of the feeder after introducing P_k active power to the node k will be:

$$\delta(\Delta P_T) = \Delta P_{T(s)} - \Delta P_T = \frac{1}{U_n^2} \cdot \sum_{\alpha=1}^{k+1} \left[R_{\alpha-1,\alpha} \cdot \left(P_{\alpha-1,\alpha}^2 - P_{0(\alpha-1,\alpha)}^2 \right) \right], \tag{6.7}$$

where $P_{0(\alpha-1,\alpha)}$ is the active power flowing in the branch $(\alpha - 1, \alpha)$ when $P_k = 0$. The total losses in the network will be reduced if $\delta(\Delta P_T) < 0$.

Usually, the energy source covers the local load demand, which is a relief for the supplying network. For most feeder branches the losses are reduced. However, if the source power is relatively large, the reduction in losses may not occur.

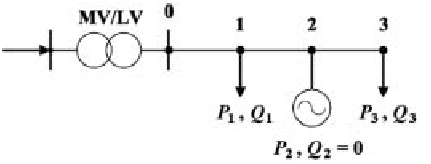

Figure 6.5 Example of a three-node feeder

Let us consider the simple three-node feeder like in Figure 6.5. After connecting the source to node 2, the active power flow in the feeder branches will be:

$$\begin{aligned} P_{12} &= P_3 - P_2 \\ P_{01} &= P_1 + P_3 - P_2. \end{aligned} \tag{6.8}$$

The difference in active power losses in the feeder will be:

$$\delta(\Delta P_T) = \frac{R_{01}}{U_\mathrm{n}^2}\left[P_2^2 - 2P_2(P_1 + P_3)\right] + \frac{R_{12}}{U_\mathrm{n}^2}\left(P_2^2 - 2P_2P_3\right). \tag{6.9}$$

Assuming that R_{01} is equal to R_{12}, $\delta(\Delta P_T) < 0$ if

$$0 < P_2 < P_1 + 2P_3. \tag{6.10}$$

Changes in power losses as a function of power generated by the source are presented in Figure 6.6. Power losses ΔP_T are expressed in relation to the value ΔP_{T0} obtained for $P_2 = 0$. The source power P_2 is referred to the sum of load power ($P_1 + P_3$). The following data were assumed for the feeder: line nominal voltage $U_\mathrm{n} = 0.4$ kV, wire cross-sections $s_{01} = s_{12} = s_{23} = 35$ mm^2, wire conductivity $\gamma = 34$ m/Ω mm^2, and feeder section lengths $l_{01} = l_{12} = l_{23} = 500$ m. The loads consume the constant reactive power with tg $\varphi_1 =$ tg $\varphi_3 = 0.4$, the source reactive power is equal to zero.

It is clear from the figure that the range over which the power losses are reduced depends on the location of the local loads and their powers. The larger the load at the end of the feeder, the larger range of power generated by the source for which the losses in the feeder are reduced. If the total load power is located at node 1, then the reduction of losses will occur only if the source power does not exceed the load power. In this case, the network supplies only the reactive power. On the other hand, if the total load power is located at node 3, then the reduction of losses will occur for generated power from 0 to twice a total load power. For each individual case one can determine the source power that gives the minimum losses in the feeder.

Similar analysis can be performed for different feeder data and the influence of feeder section length or cross-section can be easily determined. For any individual load case and the source power it is also possible to select the optimal location of the source for which the feeder operation is the most effective. For larger distribution networks different optimization methods are applied that allow one to determine the optimal allocation of DG with the aim of minimizing power losses and keeping the voltage profile and reliability levels in the required range [16].

In practice, the connection of a single source may not cause a large reduction in losses, however in the case where many sources are connected in the microgrid this effect may be

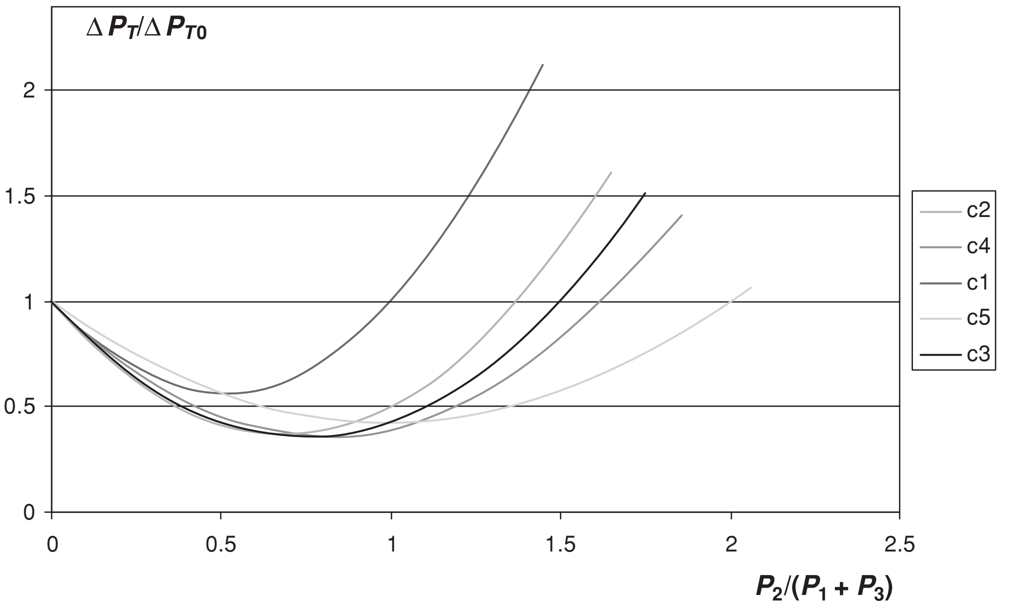

Figure 6.6 Changes of power losses in the example feeder from Figure 6.5 depending on the source power: c1 – $P_1 = 80$ kW, $P_3 = 0$ kW; c2 – $P_1 = 50$ kW, $P_3 = 30$ kW; c3 – $P_1 = 40$ kW, $P_3 = 40$ kW; c4 – $P_1 = 30$ kW, $P_3 = 50$ kW; c5 – $P_1 = 0$ kW, $P_3 = 80$ kW

significant. The results of studies are presented in [17] that show that for countries where peak demand occurs on hot summer days, PV generation contributes to the reduction of losses in some distribution networks by up to 40%. A similar effect can be obtained if peak demand occurs on a winter evening and CHP is applied in the network.

6.3 Microgrids

6.3.1 Concept

Together with a growing use of DERs, conventional distribution networks change their structure from passive to active. The active network in which the processes of energy generation, distribution, and use are executed in a controllable way forms an electrical power microgrid.

The microgrid integrates energy sources, including renewables, storage systems, controllable and uncontrollable loads. Energy sources produce power and heat mainly on the local load demand. The storage equipment supports the operation of variable power sources and is involved in energy balancing in order to optimize economical profits. Additional 'custom power' devices may be applied to improve supply quality and the system stability. The operation of a microgrid is monitored and supervised in real-time by the control system. This is a key issue in the microgrid concept, which decides on how smartly the microgrid can act. Real-time monitoring makes the network observable. The measured data are transferred to the management and decision centres. Smart prognostic and decision-making algorithms

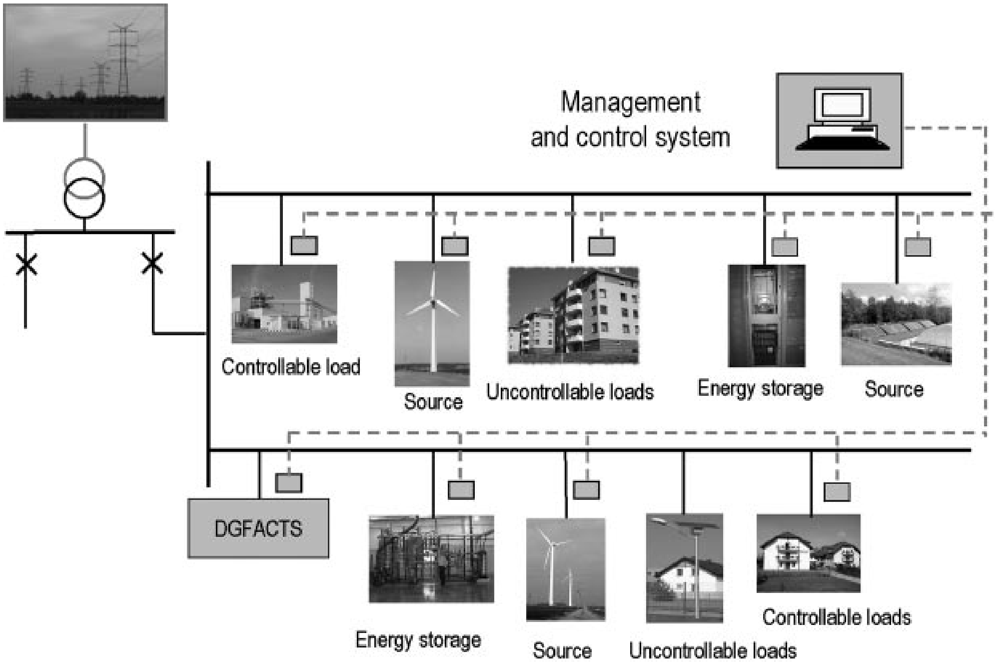

Figure 6.7 Illustration of LV microgrid

enable them to predict the consequences of the existing situation and to make decisions that are optimal with respect to a given criterion.

So the characterized microgrid is a smart grid, which in more broad sense is defined by European Technology Platform as '*an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies*'. This definition is not constrained to any voltage level, however the microgrids refer rather to low voltage networks. The microgrid is illustrated in Figure 6.7.

Many research studies and demonstration activities regarding microgrid development are reported in the literature. Reference [18] gives an overview of ongoing projects in Europe, Japan, the USA and Canada.

The basic configuration of a microgrid is radial with several feeders supplied from a distribution substation [5]. These feeders could be part of the distribution system or a building's electrical system. A static switch usually connects the microgrid with the LV bus of the distribution transformer. Usually, the microsystem operates in connection with the electrical power grid, but autonomous operation is also possible as well as a transition between these two modes [19–21]. In grid-connected mode the excess power generated by the microgrid may be sold to the utility; in this case the microgrid will participate in the market operation or provide ancillary services [22]. The transition to island operation follows the loss of connection with the grid in fault conditions. During autonomous operation, which lasts until the connection with the network is restored, there is partial or full energy delivery to customers. Where there is intentional long-time island operation the length of time and the range of loads supplied is agreed by all the parties involved. The communication required for control and protection is an important element of microgrid architecture. Various techniques can be used such as the internet, radio communication, power-line carrier and telephone lines [23]. Work is continuing on the establishment of standard communication protocols.

The existing microgrid test networks around the world are reviewed in [21,23]. Test systems include representative sources from all currently important technologies, such as PV, micro-turbines, wind turbines, fuel cells. Information about microgrid standards and technologies is given in [20, 21]. Economic and regulatory issues are the concern of [8]. Planning and design aspects are presented in [4].

Microgrid technology and architecture provides an opportunity to improve the efficiency of energy consumption. The installation of energy sources close to the demand centres leads to the reduction of transmission and distribution losses. CHP generation technology offers the possibility for customers to use waste heat. An energy management and control system and the application of storage enable the microgrid to operate at minimum cost. Finally, the custom power devices contribute to the reduction of negative effects and the costs of bad power quality.

6.3.2 Energy Storage Applications

Energy storage systems have found many and various applications in electrical power microgrids. Storage technologies can provide solutions for the key issues that nowadays affect microgrid development, such as the intermittency of renewable energy sources (RES), demand fluctuation and power quality. They can help in better utilization of electrical energy for the benefit of both utilities and end-users. Utility applications include: the integration of RES with the grid, load levelling and ancillary services (see Section 6.3.5), whereas the end-user applications concern mainly peak shaving and uninterruptible power supply.

6.3.2.1 Integration of Renewable Energy Sources

Much work has been carried out on the integration of renewable energy sources, such as wind and solar systems, with the supply network. Daily power generation of such sources is stochastic and does not correspond to a typical demand curve. Usually, the highest generation is during off-peak hours. The application of a storage system enables one to capture part of this generation and transfer it to peak hours. The system stores the surplus energy generated during low-load periods and releases it during high-load periods. In this way local generation decreases peak power flows in the grid, which in consequence leads to the reduction of losses.

From the market point of view it means that energy is stored at times of low energy prices (low load) and injected to the grid at times of high prices. The benefit for the source owner can be in saving energy delivered from the grid to cover his demand. As regards big wind farms supplying energy to the grid, it also means economical profits. The technical and economical impact of this application is analysed in [24, 25].

Using a storage system as a power and energy buffer makes dispatching power generated by RES possible. Another purpose of the application is the mitigation of power output fluctuations, thus improving power quality. This function is important when there is a high level of RES penetration. Storage can lead to the increasing use of renewables, which in consequence contributes to a reduction in the use of fossil fuels and an increase in grid efficiency.

6.3.2.2 Load Levelling

In every electrical power grid power generation must match power consumption. The consumer's demand changes according to the daily load curve. This requires the grid to have a proper capacity to handle demand fluctuation, regardless of how it runs. Traditionally, electricity networks are dimensioned on peak power. Investigations showed that the energy transported through lines as a percentage of the total energy capacity needed for the peak demand is no more than 68% [26]. Energy storage systems can provide balancing service, reducing the stress on the network for peak loads and keeping the power transmitted from the network at lower level. It allows one to dimension the network for a lower value of the demand power.

In conditions when the network equipment is overloaded as a result of growing energy demand, energy storage systems can bring relief and may contribute to the increase in the network stability and reliability. From an economic point of view, it means the development of existing networks while postponing or omitting network reinforcement investments.

6.3.2.3 Ancillary Services

Ancillary service applications concern storage systems connected to the grid through coupling inverters and may include voltage control, Var support, and power quality improvement. Even though technically proven, this type of applications is not yet widely used but may be a promising opportunity for future microgrids.

The typical control strategy of a storage inverter assumes two objectives:

1. The generation or consumption of active power according to the energy management system (charging and discharging strategy)
2. Compensation of PQ phenomena caused by disturbing loads or fault events.

PQ control can include:

- compensation of disturbances introduced to the network by loads – voltage amplitude variations, harmonics, flicker, unbalance
- mitigation of voltage dips coming from the network.

The specific tasks performed by the unit depend on its operation mode.

In the current control mode, which is assumed for load compensation, the inverter must inject currents to the network in such a way that undesirable components of the load current e.g. harmonic, reactive and negative sequences are cancelled and the network current becomes a fundamental harmonic and a positive sequence. At the same time the inverter is expected to generate or consume the active power to meet the requirements of the management system. It is also possible to stabilize the voltage at the point of connection. To stabilize the voltage, the inverter must inject a reactive current of fundamental frequency and positive sequence, which gives an appropriate voltage drop on the reactances of the supply network.

6.3.2.4 Peak Shaving

In many countries a distinction is made in tariffs between peak and off-peak hours. As the energy delivered during peak hours is more expensive, end-users may be interested in lowering their consumption in those periods, which is possible using energy storage. The storage unit is charged during off-peak hours when energy is cheaper and is discharged during peak load periods supplying customer loads. For industrial users who are charged not only according to energy consumption but also according to the highest power demand, the reduction of peak power demand means decreasing demand charges. This application is profitable for customers with a high peak to low demand ratio, particularly where there is a large difference between peak and off-peak energy charge.

6.3.3 Management and Control

Apart from new architecture, the key issue in the microgrid concept is the management and control system. It is intended to coordinate and optimize the operation of various energy sources and loads and to achieve the integration of distributed resources in the electrical power network without redesigning the network itself [27].

The system may perform the following tasks [22, 28, 29]:

- optimize production of local sources and power exchanges with utility;
- ensure the proper operation of sources satisfying the operating limits;
- increase the system reliability and efficiency through using storage;
- optimize heat utilization;
- ensure the uninterruptible supply of sensitive loads.

The system should also be responsible for the smooth transfer of the microgrid from grid-connected to island operation and supervise its operation in island mode [28].

An optimal power sharing scheme is established by the minimization of the total costs of electricity production, while providing the required power to the load. Load profiles and RES generation are known from daily forecasts. Mathematically the problem is formulated as multiobjective optimization at given constraints: find the settings for the energy supply equipment such that the total cost of electricity production is a minimum. The objective function may include the following components:

- fuel consumption rate, operation and maintenance costs, start-up costs – for each controllable unit,
- costs of power exchange with the supplying network,
- environmental emission costs,
- penalty costs when violating boundary conditions.

Objective constrains may encompass:

- power balance,
- generation capacity limits, minimum up/down time limits, and the maximum number of starts and stops – for each source,

- load carrying capacity for lines and transformers,
- voltage limits in nodes of the grid.

Various forms of the objective function are reported in literature for different microgrid architectures. The environmental impact of generation emission is taken into account in [30–32]. Renewable sources are assumed to work at the maximum available power and they are considered as negative loads. In [31, 32] energy storage is taken into account; this is used for storing excess energy to support the operation of renewable sources. The state of charge of the storage is monitored and storage power is considered in power balance. In microgrids with heat demand, optimization involves both electricity and the production of heat [33–36]. If storage systems are included in the optimization, storage power is added as a new variable and the problem is formulated as minimization of overall energy costs over the scheduling time period. This is because the operation of storage in any time period affects its operation in the following periods. In such cases the charging and discharging pattern of the storage is controlled [34, 35, 37].

The microgrid concept also assumes demand-side control. This is an important feature that, in practice, has not so far been present in conventional networks. It needs smart metering and controllable load devices to be installed at customer sites. Controllable loads may be entered into the demand response control strategy executed and supervised through the energy management controller to reduce peak load and level the load profile [19]. Demand-side control may also be implemented by customers individually. As the customer is provided with information about tariffs and energy consumption, he or she can control the loads in order to minimize energy costs. In this way active demand is accomplished, by the interaction of consumers with utilities. Decreasing peak loads through demand-side management (DSM) contributes to more reliable and efficient power supply. Demand-side management is used to control both electrical and thermal consumption [4] and is beneficial for end-users and utility.

Control strategy may be centralized and decentralized [19, 22]. The centralized control scheme is hierarchical and consists of central management which optimizes the microgrid operation and local control of generators, loads or storages. The central controller provides set points to the local control. Its common structure includes modules with different functionalities. In [34, 37, 38] three modules are proposed: forecasting, economic optimization, and on-line control. In the first module load profiles and RES generation forecasts are produced for a day ahead. The second module determines set points for all controllable devices based on the forecasts. An on-line control module adjusts the operating points for sources to maintain the power balance and the required power quality during real-time operation. Local controllers follow the orders of the central controller and are designed to control the operating points of sources and loads. The measured data for local controllers are local voltages and currents.

The use of centralized control is beneficial for small-scale microgrids when the owners of microsources and loads have common goals [22].

The decentralized control (also called autonomous control – [19, 22, 30]) is used in microgrids that have different owners and operate in market conditions. This control would be appropriate if local microsources have other tasks besides supplying power to the grid, such as heat production, maintaining the voltage at a certain level or providing a backup supply for local critical loads [22]. In this case each unit participating in the market performs its action autonomously. A multi-agent system approach is proposed to solve the problem [18, 39].

So far, most approaches assume a hierarchical-type two-level management and control scheme: central energy management and local power and voltage control of individual units [40]. However multi-agent-based approaches are proposed for future smart grids [23, 41].

A separate issue concerns microgrid control under islanding operation [40]. This includes maintaining suitable voltage and frequency levels for islanded loads. Energy sources have to be able to follow a load time course, so generation and load management become very important. To balance power generation and consumption various techniques can be used for both generation and load sides (load shedding).

Microgrid management and control is currently the subject of intensive research. It is a very challenging option in the search for energy savings. According to [35, 41], through optimized operation and management of microgrids that supply buildings, about 20% to 30% of building energy consumption can be saved. By considering the microgrid as an integrated energy system that provides customers with both electricity and heat, the optimal microgrid structure and technology of the sources may be identified. The objective is to meet customers' requirements with minimum costs. Research on designing microgrids using this approach has already been undertaken and some examples are presented in [17, 33, 35]. The development of the control strategy is the key issue in the practical transition towards microgrid-oriented system designs [4].

6.3.4 Power Quality and Reliability in Microgrids

Maintaining a high level of supply quality is one of the tasks of microgrid operation. High quality of power is required by customers and it contributes to the improvement of energy efficiency. Power quality control includes the stabilization of power produced by renewable sources and the mitigation of disturbances occurring at the grid, which deteriorate power quality. Traditionally, additional 'custom power' equipment has been applied for the mitigation of electromagnetic disturbances and improvement in power quality. Compensating devices such as DSTATCOM or APF systems play a similar role in distribution networks as FACTS systems do in transmission networks, therefore they are also called 'DGFACTS'.

Improving power quality by means of additional equipment is cost effective; therefore the decision to install a new device should be taken on the basis of detailed cost–benefit analysis. Customers' requirements are different; some of them may need the high level of power quality, while others do not. As power quality is controlled locally the level of power quality can be tailored more precisely to the requirements of end-users. According to [17] it might yield considerable benefits.

Networks with distributed generation provide the operator with new possibilities and solutions. Some of DER uses a power electronic interface to convert energy obtained by the source into AC power that is compatible with the grid. These converters can be used for accomplishing tasks similar to those performed by power electronic compensators. The additional functions of grid-coupling converters beyond their basic task, i.e. transferring active power/energy to the grid, are called ancillary services. The capability of DER to provide ancillary services is a unique option for microgrids to improve power quality and energy efficiency [21].

Figure 6.8 illustrates the possible operation of an inverter connected energy source providing ancillary services. In this case the system compensates for the reactive power and load unbalance. In 0.5 s the active power set value was decreased from 50 kW to 30 kW (load

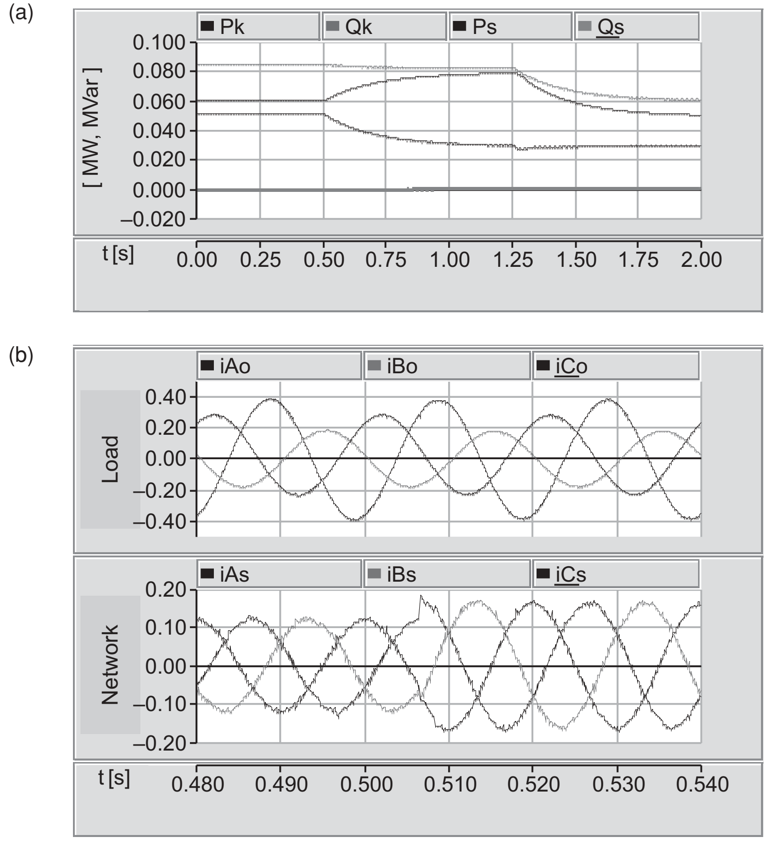

Figure 6.8 Operation of inverter connected energy source with ancillary services – results of simulation: (a) Pk, Qk are active and reactive powers of the source, Ps, Qs are active and reactive powers of the network; (b) iAo, iBo, iCo are load currents, iAs, iBs, iCs are network currents.

power constant), then in 1.25 s the load power was decreased by 30% proportionally in each phase (Figure 6.8(a)). The source reactive power changes as a result of load power changes (constant power factor) in order to keep the reactive power flowing to the grid constant. At the same time the system accomplishes the task of current compensation; load and network currents are presented in Figure 6.8(b).

Apart from various technical problems associated with DG integration, there are some non-technical issues that should be considered before the development of microgrids. They concern regulatory issues, pricing, decision priority, responsibility and incentives.

For example, taking advantage of the autonomous operation of the microgrid needs changes in the existing regulations, which require DES to trip in the case of any disturbance in the supplying network. Further, for DER with different owners the question is who will be responsible for controlling the operation of the microgrid. Or what are the incentives needed to get the DER owner interested in making his DER available for control or ancillary services?

The practical implementation of microgrids is a challenging task and needs further research and significant changes at the policy level in order to fully utilize the potential benefits.

References

[1] Directive No 2001/77/WE of 27 September 2001. Directive on the Promotion of Electricity Produced from Renewable Energy Sources in the Internal Electricity Market.
[2] M. H.-J. Bollen, Y. Yang and F. Hassan, Integration of distributed generation in the power system – A power quality approach, *Proc. 13th International Conference on Harmonics and Quality of Power*, Wollongong, Australia, 2008.
[3] R. Smit, *Cogeneration, Power Quality Application Guide*, Section 8 – Distributed Generation, LPQI, www.lpqi.org
[4] J. Driesen and F. Katiraei, Design for distributed energy resources, *IEEE Power & Energy Magazine*, May/June 2008.
[5] H. Jiayi, J. Chuanwen and X. Rong, A review on distributed energy resources and MicroGrid, *Renewable & Sustainable Energy Reviews*, **12**, 2008, pp. 2472–2483.
[6] Z. Styczynski and P. Komarnicki, *Distributed Energy Sources and Power Quality, Energy Storage Systems*, Leonardo Power Quality Initiative, http://www.leonardo-energy.org/
[7] Directive No 2004/8/WE of 11 February 2004. Directive of the European Parliament and of the Council on the Promotion of Cogeneration Based on a Useful Heat Demand in the Internal Energy Market and amending Directive 94/42/EEC.
[8] C. Marnay, H. Asano, S. Papathanassiou and G. Strbac, Policymaking for microgrids, *IEEE Power & Energy Magazine*, May/June, 2008.
[9] A. Oudalov, T. Buehler and D. Chartouni, Utility scale applications of energy storage, *Proc. 2008 IEEE Energy 2030 Conference (ENERGY 2008)*, 2008.
[10] A. Oudalov, D. Chartouni, C. Ohler and G. Linhofer, Value analysis of energy storage applications in power systems, *Proc. 2006 IEEE Power Systems Conference and Exposition (PSCE'06)*, 2006.
[11] P. Tomczyk, *Energy Storage Systems* (in Polish), http://www.smartgrid.agh.edu.pl/index.php/materialy5
[12] http://www.piller.com
[13] http://www.amsuper.com
[14] S. C. Smith and P. K. Sen, Ultracapacitors and energy storage: Applications in electrical power system, *Proc. 40th North American Power Symposium (NAPS'08)*, 2008.
[15] H. Wei, W. Xin, G. Jiahuan, Z. Jianhua and Y. Jingyan, Discussion on application of super capacitor energy storage system in microgrid, *Proc. International Conference on Sustainable Power Generation and Supply (SUPERGEN'09)*, 2009.
[16] C. L. T. Borges and D. M. Falcão, Optimal distributed generation allocation for reliability, losses, and voltage improvement, *Electrical Power and Energy Systems*, **28**, 2006, pp. 413–420.
[17] C. Marnay, G. Venkataramanan, M. Stadler, A. Siddiqui, R. Firestone and B. Chandran, Optimal technology selection and operation of commercial-buildings microgrids, *IEEE Transaction on Power Systems*, **23**(3), 2008.
[18] N. Hatziargyriou, H. Asano, R. Iravani and C. Marnay, Microgrids. An overview of ongoing research, development and demonstration projects, *IEEE Power & Energy Magazine*, July/August, 2007.
[19] F. Katiraei, R. Iravani, N. Hatziargyriou and A. Dimenas, Microgrid management. Controls and operation aspects of microgrids, *IEEE Power & Energy Magazine*, May/June, 2008.
[20] B. Kroposki, T. Basso and R. DeBlasio, Microgrid standards and technologies, *IEEE Power and Energy Society General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.
[21] B. Kroposki, R. Lasseter, T. Ise, S. Morozumi, S. Papathanassiou and N. Hatziargyriou, Making microgrids work, *IEEE Power & Energy Magazine*, May/June, 2008.
[22] R. Zamora and A. K. Srivastava, Controls for microgrids with storage: Review, challenges, and research needs, *Renewable and Sustainable Energy Reviews*, 14, 2010, pp. 2009–2018.
[23] N. W. A. Lidula and A. D. Rajapakse, Microgrids research: A review of experimental microgrids and test systems, *Renewable and Sustainable Energy Reviews*, **15**, 2011, pp. 186–202.

[24] S. Faias, P. Santos, F. Matos, J. Sousa and R. Castro, Evaluation of energy storage devices for renewable energies integration: application to a Portuguese wind farm, *Proc. 5th International Conference on European Electricity Market (EEM 2008)*, Lisbon, Portugal, 2008.

[25] K. Qian, C. Zhou, Z. Li and Y. Yuan, Benefits of energy storage in power systems with high level of intermittent generation, *Proc. 20th International Conference on Electricity Distribution – Part 1 (CIRED 2009)*, Prague, Czech Republic, 2009.

[26] E. Veldman, M. Gibescu, J. G. Slootweg and W. L. Kling, Technical benefits of distributed storage and load management in distribution grids, *Proc. 2009 IEEE Bucharest Power Tech Conference*, Bucharest, Romania, 2009.

[27] R. H. Lasseter and P. Piagi, Microgrid: A conceptual solution, *PESC'04*, Aachen, Germany, 20–25 June, 2004.

[28] B. Awad, J. Wu and N. Jenkins, Control of distributed generation, *Elektrotechnik & Informationstechnik*, **125**(12), 2008.

[29] A. Chuang and M. McGranaghan, Functions of a local controller to coordinate distributed resources in a smart grid, *IEEE Power and Energy Society General Meeting – Converse and Delivery of Electrical Energy in the 21st Century*, 2008.

[30] E. Alvarez, A. C. Lopez, J. Gomez-Aleixandre and N. Abajo, On-line minimization of running costs, greenhouse gas emission and the impact of distributed generation using microgrids on the electrical system, *IEEE PES/IAS conference on Sustainable Alternative Energy*, 2009.

[31] F. A. Mohamed and H. N. Koivo, On-line management of microgrid with battery storage using multiobjective optimization, *International Conference on Power Engineering, Energy and Electrical Drive POWERENG 2007*, 12–14 April, 2007.

[32] H. Vahedi, R. Noroozian and S. H. Hosseini, Optimal management of microgrid using differential evolution approach, *7th International Conference on the European Energy Market (EEM)*, 23–25 June, 2010.

[33] H. Asano and S. Bando, Economic Evaluation of Microgrids, *IEEE Power & Energy Society General Meeting*, 2008.

[34] W. Gu, Z. Wu and X. Yuan, Microgrid economic optimal operation of the combined heat and power system with renewable energy, *IEEE Power Energy Soc. Gen. Meet.*, 25–29 July, 2010.

[35] X. Guan, Z. Xu and Q.-S. Jia, Energy-efficient buildings facilitated by microgrid, *IEEE Trans. Smart Grid*, **2**(1), 2011.

[36] C. A. Hernandez-Aramburo and T. C. Green, Fuel consumption minimization of a microgrid, *39th Industry Application Conference Annual Meeting*, 3–7 October, 2004.

[37] S. Chakraborty and M. G. Simoes, PV-microgrid operational cost minimization by neural forecasting and heuristic optimization, *IEEE Industry Applications Society Annual Meeting*, 2008.

[38] A. Borgetti *et al.* An energy resource scheduler implemented in the automatic management system of a microgrid test facility, *International Conference on Clean Electrical Power, ICCEP'07*, 21–23 May, 2007.

[39] A. Dimeas and N. Hatziargyriou, Operation of a multi-agent system for microgrid control, *IEEE Transaction on Power Systems*, **20**(3), 2005.

[40] J. A. Pecas Lopes, C. L. Moreira and A. G. Madureira, Defining control strategies for microgrids islanded operation, *IEEE Trans Power Syst.*, **21**(2), 2006, pp. 916–24.

[41] C. M. Colson and M. H. Nehrir, A review of challenges to real-time power management of microgrids, *IEEE Power & Energy Society General Meeting*, 2009.

Further Readings

T. Ackermann, G. Andersson and L. Söder, Distributed generation: a definition, *Electric Power System Research*, **57**, 2001, pp. 159–204.

I. J. Balaguer, U. Supatti, Q. Lei, N.-S. Choi and F. Z. Peng, *Intelligent Control for Intentional Islanding Operation of Microgrids*, ICSET, 2008.

E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo and T. C. Green, Energy management system with stability constraints for stand-alone autonomous microgrid, *Systems of Systems Engineering*, 2007.

S. Chowdhury, S. P. Chowdhury and P. Crossley, *Microgrids and Active Distribution Networks*, IET renewable energy series 6, London IET, 2009.

N. Jenkins, R. Allan, P. Crossley, D. Kirschen and G. Strbac, *Embedded Generation*, IEE Power and Energy series 13, IET, London, 2000.

R. Mieński, R. Pawełek, I. Wasiak, P. Gburczyk, C. Foote, G. Burt and P. Espie, Power quality improvement in LV network using distributed generation, *IEEE 11th International Conference on Harmonics and Quality of Power*, Lake Placid, USA, 12–15 September, 2004.

R. Mieński, R. Pawełek, I. Wasiak, P. Gburczyk, C. Foote, G. Burt and P. Espie, Voltage dip compensation in LV networks using distributed generation, *IEEE 11th International Conference on Harmonics and Quality of Power*, Lake Placid, USA, 12–15 September, 2004.

R. Pawelek, I. Wasiak, P. Gburczyk and R. Mienski, Study on operation of energy storage in electrical power microgrid – modelling and simulation, *Proc. 14th International Conference on Harmonics and Quality of Power, September 2010*, Bergamo, Italy.

S. C. Smith, P. K. Sen and B. Kroposki, Advancement of energy storage devices and applications in electrical power system, *Proc. 2008 IEEE Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21th Century*, 2008.

G. Venkataramanan and C. Marnay, A larger role for microgrids, *Energy Magazine*, May/June, 2008.