Contribution of Microgrids in the Development of the Smart Grid

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Abstract

Microgrids are often regarded as fundamental building blocks of the smart grid. With respect to this characteristic, this chapter discusses the practical contribution of the microgrid in the development of the smart grid concept. Therefore, firstly, some applications of microgrids and their respective achievements are summarized. Secondly, the microgrid control, which is conceived as a hierarchical control, is discussed. The basic distinction between the two microgrid control levels considered here is based on the spatial perspective (local versus remote) and the time horizon. The primary controller is a fast, local and mostly automatic controller, the secondary controller is more remote and operates on a slower time frame. The microgrid secondary controller fits directly in the smart grid concept as it effectively uses the communication and metering assets of the smart grid. It is illustrated that the microgrid local primary controller can contribute significantly in easing the smart grid communication burden and enables fast and automatic control actions. This is demonstrated through a specific microgrid local controller called the voltage based droop controller, that eases the market participation of the microgrid and enables to control the local voltage.

1 Introduction

An approach to deal with the large increase of decentralized unpredictable power sources, the aging grid infrastructure and the increasing (peak) consumption of electric power, while mitigating the massive investments for this, is to add more intelligence to the power system. The usage of widespread information and communication technologies (ICT) to monitor and manage the distributed energy resources allows the grid to become more efficient and sustainable [1]. These ICT and new remote management abilities couple the grid elements via an interactive intelligent electricity network, the so-called smart grid. In brief, a smart grid involves the use of sensors, communication, computational ability and control to enhance the overall functionality of the electric power delivery system [2]. The smart grid offers many advantages, such as increasing the share of clean renewable energy, reducing costs, improving the system reliability in the face of increasing intermittency, enabling more customer choices and involvement for their energy management, a more efficient usage of the current assets and help utilization of electrical vehicles [3].

A barrier for the development of the smart grid is that the individual benefits for the consumers should be clear. A main challenge to increase the customer acceptance for smart grids is how to face the customers' concerns regarding cost, privacy and security, together with their fear of possible discomfort when they provide flexibility to the grid, e.g., potential disruptions for peak shaving. It is, thus, important to overcome the lack of understanding about the smart grid functionality and increase the customers' knowledge about the explicit benefits for them in specific. Along with lacking awareness about smart grids, consumers are not aware of which appliances are contributing most to their electricity bill. This leads to frustration as, despite best intentions, they are unable to significantly lower their bill [4]. Smart devices can help to address this issue by monitoring

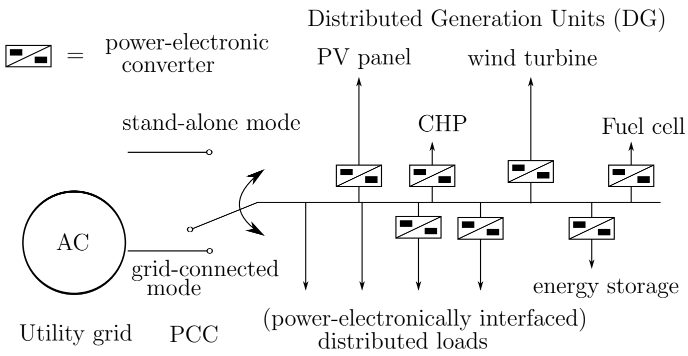

Figure 1: Microgrid with (power-electronically interfaced) loads, storage and DG units in stand-alone (islanded) or grid-connected mode

the consumption and comparing it with other consumers. End-user acceptance will ultimately determine the success of many aspects of smart grids [4].

With the massive penetration of distributed generation (DG) units, the current fit-and-forget principle of integrating these units into the electric power system is no longer a sustainable option and a coordinated approach is required. A method to capture the emerging potential of DG and to cope with the problems caused by the unconventional behavior and increasing penetration of DG, is to take a system approach instead of considering each unit separately [5–8]. In the system approach, the generators and loads are regarded as a subsystem, or microgrid as depicted in Fig. 1. Microgrids are small-scale electricity networks, consisting of an aggregation of (converter-interfaced) DG units, (controllable) loads and storage elements, that are connected to the utility network through a single point of connection, the point of common coupling (PCC) as shown in Fig. 2. In comparison with a single DG unit, a microgrid has more control flexibility to ensure the system's reliability and power quality requirements [9]. By cooperating, the microgrid elements can jointly achieve certain objectives, such as befitting from market participation and reducing the electricity cost through flattening of the aggregated load profile [10, 11]. Hence, microgrids are regarded as an important part in the successful integration of massive amounts of DG units and renewable energy sources [12, 13] and help in power quality issues [11, 14, 15]. Microgrids also offer potential to integrate local electrical and thermal networks to achieve a coherent generation, storage and load control, and to benefit from combined heat and power (CHP) generation, which is an important means of efficiency improvement [9].

Smart grids focus on system-wide improvements with microgrids as fundamental building blocks of the smart grid [16]. The grid will not become smart at once, but through a gradual evolution, hence, the smart grid will probably emerge as a system of integrated smart microgrids [3, 17]. Microgrids are better suited than the overall smart grid to clarify the benefits for the consumers because they inherently are geographically confined entities in which the microgrid elements are aggregated to focus on the specific benefits within the local entity, while smart grids focus on the more system-wide benefits.

Microgrids can provide power to a small community, which can range from a residential district and an isolated rural community, to academic or public communities such as universities or schools, and to industrial sites. Industrial parks can be managed as microgrids, e.g., to decrease the energy dependency, operate as low carbon business parks[1] and increase the economic competitiveness (increase the reliability, reduce the purchase of energy, reduce the peak consumption). Microgrids can operate either connected to the utility network in the grid-connected mode or independently from a main grid in the islanded mode.

The key objectives of microgrids are to provide a coordinated integration of DG in the electric power system, to improve the reliability, allow a more efficient use of energy and become a controllable entity in the network. Hence, the objectives of smart grids and microgrids are strongly

[1] www.ace-low-carbon-economy.eu

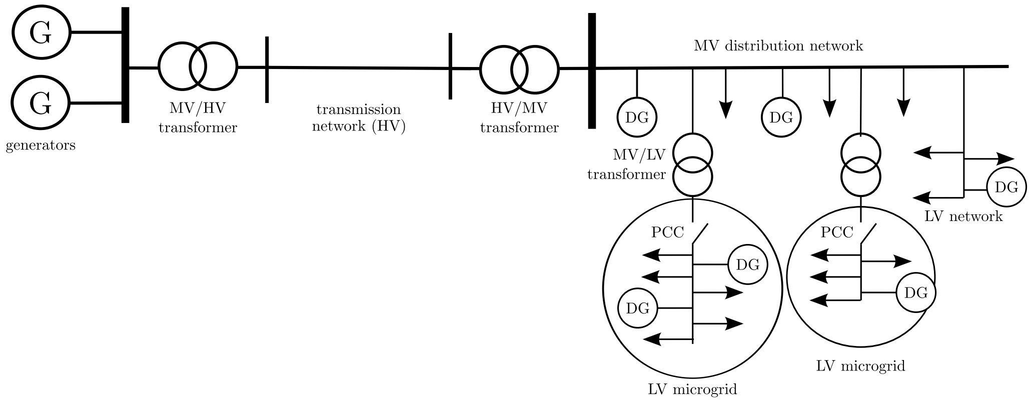

Figure 2: Microgrid connected to utility network through a PCC

related. In this sense, microgrids are fundamental building blocks of the smart grid that specifically focus on local issues and benefits, by making the end user not only a consumer, but an active part of the electricity network by enabling him to control and manage (part of) the energy that he will consume.

2 Microgrids

2.1 Benefits

Microgrids offer significant benefits in both the grid perspective and the consumer perspective. A key advantage from the grid's point of view is that the microgrid elements are collectively regarded as a single controllable unit, enabling the microgrid to deliver the cost benefits of large units [18]. In this way, utilities do not have to consider each unit separately for their system management. While not always obvious to utilities, microgrids can improve the economics and reliability of their service, help to meet renewable energy obligations, reduce congestion, improve power quality under high penetration levels of DG and support demand response. For example, microgrids can optimize a "troublesome" business complex or university campus, making it more economic and reliable to serve [1].

From the customers' point of view, firstly, the impact of the microgrid on the reliability of the distribution network is relevant, certainly in the future, with more unpredictable generation and higher consumption (peaks) [19–21]. Reliability is the first requirement of the electric power system. The cost of unreliability can have a considerable impact on the economy. The outage cost in the United States is estimated to amount to some US$ 79 billion per year, among which the momentary outages ($<$ 5min) account for US$ 52 billion [22, 23]. The consequences of grid failure are gigantic because the industry as a whole and the transportation, financial, communication and other critical sectors in specific are largely dependent on a guaranteed and reliable supply of energy [24]. Most of the reliability improvements will need to be introduced in the distribution system as most outage and power quality issues arise there. To increase the local reliability, back-up gensets and other emergency supplies are often installed near critical loads to provide uninterruptible power supply (UPS) functionality [25]. The costs of these designated devices, that run only during a limited amount of time, are significant. In this context, microgrids can provide the UPS functionality by exploiting the locally-available DG, storage and loads.

Secondly, aggregation of mixed assets in a microgrid can also provide considerable economic benefits to the microgrid subsystems, i.e., by allowing them to participate in the electricity and ancillary services markets.

Other benefits that can arise with the introduction of microgrids is that they can reduce feeder losses, remove transmission and distribution bottlenecks, provide reactive power and local voltage support, provide various other ancillary services such as heterogeneous power quality and reliability (i.e., differentiation based on the specific needs of the customers), increase efficiency through CHP and provide an easier large-scale integration of DG units [19, 26–29].

The main reasons for aggregating units in a microgrid are:

- to deal with power quality challenges. For example, some costumers require a higher power quality than others. In this sense, it is more economically attractive to locally increase the power quality than to upgrade the power quality of the entire power system. With respect to voltage quality in the distribution networks, microgrids are especially beneficial to provide voltage control as voltage is a local issue (in contrast with grid frequency for instance).
- to increase the reliability. The power system is exposed to several incidences that may affect the security of supply, such as lighting strikes, arc flashes on rainy days, falling trees, man-made faults and other accidents. Although these incidents are mostly covered by the protection devices, they can affect the reliability of the system. The common defense mechanism is to invest in the grid assets. However, grid extensions are increasingly countered by social resistance following the not-in-my-backyard principle. Even if these investments are made, natural disasters can completely annihilate part of transmission and distribution infrastructure. Hence, even if a certain area is not directly affected by the disaster, the power supply may be interrupted for long time. Microgrids can locally restore the system faster.
- optimal utilization of DG. Microgrids can coordinate their local generation, consumption and storage for using the available (renewable) energy optimally. Also, the connection of DG units in low-voltage networks can give rise to overvoltage problems. Rather than using the current full on-off control of the DG units, the microgrid can coordinate the loads and generation units to restrain the voltage in the microgrid while capturing as much renewable energy as possible.
- peak load limitations. A microgrid can manage its own generation and load, and, hence, reduce the peak consumption, which can have a significant impact on the electricity bill.
- reduction of transmission and distribution losses (with the subsequent energy costs). By locally coordinating its assets, the microgrid can become more independent of the rest of the power system.

2.2 Operating modes

Thanks to the single connection point between the microgrid and the utility network, microgrids can run in two operating conditions: grid-connected and islanded mode. Dependent on the operating mode, the microgrid can tackle one or more of the aforementioned issues.

2.2.1 Grid-connected mode

In the grid-connected mode, the microgrid supports the utility grid while exchanging power with it. In this mode, the microgrid can take economical decisions, such as controlling the power exchange with the utility network dependent on the on-site generation, its cost, the consumption and the prices on the energy markets. For the energy management, grid-connected microgrids have the following three assets at their disposal [8]:

1. dispatchable distributed energy resource (DER) controllers (DG and optional storage);
2. load management;
3. control of the power exchange with the main grid.

Generally, the normal condition of the microgrid is the grid-connected operation. A first advantage is that for the rest of the network, the microgrid can be seen as a controllable entity. This provides significant benefits for both the microgrid participants through scaling and aggregating, and for the distribution network operator, that does not need to consider all units separately [19, 27–29]. A second feature is that because of the single connection point between microgrid and utility network, the power exchange can be determined unambiguously and controlled to a predefined value. Hence, in the electricity markets, not the output power of each unit needs to be measured and traded, but solely the aggregated exchange. From the customers perspective, the main benefit of a grid-connected microgrid is that it can deliver the required scaling benefits to enable a profitable participation in the electricity markets. By aggregating several DG units, the installed power can be sufficient to enable the units, that are otherwise too small (a minimum capacity is required in the markets), to participate in the electricity markets and get better prices for their energy. Also, by aggregating different kinds of units, the risks of deviating predictions of production can be reduced. Thirdly, microgrids can provide ancillary services to the networks, such as reserve provision or reactive power support, become more self-reliant and decrease transmission and distribution losses.

2.2.2 Islanded mode

Although the normal operation mode of a microgrid is grid-connected, it offers the unique characteristic of islanding. By locally generating the consumed energy, and controlling the consumption to cancel the interchange of energy with the main grid, the microgrid can operate in a stable islanded mode. In the islanded operation, the microgrid operates independently of the main grid and consequently, the DG units, loads and storage devices are collectively responsible to maintain the integrity of the microgrid without the assistance of a main grid.

There are various reasons to go into an islanded mode. Reliability is one of the major concerns of the electric power system, mainly due to the high outage costs. These costs are however different for different types of customers. For instance,

- residential consumers mainly face a discomfort in case of a power outage;
- utilities can be faced with large costs due to loss of production;
- hospitals are affected significantly concerning people safety.

Critical systems like data centers and hospitals have emergency backup power, mostly from diesel-power generators, but these are inefficient, environmentally unfriendly and costly. Diesel generators are prone to failure and the diesel delivery can be problematic in case of large grid outages when the transportation routes are cut off. Also, opposed to microgrids, firstly, for diesel backup, there is usually a delay between the grid outage and the full operation of the diesel generation and secondly, diesel backup systems are not built to run for a long time. Transition from a purely diesel powered backup generator to a hybrid microgrid system that integrates different on-site sources with energy storage and load control increases the reliability of the back up system significantly [30]. Hence, in order to ensure the continuity of supply for the local load, a (short term) islanded mode can occur in case of special situations such as grid faults, outage of the bulk supply or power quality problems [12, 31–33].

It is important to note that the grid goes out a lot more than most people realize. In an average year, according to a 2008 Lawrence Berkeley National Laboratory study, the power is out an average of 92 minutes in the Midwest and 214 minutes in the Northeast. Many of these power outages are weather-related, i.e., caused by tornado, hurricane/tropical storm, ice storm, lightning, wind/rain. According to the Center for Research on the Epidemiology of Disasters, 100 million to 200 million people were affected by weather-related disasters between 1980 and 2009, with economic losses ranging from $50 billion to $100 billion annually. Another reason for grid outages can also be that much of the infrastructure which serves the U.S. power grid is aging. The average age of power plants is over 30 years, with most of these facilities having a life expectancy of 40 years [34]. Electric transmission and distribution system components are similarly aging, with power transformers averaging over 40 years of age and 70 % of the transmission lines being 25 years old or older. Lawrence Berkeley National Laboratory (LBNL) statistics show that 80 to 90%

of all grid failures in North-America originate in the distribution level of electricity service [3, 23]. For instance, momentary sags and surges on local distribution feeders are a common cause of breakdown and work stoppage at high-tech facilities like semiconductor fabs, research labs or data centers. The remaining 10 % of the grid failures stem from generation and transmission problems, which can cause wider-scale outages affecting larger numbers of customers.

Microgrids are able to deal with these power outages by operating in islanded mode. In this way, microgrids offer a potential improvement of the reliability, quality and costs of the system. Hence, microgrids are a good option in applications where electrical energy must be guaranteed at all times. For example, for hospitals, server centers and industrial facilities. However, they are a step beyond either emergency backup systems or stand-alone solar-panel arrays. They use special software and power electronics to integrate multiple sources of power and energy storage to provide electricity around the clock, even when the sun is not shining or regulations limit the use of diesel generators.

Other than to deal with rare (weather) incidents, islanding is also interesting when the main grid is not robust enough due to factors such as long distances from the main grid [35]. In this way, in extensive, highly dispersed countries such as Canada, USA and Japan, major efforts into microgrid research are being made. Microgrids can also switch into islanded operation due to planned maintenance operations.

In conclusion, true microgrids are much more than backup systems. They include real-time control to match the microgrid generation, storage and consumption. In the normal, grid-connected mode, they interact with the utility network in order to deliver power when the cost is highest and consume power from the grid when the cost is lower. In islanded mode, they can achieve independence of the main grid.

Examples

1. Reliability: Hurricane Sandy (U.S.)

In Oct. 2012, the super storm Sandy reached the east shore of the United States. This led to an electricity outage at a lot of places. Over two million connections were de-electrified, of which 750,000 connections in New York City. Two days after the super storm, still 6 million American people had no electricity, of which two thirds live in the states New York and New Jersey, according to the U.S. Department of Energy. The American president Obama pointed out that the restoration of the electricity supply was priority. However, one week after Sandy, still 1.4 million American people had no electricity according to the Department of Energy in Washington. This shows the vulnerability of the electricity grid facing extreme weather circumstances and the difficulty in restoring this massive system. Microgrids provide the unique opportunity of enabling a more reliable energy supply.

Although a lot of places had no electricity, a number of colleges, including Princeton and New York Universities, relied on their microgrids to keep power flowing to vital services during the Sandy storm. Princeton University typically gets its electric power from both from the local grid and on-site generation. During hurricane Sandy, Princeton was able to switch off the grid and power part of the campus with about 11 megawatt of local generation.

2. Reliability: 2011 earthquake and tsunami (Tohoku, Japan)

After the Great East Japan Earthquake and tsunami in 2011, around 4.4 million households in north-eastern Japan were left without electricity. In some areas, the outages would last for weeks. Likewise, the port city of Sendai was heavily hit, and faced two days of outage. But in one small section of the city, the lights stayed on. The Tohoku Fukushi University had an experimental microgrid project fed by three types of energy generators: fuel cells, solar panels, and natural gas microturbines. The microgrid system was able to island and operate as an independent energy source making it less vulnerable to the problems in the larger system. The microgrid continued to provide reliable power to a number of loads, including a hospital, for two days while the larger macrogrid halted power supply.

Even if a certain area is not directly affected by a natural disaster, the power supply may be interrupted for weeks or even months if the connection to the utility network is interrupted by the event. As the microgrid is not dependent of the utility grid, the immediate construction of microgrids appears feasible in some areas [36], e.g., in Japan after the tsunami strike. Microgrids can be planned and assembled in a short time. Furthermore, a power system disturbance can trigger a cascading outage, in which microgrids are virtually not affected.

3. Reliability: jail (U.S.)

At the Santa Rita Jail in California, a local microgrid project was officially launched in 2012. Since mid-1990, the jail has done major effort in efficiency upgrades. This has been pushed by the local government to protect the jail against rolling blackouts and spikes in the electricity prices, due to the California electricity crises in 2000-2001. Therefore, the jail has a significant amount of PV panels, a fuel cell power plant and some small wind turbines as on-site generators; and some diesel generators and batteries for backup. Next to efficiency improvements (lower costs), power reliability is a primary concern for the jail to ensure that large amounts of electricity are constantly kept available. Now, the facility forms a microgrid that can operate in islanded mode. The system keeps the power on, e.g., when storms take down the grid, which is essential for safety at the maximum security facility.

4. Integration of DG: jail (U.S.)

In Alcatraz, near San Francisco, there is a similar story. A feasibility study conducted by researchers from the University of Washington indicated that installing an undersea transmission cable from the Alcatraz island to San Francisco would be too costly. Hence, at first, some diesel generators were responsible for feeding the island. However, as the price of diesel began to climb, and the cost of solar PV fell, developing a state-of-the-art microgrid appeared attractive. Thanks to the combination of a PV installation and battery packs, it is expected that the solar-powered microgrid will reduce the running time of the diesel generators from 100% to 40%.

5. Power quality: industrial areas

In highly sensitive industrial areas, e.g., with chemical or semiconductor manufacturing facilities, a reliable power at high power quality is required. A high power quality is also very significant in the modern health-care [37]. Electronic equipment is commonly designed for power supplies with specific voltage and current characteristics. When voltage or current levels deviate from the specified quality standards, electronic equipment can be damaged or fail, which may cause high-tech medical equipment to malfunction, resulting in extended patient discomfort, misdiagnoses, increased equipment downtime and service costs, and even life-threatening situations [37].

Health-care facilities with extremely sensitive electronic equipment and high reliability needs are increasingly recognizing the limitations of the traditional solutions to the costly occurrence of power-quality problems. Microgrids can be tailored to the specific needs of these end-user and provide so-called premium power customers with finely calibrated power flows [37]. They can provide an integrated power supply with different levels of power quality. Hence, instead of alleviating the power quality levels of the entire grid, microgrids can locally ensure the required power quality at a more acceptable cost.

6. Maintenance: Hydro-Quebec (Canada)

The islanded microgrid of the Canadian electric utility Hydro-Québec was the result of an urgent need for the maintenance of the transmission line feeding a substation named Senneterre, where a privately-owned thermal power plant (Boralex) was connected to. The substation feeds three distribution lines, serving 3000 customers in the municipality of Senneterre and its surrounding area. Standing on wooden structures, this line, more than 55 years old, required urgent replacement of its angle and stop portals [38]. This type of maintenance can only be performed on a de-energized line [38]. To avoid service interruption for the customers during the restoration of the transmission line, the Boralex power plant was used for islanding the microgrid. The first maintenance work of the transmission line began in fall 2006 [38].

7. Mobile: military bases

The United States Department of Defence put high urgency on mobile tactical microgrids. These microgrids need to be very modular. They need to be deployed very fast (matter of days) and afterwards deconstructed and moved to another location. The ability for fast construction and deconstruction is not the only reason for using the microgrid concept in military systems. Microgrids can significantly attenuate the cost of the transport of oil and gas to the military bases, which are often stationed in remote locations.

8. Reliability and energy cost: BC Hydro Boston Bar substation (Canada)

In areas with frequent loss of electrical power, e.g., in countries with weak grid infrastructure, extended lines or harsh weather circumstances, islanded systems can reduce the loss of electrical power. An example is deployed by the Canadian electric utility BC Hydro. In the Boston Bar area, BC Hydro can switch to an islanded operating mode of the interconnected feeder during outages in its radial transmission line. This line had proved to be insufficiently reliable because it is a single radial supply with a long feeder, which is moreover subjected to frequent outages because of falling rocks and trees, mud, storms and motor vehicles. By including the ability to island, the reliability of the system has significantly increased.

9. Dealing with the growing demand for electricity: independence

The increasing usage of electricity[2], demands for the construction of new power plants and power lines. However, due to the common not-in-my-backyard attitude, these investments are significantly being delayed. Microgrid structures can ease this attitude as they limit the construction of new lines and when installed, the direct need for the local consumer is inherently clear, opposed to the case where long transmission lines are built. Hence, they can relieve distribution and transmission expansion issues.

2.2.3 Remote islanded mode

Although not strictly according to the definition of a microgrid, an islanded microgrid can also exist in case of remote electrification, where no main grid is available due to, e.g., geographical issues. According to the World Bank's 2010 development report, 1.6 billion people in developing countries do not have access to electricity [39]. The most important reason is the extensive investment needed to install power lines across large distances and/or rough terrain for expanding the electricity supply to a few people. It is recognized that electricity is a key driver in economical growth and to combat poverty. Hence, islanded microgrid projects provide great opportunities to realize sustainable human development. According to the International Energy Agency (IEA 2009), 83 % of the people that do not have access to electricity live in rural areas [40], e.g., over one third of India's rural population. The Indian government targets at providing all its households with electricity in the near future [41]. In case a conventionel grid connection is not cost-effective to accomplish this, decentralized electric power with local distribution is taken under consideration, i.e., islanded microgrids, with an example in the Sundarbans Islands region in India [41].

Two examples of remote islanded microgrid are given below.

1. Serving loads in remote locations that lack infrastructure (Uganda, India)

Uganda faces a limited supply of electricity, less than 10 % of the Ugandan population have access to electric power. Especially rural areas are not yet electrified because of the high costs of the grid extensions this would require. Without electricity, economic growth is constrained, limiting the chances of combating poverty in the regions. Also, hospitals can only deliver a limited service. A solution can be provided by small decentralized (hydro) power stations. Therefore, in Uganda, several projects are running, such as the Suam project, which enable to use small microgrids that are often fed by hydro power for the electrification.

Remote microgrids are also apt to electrify Indian villages which do not yet have power. Nearly 400 million Indian people, most living in rural communities, lack access to the grid. For the electricity access, these people need to go to the city. They also generally use kerosene filled lamps, which are unhealthy and unsafe, instead of electric lighting. Microgrids offer a great opportunity in delivering electricity to these communities.

2. Serving islands (Greece)

As of today, many Greek Aegean Islands are not connected to the mainland grid and, thus, rely on polluting and costly-inefficient diesel generation to fulfill their electricity demands. Fortunately, most islands have optimal wind potential and solar resources. The exploitation of these resources

[2]For energy efficiency reasons, both the transportation and heating are becoming more and more electrified, e.g., through the usage of electrical vehicles and heating pumps.

provides a cheaper alternative to the current diesel generation and would result in significant savings and lower electricity prices.

2.3 Smart microgrids

It is not realistic that the growth of the smart grid would be a revolution. Instead, a gradual evolution is expected [3,17]. Because of their flexibility and scalability, microgrids are likely to play a key role in the evolution of the smart grid [42] with smart microgrids as small pilot versions (building blocks) of the future power system [16]. Hence, the smart grid will probably emerge as a system of integrated smart microgrids [3]. Smart microgrids are microgrids combined with an overlaying intelligence scheme. The intelligent software implemented in the microgrid can:

- contain energy management systems;
- monitor the system (energy supply, storage and demand) and actively intervene in the consumption/generation;
- identify and maximize energy efficiency opportunities;
- use an extra communication and sensor layer to maximize cost savings and reduce carbon emissions;
- generate a more active participation of the consumers.

A balance between the cost to incorporate intelligence in the grid and the subsequent benefits needs to be made. Furthermore, the infrastructure and control centers for smart grids can be hard to implement on a large scale and this may take many years. Rather than investing in incorporating intelligence on a large scale, investing in small smart microgrids (such as business areas) can be done at a lower cost and more quickly. Also, a high level of intelligence built everywhere in the system is not necessary: different areas require different levels of smartness. The areas that allow more and benefit most from high levels of smartness of the system, such as areas with high penetration of DG, can fit directly into the microgrid concept. In these microgrids, smart features can be installed faster than in the rest of the network with locally higher levels of intelligence than average. In this way, the smart microgrids can enable a new energy strategy while restraining the cost of making the whole system smart.

3 Microgrids in the smart grid paradigm

3.1 Similar benefits and aims

Essentially, the goals of microgrids and smart grids are the same: to minimize costs, meet the growing demand, integrate more sustainable generation resources by maximizing generation assets and increase the efficiency of the power system.

The main difference between microgrids and smart grids is that the microgrid is a building block of the overlaying smart grid. Microgrids aim at a local control and an optimization of their local assets, with contribution to the higher level utility network. Because of this local scope, microgrids directly focus on the value proposition of their customers. In contrast, as smart grids focus on more system-wide issues, an important challenge of smart grids is making the value for the achieved benefits clear to the customers.

3.2 Microgrid control

Like in the conventional power system, the microgrid control can be conceived in a hierarchical control structure. Microgrid control can be divided in

- local primary control
- supporting (smart grid) services in an overlaying (secondary/tertiary) control

3.2.1 Smart microgrid control

The smart microgrid control is conceived as a high-level (secondary) control structure, which defines new set points for the local controllers. Smart microgrid control can take full benefit from smart grid features, such as communication and metering data. With respect to this control level, the microgrid is a building block of the smart grid. Like the primary controller, the secondary controller can tackle technical issues, but extended with possible economical/societal/environmental objectives. The secondary controller can achieve a further optimization of the microgrid (e.g., fuel savings), coordinate the primary control actions, restore pre-agreed consumption patterns, restore the voltage to its nominal value (amplitude and/or frequency) and control the import/export of microgrid energy. For instance, the secondary/tertiary controller can address social issues of the producers if the physical position in the grid impacts the amount of power one can inject (and hence, also impacts the financial reimbursement for the energy delivered to the grid).

3.2.2 Local microgrid control

The local microgrid control is a primary control level operating without communication. In this sense, it goes beyond the smart grid control as it is faster and depends on local measurements only. In islanded microgrids, the local microgrid controller is responsible for the reliability of the system. In grid-connected microgrids, the local controller can contribute in achieving a proper voltage quality. The contribution of the local microgrid controller in easing smart grid communication is clear as the local controller can achieve fast and reliable control actions, not depending on communication and remote measurements.

An overview of various primary control strategies is given in [43]. For (extended) islanded microgrids, the droop concept is most promising to ensure a reliable system operation. Here, the active power/grid voltage (P/V) droop concept in general and the voltage-based droop (VBD) controller [44] in specific are highlighted in this chapter.

Droop controllers in microgrids are derived from the well-known active power/grid frequency (P/f) droop control principle incorporated in the large central synchronous generators in the conventional electric power system. While the P/f droop control method works well in a microgrid with mainly inductive line impedances, it leads to a concern when implemented on a low-voltage microgrid, without significant inertia and where the line resistance should not be neglected [9]. In case of mainly resistive lines, the active power (P) is linked with the voltage difference (V), while reactive power (Q) is linked with the phase angle, hence frequency (f). This leads to P/V and Q/f droops as opposed to the conventional P/f and Q/V droops [45–47]. The active and reactive power are measured and drooped to obtain the rms voltage and its frequency ($\omega = 2\pi f$) respectively:

$$V_{\mathrm{g,i}} = V_{\mathrm{g,ref}} - K_{\mathrm{P}}(P_i - P_{\mathrm{i,ref}}) \tag{1}$$

$$\omega_i = \omega_{\mathrm{ref}} + K_{\mathrm{Q}}(Q_i - Q_{\mathrm{i,ref}}) \tag{2}$$

with K_{P} and K_{Q} the droop coefficients.

The voltage-based droop (VBD) control of [44] is a variant of P/V droop control that focuses on the optimal integration of renewables in the network and also incorporates a dc-bus controller. In the VBD control, the P/V droop controller is divided into two droop controllers and constant-power bands are included as depicted in Fig. 3. Further details of these control loops are given in [44]. The parameter $2b$ determines the width of the constant-power band. In case the terminal voltage of the DG unit is in the constant-power band, i.e., $(1-b)\,V_{\mathrm{g,ref}} < V_{\mathrm{g}} < (1+b)\,V_{\mathrm{g,ref}}$, the DG unit delivers its reference power. Otherwise, the power of the DG unit is changed. A distinction is made between dispatchable and less dispatchable DG units.

For dispatchable DG units, analogous as for the central large generators, P_{ref} represents the scheduled power that can be determined in the electricity markets. In this case, the value of b is small, such that the unit reacts on small variations of the grid voltage.

For less dispatchable DG units, such as many renewables, a wider constant-power band is used. In this way, these units do not react on all load variations but change their output power only in case

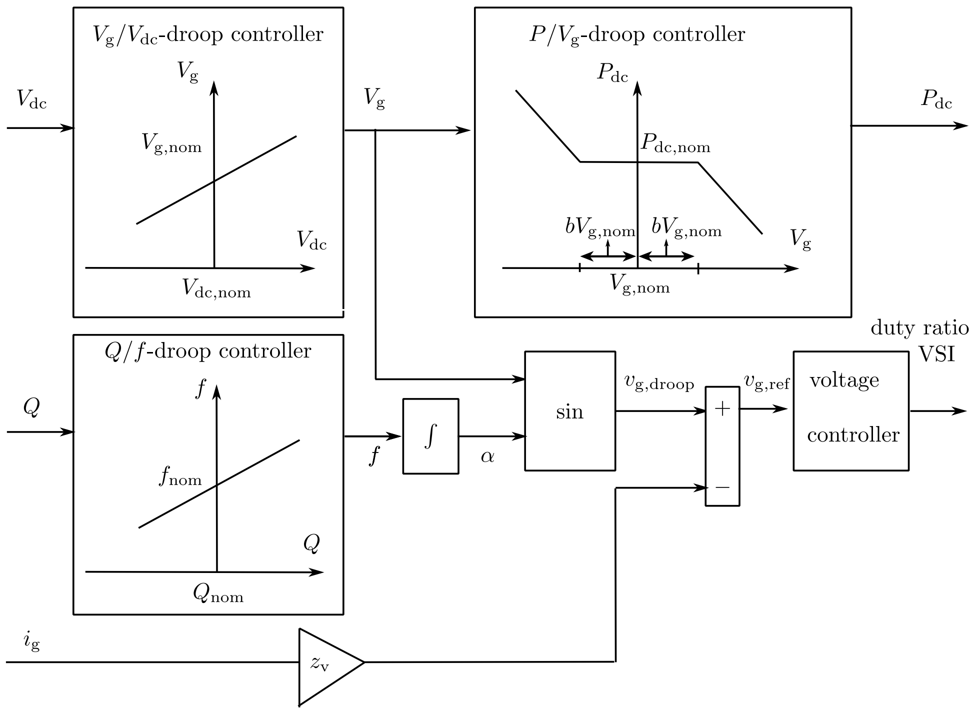

Figure 3: VBD controller and virtual impedance loop

of more extreme voltage variations compared to the dispatchable DG units. These extreme voltages occur merely when the power limits of the dispatchable DG units are nearly reached. Consequently, an optimized integration of renewables is possible because the VBD control prioritizes the power changes of the units, by setting different values of b, without the need for communication. In these units, P_{ref} can, for example, represent the instantaneous maximum power point of a wind turbine. Also, as voltage is a local parameter, the voltage limits are sometimes already reached in areas where the ratio dispatchable versus less dispachtable DG units is low. The current fit-and-forget strategy of integrating DG, solves these voltage problems by turning the DG units off. In contrast, the VBD controller uses soft power curtailment to capture more of the renewable energy. In this way, voltage problems can be overcome as the renewables also take part in the voltage control.

As shown in Fig. 3, the V_g/V_{dc} and Q/f droop controllers, which are digital controllers, determine the droop voltage $v^{\star}_{g,droop,k} = V_{g,k}\sin(\alpha_k)$ (k is the discrete time instance). Discrete values are used because pulse width modulation with sampling period T_s is used in the converter. The amplitude V_g of the droop voltage is obtained from the V_g/V_{dc} droop controller and the phase angle is obtained from the frequency f in the Q/f droop controller. Together, they determine

$$v^{\star}_{g,droop,k} = V_{g,k}\sin(\alpha_{k-1} + 2\pi f_k T_s) \tag{3}$$

Fig. 3 also shows the virtual output impedance loop. A resistive output impedance $z_v = R_v$ is chosen as this provides more damping in the system [48] and complies with the power control strategies of the loads and generators, where the active power is changed based on the grid voltage:

$$v^{\star}_g = v^{\star}_{g,droop} - R_v i_g \tag{4}$$

with $v^{\star}_g$ the reference voltage for the voltage controller, $v^{\star}_{g,droop}$ the voltage obtained by the VBD controller and i_g the current injected into the microgrid, as illustrated in Fig. 4.

In this chapter, the contribution of the VBD control in grid-connected microgrid for operating the grid in a smarter manner is illustrated.

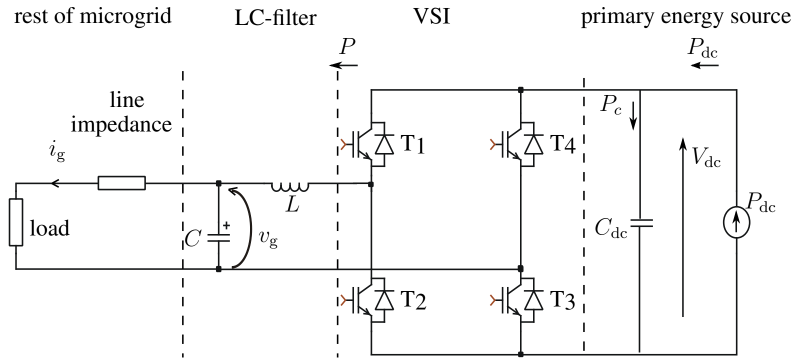

Figure 4: DG unit connected to the microgrid. Parameters (v_{g}, i_{g}, V_{dc}, P, P_{dc})

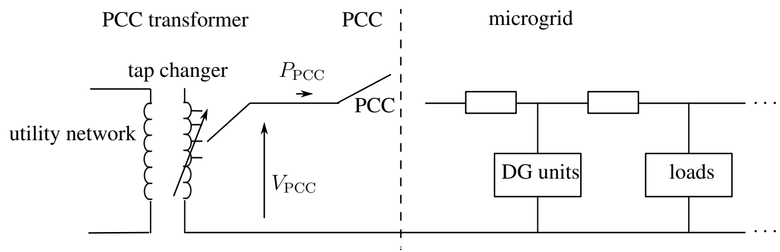

Figure 5: Smart transformer located at the PCC of a microgrid

1. Market operation The amount of power export/import is pre-agreed in the markets, e.g., on a day-ahead basis. For example, when the electricity price is high, the microgrid will import as little power as possible from the grid or even export power. A requirement for market participation of a microgrid is, thus, that the power exchange between microgrid and utility networks can be controlled to the value which is agreed upon. This is conventionally achieved by using a microgrid central controller that communicates new set points to all units. However, this may lead to possible delays and a significant communication burden. Therefore, in [49], the usage of a so-called smart transformer is discussed. The smart transformer is a tap changing transformer, connected at the point of common coupling (PCC) of the microgrid as depicted in Fig. 5. The transformer is smart in the sense that the control strategy for changing the microgrid-side voltage is able to control the power exchange to the set value by changing its taps. In MV networks, on-load tap changing transformers are sometimes already available, hence, controlling these as smart transformers requires only little modifications. In the lower voltage networks, most PCC transformers are manual tap changing transformers, from which the voltage can only be controlled offline and not automatically. This puts a significant stress on the electrical grids which face and increased penetration of DG units. Historically, the planning of the low-voltage grids is based on a worst-case scenario ensuring that in case of maximum consumption, the voltage does not drop below the lower voltage limit. Therefore, many tap changing transformers at the beginning of the low-voltage lines are set somewhat above the nominal voltage. However, with the increasing degree of DG units, the risk of overvoltages becomes higher. Also, the planning becomes more difficult because of the larger voltage variations (e.g., sunny day times versus night times). Hence, the ability of automatically changing the tap settings becomes more interesting as it is more effective, fast and cheaper to implement than the conventional approach of investing in more lines and larger transformers. Therefore, in future, it can be beneficial to install an on-load tap-changer (OLTC). Moreover, it is well known that a lot of the assets in distribution networks are end-of-life and have to be replaced anyhow in the following years. Hence, the manual transformers can gradually be upgraded to OLTCs.

The OLTC transformer, with smart control strategy, i.e., the smart transformer, controls the PCC power (P_{PCC}) by changing the microgrid side voltage (V_{PCC}). If the microgrid elements are equipped with the VBD control strategy, these elements automatically react by changing their input/output power dependent on the grid voltage. For example, when the PCC power exported to the utility network is lower than its pre-agreed value ($P_{\text{PCC,ref}}$), the smart transformer will lower V_{PCC}. The microgrid DG units react on this voltage drop by increasing their output power P, hence, increasing P_{PCC}. In this way, the PCC power can be controlled by the smart transformer, without the need to communicate new set points to all grid elements as they automatically react. A second advantage is that in this way, a virtual islanded mode is achieved. The utility grid is not seen as a slack bus, but is conceived as a constant-power load/generator, i.e., the power agreed upon in the markets. The smart transformer can facilitate the distribution network management as the distribution network operator only needs to communicate to the microgrid central controller, which instead of facing all microgrid elements separately can rely on an automatic response of the microgrid elements on a changing grid voltage induced by the smart transformer.

2. Voltage control in low-voltage networks Although developed for islanded microgrids, the VBD controller can be used in grid-connected microgrids as well [50]. Moreover, it offers significant advantages, firstly in the voltage control (avoiding over voltage) and secondly in avoiding on-off oscillation of DG units (increasing the renewable energy capturing).

Firstly, a well known issue of connecting DG units in the low-voltage systems is the possible over-voltage due to the injection of active power by the DG unit. Generally, in low-voltage networks, other than the system planning, there is little or no means for voltage control. On the other hand, the large penetration of small DG units in these networks offers a unique opportunity to use their controllability for voltage control in the network.

The conventional approach for voltage control is by injecting/consuming reactive power, mirrored with the voltage control in the transmission network. In [51], the required amount of reactive power Q that a DG unit should consume to erase its impact on the voltage is calculated. A minimal impact is achieved when the DG unit consumes (minus sign) reactive power according to:

$$Q = -\frac{R}{X}P, \tag{5}$$

with R and X the line parameters and P the generated active power of the DG unit. Here, a uniform distribution of load along the feeder and a constant resistance and reactance per unit length are assumed. Still, a small impact remains due to the power losses associated with transport of power over the network, which are not included in (5). In this chapter, low-voltage networks, which are mainly resistive, are considered, hence, with a high R/X, i.e., generally larger than three. According to (5), in these networks with $R >> X$ (low-voltage microgrids), a DG unit needs to consume a lot of reactive power to minimize the voltage rise due to its active power injection in the grid. Conversely, reactive power consumption only has little effect on the voltage of the system. Hence, it will predominantly increase the network losses. Furthermore, such large amounts of reactive power can generally not be consumed by the generators without significant overrating.

The VBD control achieves an automatic soft curtailment of the DG units, but because of the usage of constant-power bands, this is done in a predefined priority order. The renewables are softly curtailed only when absolutely necessary. In this way, the DG units can control the system voltage by using the VBD controller, without the need for designated devices for voltage control.

Currently, renewables fully turn off when their terminal voltage exceeds a certain voltage level. As a single unit can have large impact on the grid voltage, this may lead to the voltage dropping significantly, such that the unit may turn on again. This may lead to on-off oscillations of renewables in LV networks. An example of a measurement of such an oscillation is depicted in Fig. 6. The on-off oscillations can also occur between multiple units that turn on and off in turn. In [50], it is illustrated that the grid-connected VBD control can firstly, avoid these on-off oscillations, and secondly, subsequently can achieve a higher renewable energy capturing. A result from this paper is depicted in table 1. The output energy for three DG units, which are connected to a

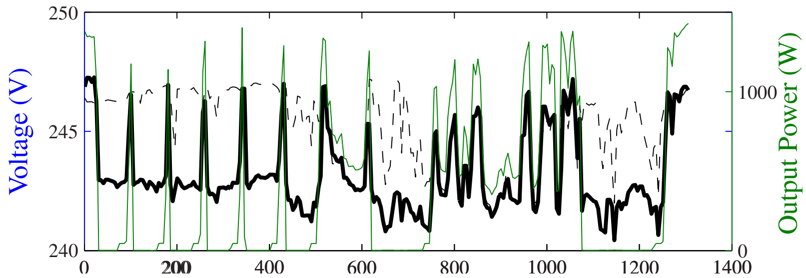

Figure 6: On/off control of DG leading to grid-oscillations: measurements of PV panels in Oostende, Belgium (— = DG unit 1, --- = DG unit 2, ━━━ = V_{PCC})

Table 1: Renewable energy capturing: comparison on/off control versus VBD control

	On-off control	VBD control	gain
DG 1 (E [J])	9794	11539	18 %
DG 2 (E [J])	9122	9402	3 %
DG 3 (E [J])	4002	4741	18 %

feeder with multiple RL loads is given. The details about the configuration are given in [50]. The on-off control of the units leads to on-off oscillations in the system, which in turn lead to a lowered captured renewable energy compared to the case with VBD control. Hence, although soft curtailment instantly results in a loss of the available renewable energy, it may increase the total energy capturing by avoiding on/off oscillations, when the priority is set, e.g., by using the VBD concept.

4 Conclusion

This chapter illustrates that microgrids can significantly contribute in developing the smart grid. Some examples of microgrids in grid-connected and islanded mode are given, including the benefits they bring to the smart grid. The microgrid control consists of two layers: a fast and automatic primary controller and an overlaying slower controller. The latter can take full advantage of the communication and metering of the smart grid, hence, fits fully in the smart grid scope. The primary controller brings a significant contribution to the smart grid in the sense that it facilitates the smart grid control and eases the communication burden. This is illustrated through a discussion of the contribution of VBD control in firstly, controlling the power exchange between microgrid and utility networks with a minimum of communication and secondly, in the voltage control.

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References

[1] K. Iniewski, Ed., *Smart Grid Infrastructure & Networking.* McGraw-Hill Professional, 2012.

[2] C. W. Gellings, *The Smart grid, enabling energy efficiency and demand response.* The Fairmont Press, 2009.

[3] H. Farhangi, "The path of the smart grid," *IEEE Power & Energy Magazine*, vol. 8, no. 1, pp. 18–28, Jan./Feb., 2010.

[4] DNV KEMA, "Global ineventory and analysis of smart grid demonstration projects," Netbeheer Nederland, Tech. Rep., Oct. 22, 2012.

[5] R. H. Lasseter, J. H. Eto, B. Schenkman, J. Stevens, H. Vollkommer, D. Klapp, E. Linton, H. Hurtado, and J. Roy, "CERTS microgrid laboratory test bed," *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 325–332, Jan. 2011.

[6] M. Popov, H. Karimi, H. Nikkhajoei, and V. Terzija, "Modeling, control and islanding detection of microgrids with passive loads," in *14th Internat. Power Electronics and Motion Control Conf. (EPE/PEMC)*, Ohrid, Republic of Macedonia, Sept. 6-8, 2010.

[7] A. Engler, O. Osika, M. Barnes, N. Jenkins, and A. Arulampalam, *DB1 Local Micro Source controller strategies and algorithms.* www.microgrids.eu/micro2000, European Commission, Feb. 2004.

[8] J. Driesen and F. Katiraei, "Design for distributed energy resources: Microgrid planning and architectures for improved reliability and integration," *IEEE Power & Energy Magazine*, vol. 6, no. 3, pp. 30–40, May/June 2008.

[9] Y. W. Li and C. N. Kao, "An accurate power control strategy for power electronics interfaced distributed generation units operating in a low voltage multibus microgrid," *IEEE Trans. Power Electron.*, vol. 24, no. 12, pp. 2977–2988, Dec. 2009.

[10] R. H. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A. Meliopoulous, R. Yinger, and J. Eto, "The CERTS microgrid concept, white paper on integration of distributed energy resources," in *California Energy Commission, Office of Power Technologies - U.S. Department of Energy, LBNL-50829, http://certs.lbl.gov*, Apr. 2002.

[11] R. H. Lasseter and P. Paigi, "Microgrid: A conceptual solution," in *Proc. IEEE Power Electron. Spec. Conf. (PESC 2004)*, Aachen, Germany, 2004.

[12] M. Bollen, J. Zhong, O. Samuelsson, and J. Björnstedt, "Performance indicators for microgrids during grid-connected and island operation," in *Proc. IEEE Power Tech. Conf.*, Bucharest, Romania, June 28 - July 2, 2009.

[13] A. Vaccaro, M. Popov, D. Villacci, and V. Terzija, "An integrated framework for smart microgrids modeling, monitoring, control, communication, and verification," *Proc. IEEE*, vol. 99, no. 1, pp. 119 – 132, Jan. 2010.

[14] N. Pogaku, M. Prodanović, and T. C. Green, "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 613–625, Mar. 2007.

[15] M. A. Pedrasa and T. Spooner, "A survey of techniques used to control microgrid generation and storage during island operation," in *Australian Universities Power Engineering Conf. (AUPEC2006)*, Dec. 10-13, 2006.

[16] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, "Secondary control scheme for voltage unbalance compensation in an islanded droop-controlled microgrid," *IEEE Trans. on Smart Grid*, vol. 3, no. 2, pp. 797–807, Jun. 2012.

[17] M. Kezunovic, V. Vittal, S. Meliopoulos, and T. Mount, "The big picture: Smart research for large-scale integrated smart grid solutions," *Power and Energy Magazine, IEEE*, vol. 10, no. 4, pp. 22–34, 2012.

[18] A. G. Tsikalakis and N. D. Hatziargyriou, "Centralized control for optimizing microgrids operation," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 241–248, Mar. 2008.

[19] P. M. Costa and M. A. Matos, "Assessing the contribution of microgrids to the reliability of distribution networks," *El. Power Systems Research*, vol. 79, no. 2, pp. 382–389, Feb. 2009.

[20] K. De Brabandere, "Voltage and frequency droop control in low voltage grids by distributed generators with inverter front-end," Ph.D. dissertation, KU Leuven, Leuven, Belgium, Oct. 2006.

[21] R. H. Lasseter and P. Piagi, "Control and design of microgrid components," Power Systems Engineering Research Center (PSERC), Tech. Rep., Jan. 2006.

[22] X. Tan, Q. Li, and H. Wang, "Advances and trends of energy storage technology in microgrid," *Internat. Journal on Electrical Power and Energy Systems*, vol. 44, no. 1, pp. 179 – 191, 2013.

[23] K. H. LaCommare and J. H. Eto, "Understanding the cost of power interruptions to u.s. electricity consumers," Ernest Orlando Lawrence Berkely National Laboraty, Tech. Rep., 2004.

[24] S. M. Amin and B. F. Wollenberg, "Toward a smart grid," *IEEE Power & Energy Magazine*, vol. 3, no. 5, pp. 34–41, Sep./Oct. 2005.

[25] C. Marnay and R. Firestone, "Microgrids: an emerging paradigm for meeting building electricity and heat requirements efficiently and with appropriate energy quality," Environmental Energy Technologies Division, U.S. Deparment of energy, presented at the European Council for an Energy Efficient Economy 2007 Summer Study, La Colle sur Loup, France, Tech. Rep., June 4-9, 2007.

[26] T. C. Green and M. Prodanovíc, "Control of inverter-based micro-grids," *Electric Power Systems Research*, vol. 77, no. 9, pp. 1204–1213, Jul. 2007.

[27] H. Jiayi, J. Chuanwen, and X. Rong, "A review on distributed energy resources and microgrid," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 9, pp. 2472–2483, Dec. 2008.

[28] C. Marnay and G. Venkataramanan, "Microgrids in the evolving electricity generation and delivery infrastructure," in *Proc. IEEE PES General Meeting*, Montréal, Canada, June 18-22, 2006.

[29] P. Basak, A. K. Saha, S. Chowdhury, and S. P. Chowdhury, "Microgrid: control techniques and modelling," in *The 44th International Universities' Power Engineering Conference (UPEC 2009).* Glasgow, Scotland, Sep. 1-4, 2009.

[30] T. Casey. (2013, Feb. 12) The Spiders microgrid project. [Online]. Available: http://cleantechnica.com

[31] European Commission. (2003) New ERA for electricity in Europe. Distributed generation: Key issues, challenges and proposed solutions. [Online]. Available: www.smartgrids.eu

[32] F. Katiraei, M. R. Iravani, and P. W. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 248–257, Jan. 2005.

[33] H. Mohamad and P. Crossley, "Islanded operation of UK radial distribution earthing strategy," in *The 44th International Universities' Power Engineering Conference (UPEC 2009).* Glasgow, Scotland, Sep. 1-4, 2009.

[34] R. J. Campbell, "Weather-related power outages and electric system resiliency," Congressional Research Service Report for Congress, Tech. Rep., Aug. 28, 2012.

[35] E. Planas, A. Gil-de-Muro, J. Andreu, I. Kortabarria, and I. Martínez de Alegría, "General aspects, hierarchical controls and droop methods in microgrids: a review," *Renewable and Sustainable Energy Reviews*, vol. 17, no. 5, pp. 147–159, 2013.

[36] Siemens. (2011) Microgrid white paper. [Online]. Available: www.energy.siemens.com

[37] Center for Energy, Marine Transportation and Public Policy at Columbia University, "Microgrids: an assesment of the value, opportunities and barriers to deployment in new york state," New York State Energy Research and Development Authority (NYSERDA), Tech. Rep., Sep. 2010.

[38] M. Gauthier, C. Abbey, F. Katiraei, J.-L. Pepin, M. Plamondon, and G. Simard, "Planned islanding as a distribution system operator tool for reliability enhancement," in 19$^{\text{th}}$ *International Conference on Electricity Distribution*, Vienna, May 21-24, 2007.

[39] The World Bank, Washington DC. (2010) World development report 2010, development and climate change. [Online]. Available: go.worldbank.org/ZXULQ9SCC0

[40] I. E. A. IEA. (2011) Access to electricity (weo-2011). [Online]. Available: www.worldenergyoutlook.org/

[41] I. Mitra, T. Degner, and M. Braun, "Distributed generation and microgrids for small island electrification in developing countries: a review," *SESI Journal, Journal of the Solar Energy Society of India*, vol. 18, no. 1, pp. 6–20, Jan.-June 2008.

[42] N. Lidula and A. D. Rajapakse, "Microgrids research: A review of experimental microgrids and test systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 186–202, 2011.

[43] T. L. Vandoorn, J. D. M. De Kooning, B. Meersman, and L. Vandevelde, "Review of primary control strategies for islanded microgrids with power-electronic interfaces," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 613–628, Mar. 2013.

[44] T. L. Vandoorn, B. Meersman, L. Degroote, B. Renders, and L. Vandevelde, "A control strategy for islanded microgrids with dc-link voltage control," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 703–713, Apr. 2011.

[45] A. Engler and N. Soultanis, "Droop control in LV-grids," in *Proc. Internat. Conf. on Future Power Systems*, The Netherlands, Nov. 16-18, 2005.

[46] A. Engler, O. Osika, M. Barnes, and N. Hatziargyriou, *DB2 Evaluation of the local controller strategies.* www.microgrids.eu/micro2000, Jan. 2005.

[47] C. Sao and P. Lehn, "Control and power management of converter fed microgrids," *IEEE Trans. Power Syst.*, vol. 23, no. 3, Aug. 2008.

[48] W. Yao, M. Chen, J. M. Guerrero, and Z.-M. Qian, "Design and analysis of the droop control method for parallel inverters considering the impact of the complex impedance on the power sharing," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 576–588, Feb. 2011.

[49] T. L. Vandoorn, J. D. M. De Kooning, B. Meersman, J. Guerrero, and L. Vandevelde, "Voltage-based control of a smart transformer in a microgrid," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1291–1305, Apr. 2013.

[50] T. L. Vandoorn, J. D. M. De Kooning, B. Meersman, and L. Vandevelde, "Voltage-based droop control of renewables to avoid on-off oscillations caused by overvoltages," *IEEE Trans. Power Del.*, 2013, accepted for publication.

[51] M. H. J. Bollen and F. Hassan, *Integration of Distributed Generation in the Power System*, ser. IEEE Press Series on Power Engineering. John Wiley & Sons, 2011.

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