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Microgrid Evolution Roadmap Engineering, Economics, and Experience

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Microgrid Evolution Roadmap

Engineering, Economics, and Experience

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***Abstract*—This paper reports on the work of the CIGRÉ C6.22 Working Group, *Microgrid Evolution Roadmap*, which has recently finalized its first Technical Brochure. The Working Group was asked to identify the main elements required to justify, develop, and implement viable microgrids, which the Group defined as follows: *Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.* The main types of microgrids are described, and a benefits estimation approach developed and demonstrated. Also, an extensive review is made of microgrid functionality and technology, and a data base of microgrid pilot projects has been built.**

Keywords*—microgrids; distributed power; photovoltaic cells; fuel cells; power quality; converters; inverters; combined heat and power.

I. Introduction

The Conseil International des Grandes Réseaux Électriques (CIGRÉ) Working Group C6.22 *Microgrid Evolution Road-map* (WG6.22) was formed in August 2010. It has recently completed its first Technical Brochure (TB), and this paper summarizes its findings [1]. WG6.22 was asked to clarify and define microgrids, justify their deployment given the current market and regulatory environment, and survey microgrid technology and experience. The Working Group finds operation of microgrids offers distinct advantages to customers and utilities: improved energy efficiency, minimisation of overall energy consumption, reduced environmental impact, improvement of reliability of supply, network operational benefits such as loss reduction, congestion relief, voltage control, security of supply, and more cost-efficient electricity infrastructure replacement. Recently, the drivers for microgrids have diverged somewhat across the globe, most notably, resilience has been a dominant concern in the northeastern U.S. and Japan, following those areas' recent natural disasters. In many other countries, microgrids have been proposed as a novel distribution network architecture within the smart grids umbrella, capable of exploiting the full benefits of integration of large numbers of small-scale distributed energy resources (of < approx. 1 MW) into low-voltage electricity distribution systems [2].

The WG6.22 TB describes the mechanisms by which stakeholders can benefit from microgrid installations and provides a framework for analysing them. These benefits, namely reduced electricity purchased, investment deferral, reduced emissions, ancillary service provision, and improved reliability, can be used to construct business cases, as is subsequently shown by worked examples. The framework described views impacts as the measurable effects microgrids have on system operation, and benefits are the value that stakeholders accrue from impacts. Although many of the benefits identified can be captured through other means, microgrids can provide them in one coordinated ecosystem for various stakeholders.

Obviously, technology is an important microgrid enabler. The many elements that can be incorporated in a microgrid to make it viable and useful for a microgrid stakeholder are described in the TB. Much of the technology incorporated into microgrids is familiar to readers, e.g. photovoltaic (PV) arrays, and while these are covered briefly, the WG6.22 has focused on capabilities more specific to microgrids. These include the operation of distributed energy resources (DER), including generation and storage, and of their associated power electronic interfaces, as well as controllable loads. Protection information and the communication technologies required to manage generation and loads locally are also described.

WG6.22 considered methodologies for assessing business cases and presents two case studies of successful microgrid studies and actual implementations. Further examples were explored in an annex. An assessment was conducted of the context for business case studies, including microgrid technologies and control approaches (centralised, decentralised and autonomous controllers), and the operating framework (ownership, regulatory context). The two example business cases are the well-known Boston Bar milligrid in British Columbia, Canada. A *milligrid* (mgrid) is an islandable segment of the legacy regulated power distribution network, i.e. a microgrid that involves regulated assets. Secondly, a planning study for the Holme Rd. microgrid in Preston, UK is developed. Boston Bar is a remote feeder able to island using local resources in case of megagrid blackout. Holme Rd. is a mixed residential small commercial feeder to which combined heat and power and other necessary systems could be added to create a mgrid. These examples include results of the economic benefit analysis. The influence diagram appearing below as Figure 1 shows how the approach relates impacts to benefit functions, which in turn deliver benefits to stakeholders.

II. Microgrid Definition

A. Defining a Microgrid

Developing a definition of a microgrid and clarifying it relative to other definitions found in the literature and to related concepts comprised one of the major tasks in the charge to WG6.22. It took this obligation seriously and devoted considerable time to comparison and analysis of alternative existing definitions, and to discussion of the salient characteristics of a microgrid. While there may be disagreement on details and between analysts, WG6.22 found the formal definitions in wide circulation to be reasonably consistent. Most contain two fundamental requirements: that the microgrid

- contains sources and sinks under local control
- can operate either grid-connected or islanded

WG6.22 defined the concept by the following single sentence.

Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

B. Qualifiers

Generators covers all sources possible at the scales and within the context of a microgrid, e.g. fossil or biomass-fired small-scale combined heat and power (CHP), photovoltaic modules, small wind turbines, mini-hydro, etc.

Storage Devices includes all of electrical (e.g. superconducting magnetic energy storage), electrochemical (e.g. batteries), mechanical (e.g. flywheel) and heat storage technologies. While the microgrid concept focuses on a power system, thermal storage can be relevant to its operation whenever its existence affects operation of the microgrid. Similarly, the precooling or heating of buildings will alter the load shape of heating ventilation and air conditioning system, and therefore the requirement faced by electricity supply resources.

Controlled loads, such as automatically dimmable lighting, building pre-cooling or delayed pumping, are particularly important to microgrids simply by virtue of their scale. Inevitably in small power systems, load variability will be more extreme than in utility-scale systems. The corollary is that both load control and storage can make a particularly valuable contribution to a microgrid.

There are three major objectives/benefits of microgrids:

- to provide power quality and/or reliability (PQR) different from the local standard of service, e.g. to serve particularly sensitive loads such as emergency services, and potentially provide heterogeneous service to its internal loads
- to use local assets unlikely to be chosen or difficult to operate by the centralised grid, e.g. small-scale renewable resources, or interconnected plug-in electric vehicle batteries used for ancillary service (AS)
- to present a controlled profile to the wider power system, e.g. to damp the variability of a local renewable resources and loads and buffer the grid from it

While the definition specifies no time scale, i.e. no minimum survival time in island mode, the intent is that a microgrid can function for more than a few minutes as a controlled electrical island.

C. Microgrids and the Smart Grid

At the highest level, the smart grid has 3 components:

- improved operation of the legacy high voltage grid, e.g. through use of synchrophasors
- enhanced grid-customer interaction, e.g. by smart metering and/or real-time pricing
- new distributed entities that have not existed previously, e.g. microgrids and active distribution networks

While the charge of WG6.22 is squarely centered on micro-grids, the discussion would be incomplete if no wider survey were made of the evolution of power supply broadly.

D. Three Plus Microgrid Types

Two key types of microgrids should be distinguished [3]. *Customer microgrids* or *true microgrids* (µgrids) are self-governed entities, usually downstream of a single point of common coupling. Many current demonstrations are of this type, such as the Sendai Microgrid in Japan. They are particularly easy to visualise because they fit neatly into our current technology and regulatory structure. Just as a traditional customer has considerable leeway in the oper-ation of the power system on its side of the meter, so restrict-ions on the nature of a µgrid are relatively loose.

Utility or *community microgrids* involve a segment of the legacy regulated grid, and are called *milligrids* (mgrids) in the TB. There are also existing examples of milligrids, such as Boston Bar, and the Borrego Springs Microgrid in Southern California. While not necessarily technically different from µgrids, they are fundamentally different from µgrids from a regulatory and business model perspective primarily because they incorporate traditional regulated utility infrastructure. The corollary of this feature is that utility regulation comes much more significantly into play. In other words, any mgrid must either comply with existing utility codes or accommodation must be made in the code.

Similar scale isolated remote power systems (rgrids), although not true microgrids since they are not able to operate grid-connected, involve similar technology. Also practically, initial demonstration of microgrid technologies often takes place in rgrids. In fact, their relationship to microgrids is so close that from a research point of view they are also loosely described as microgrids.

Virtual microgrids (vgrids) cover DER at multiple sites but are coordinated such that they can be presented to the grid as a single controlled entity. Very few demonstrations of vgrids exist, and they are not covered in detail in the TB.

III. Functionality and Technology

A. Introduction

Some of the key microgrid technology enablers are:

- Generation, energy conversion and storage, plus load control collectively known as DER. Distributed energy storage (DES), which is also an element of DER, allows the management of intermittent and renewable energy generation, as well as serving load during islanded operation. Note that storage is more necessary in smaller power systems.
- Microgrid controls and supervisory systems, to implement various modes of operation (namely grid connected and islanding), and to ensure proper transition between these two main operation modes. They also manage real time power balancing and longer term energy requirements among internal DER units and loads. Additionally, they determine power exchange requirements with the rest of the legacy electricity supply chain (megagrid) during grid-connected oper-ation, based on pre-specified objective functions (e.g. operating cost minimisation, or maximum penetration of renewable resources, etc.)
- Microgrid protection and automation to ensure safe, sound, and autonomous operation of the microgrid internal assets, as well as fast detection and isolation of faults, either internal or external to microgrid boundaries.
- Communications and remote monitoring systems, to enable the collaborative effort of internal and external control, protection, and automation systems for management of day-to-day operation and/or imple-mentation of control and protection schemes.

B. Generating and Storage Technologies

The major on-site microgrid generating resources are well-known and are not covered in detail here. Because of its collapsing cost, reliability, and longevity, plus its inoffensive operation allowing ready deployment in populated areas, PV is particularly important to microgrids.

Wind energy harvesting through large wind power plants (utility size projects) has become a standard feature of the megagrid. Utility scale wind generation units lie in the range of several hundred kW to more than 5 MW, and the trend is toward higher power ratings, in particular at off-shore wind farms. Since the definition of microgrids includes no size boundaries, such turbines might be incorporated, but smaller wind turbines (less than 100 kW) and micro wind turbines (less than 5 kW) seem more relevant, particularly given the variability problem. On the other hand, microgrids might be designed and operated around resources possibly considered problematic by the megagrid, so low-quality, e.g. highly variable, resources should not be discounted. Note that while many current microgrid project aim to provide high PQR to sensitive loads, future microgrids might be designed and operated to provide PQR below grid standards for economic or environmental reasons.

Thermal generation and fuel cells operating at moderate or high temperatures provide high-quality heat sources for combined heat and power (CHP) systems. Together with their dispatchability, high efficiency and power density makes CHP of particular value to microgrids. Notably, use of waste heat for cooling using absorption technology also produces significant economic benefits by displacing expensive on-peak power. Rotating generators are either utilised in a conventional way with machines directly coupled with the electric system, or de-coupled by an inverter interface, which also simplifies interconnection requirements. An inverter interface allows advanced power conditioning and de-couples dynamics of the machine from the system. A fuel cell is an electrochemical device that converts the chemical energy within the fuel directly into electrical energy. Fuel cell systems can provide electrical efficiencies up to 60%, which far exceeds internal combustion engines or turbines [5,6]. In terms of part-load performance, a fuel cell system also presents superior characteristics compared to thermal generators.

The use of DES units in conjunction with the DG units is a natural process to address the inability of many DG technologies to deliver power based on the load and network requirements. DES units can also be used in specific applications to increase the quality of service, enable critical loads to run through abnormal system conditions, or to improve the power quality supplied to sensitive loads, e.g., voltage sag compensation.

Note that many of the generation, storage, and load technologies likely to be found in micrograms are asynchronous and often involve direct current (DC) in their energy production, storage, or consumption. The interconnection of these devices to alternating current (AC) microgrids via power electronic interfaces implies a low inertia system, and this is a notable microgrid feature. Conversely, since DC microgrids hold promise both for efficiency, power quality, and stability reasons.

C. Control Technology

A microgrid system may centrally controlled and managed by a Microgrid Central Controller (MGCC), installed at a distribution substation or at a local control center [4]. The MGCC communicates with controllers located at lower hierarchical levels that in turn control local DG units and DES devices. Microgrids might also be controlled by more distributed means, such as droop control or agent systems.

D. Microgrid Protection

The protection philosophy and techniques in a microgrid can be considerably different to those of conventional distribution systems, especially during islanded operation. The level of fault current capacity available in a microgrid will be drastically lower than interconnected systems. Further, due to a higher possibility of system transients and emergency response requirements, the range for voltage and frequency excursion during islanded operation can be much wider than typically considered permissible. Consequently, low/high voltage ride through and frequency ride through requirements as well as adaptive load shedding schemes will play key roles in the protection design of microgrids. Hence, the voltage and frequency based protection schemes need to be set differently in a microgrid.

E. Communications for Microgrids

Microgrid operation and fast recovery will significantly benefit from effective communication-based control, protection, and automation techniques to coordinate operation of multiple generation, energy storage, and load control devices. A considerable array of communication technologies that meet these needs of microgrids is available, and more is under development by many vendors entering this market segment with both wired and wireless offerings. Given the choice, economic considerations along with technical limitation are the main reasons for the use of particular technologies to the detriment of others.

IV. MICROGRID BENEFITS

A. Introduction

A societal justification for the installation of a microgrid must consider its potential impacts (the effects it will cause), and its costs and benefits (the consequences of its implementation and operation on stakeholders). Analysis must also must identify the stakeholders (those who will be affected by the microgrid), and these interdependent entities must be related to one another in a quantitative manner [7,8,9,10,11].

B. Microgrid Stakeholders

Stakeholders with a direct financial interest are the microgrid owner or operator, the distribution network operator, participants in the microgrid, those who may be directly affected by the existence of microgrids, etc. It should be noted that all of these listed stakeholders will be present or relevant in every microgrid.

C. Microgrid Ownership

Three microgrid ownership models have been identified: ownership by the distribution network operator (DNO), ownership by a current customer or consortium of customers, and independent ownership. In each case, the microgrid would tend to operate so as to maximise the benefit of the owning stakeholder. For example, in a DNO or utility-owned case, the microgrid would likely operate in a way that maximises distribution system technical benefits. In a participant-owned model, on the other hand, the microgrid would more likely operate in a way that maximises customer economic (or other) benefit.

In the independent model, a variety of demands must be balanced. It has been suggested that with the right financial incentives in place, profit maximization in such an independent or “free-market” model would be able to optimise the benefits for all stakeholders. That is, impacts and their resultant benefits and costs can generally be controlled by taking them into account in operations. This valuation can best be done by means of market price signals, for example, incenting less power purchase in times of high demand, or conversely export in times of megagrid need.

D. Microgrid Impacts

Simply put, impacts are the changes that are expected as a result of having a microgrid implemented. These may be changes in any of the systems of which the microgrid is a part: electrical, economic, or environmental. Cost-benefit analysis requires all impacts be classified into two categories: “known impacts,” which must be known a priori; and “discovered impacts,” which must be found through simulation or calculation. These latter impacts require certain input data and system parameters.

E. Direct Benefits

The direct beneficial technical and economic impacts obtained from microgrids have been broadly classified as improved efficiency, reduced emissions, and improved power quality and reliability. These latter benefits include increasing reliability of power provided to customers within and outside the microgrid thanks in part to the reduced dependence on the megagrid and substation. e.g. mitigating voltage swells and sags. More recently in the U.S., resiliency has emerged as the major perceived benefit of microgrids. Unfortunately, this phenomenon has emerged after WG6.22 had set out its workplan. In contrast to the probabilistic notion of reliability, resilience is a measure of robustness under extreme conditions and speed of subsequent restoration.

From these impacts, economic benefits can be obtained through the participation of microgrid loads and sources as one co-operating entity. This allows optimization of costs based on participation in the electricity market, reducing or offsetting substation and feeder loading, and provision of AS to the grid. Some examples of ancillary service provisions include reactive power and voltage control, reserve power, black start capability, as well as potentially working on a larger scale to provide frequency reserves.

F. Indirect Benefits

Indirect benefits resulting from microgrid operation can be more extensive, but also more difficult to quantify. They include environmental benefits such as a reduction in emissions of greenhouse gasses and other pollutants by integrating clean energy sources into the grid, reduction of the physical footprint required for power generation, reduction of reliance on external fuel sources and prices, and the creation of employment.

G. Cost-Benefit Method

WG6.22 provides methods for assessing business cases and presents two case studies, one actual implementation, and one microgrid study, with two further examples appearing in an annex. The approach begins with an assessment of the context of business case studies, including microgrid technologies and control approaches (centralised, decentralised and autonomous controllers), and the operating framework (ownership, regulatory context). This is followed by detailed applications of the method developed earlier for quantifying benefits. The example business cases are the actual well-known Boston Bar milligrid in British Columbia, Canada, and a planning study for the Holme Rd. µgrid in Preston, UK. Boston Bar is a remote feeder able to island using local resources in case of megagrid blackout. Holme Rd. is a mixed residential small commercial feeder to which combined heat and power systems could be added to create a mgrid. These examples include results of the economic benefit analysis. The influence diagram appearing below shows how the approach relates impacts to benefit functions, which in turn deliver benefits to stakeholders.

H. Two Cost-Benefit Examples

In the Boston Bar example, all stakeholders considered (i.e., utility, independent power producer (IPP), customers and society) perceive economic benefits. The IPP receives 1.9 M$/yr for energy cost savings, and 175 k$ for reliability improvements [12,13,14].

The utility reduces its carbon output by 5,850 t, and improves the reliability for the Boston Bar community by reducing its System Average Interruption Frequency Index (SAIFI) from 2.32 events/yr to to 0.61 events/yr, and its System Average Interruption Duration Index (SAIDI) from 33.28 h/yr to 3.0 h/yr. The economic value for these benefits has been estimated at 117 k$ and 175 k$, respectively. Customers perceive an improvement in reliability with an estimated value of 350 k$/yr. The benefit to Society is the reduction in carbon emissions at an estimated value of 175 k$/yr.

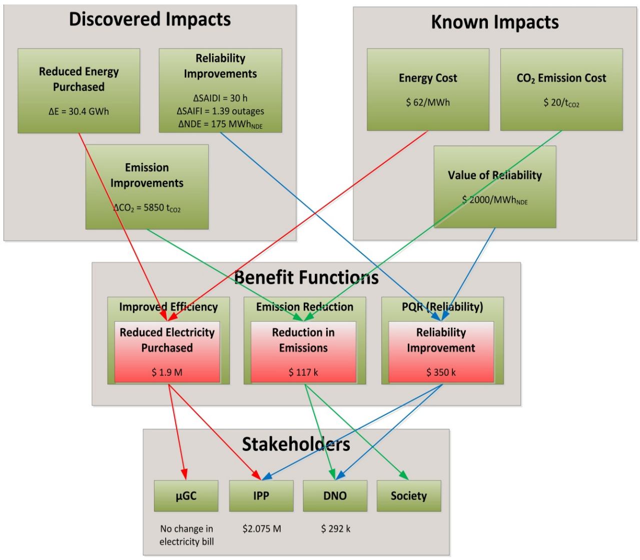

Fig. 1. Boston Bar Microgrid Impacts, Benefits, and Stakeholders illustrated through the use case paradigm and quantified on an annual basis.

Holme Rd. results suggest a strong business case for the Holme Rd. microgrid, even if only the "energy" benefits from coordinated control in response to real time prices were considered. The business case becomes significantly more attractive if the microgrid is allowed to count benefit from the provision of services to other actors too, particularly if new regulations incentivise the provision of capacity services and emission reductions are introduced. The twenty-year net present benefit is in the 2.4-3.5 M£ range, with the great majority accruing to the mgrid entity [15,16,17,18].

V. Conclusion

WG6.22's first TB covers the definition of microgrid and an overview of necessary equipment and methods needed to deploy one. These include establishment of a business case, assembling and configuring of available technology for controlling local generation and loads, and development of a mutually beneficial interaction with the wider legacy electric power system (or megagrid), from both the operations and market perspectives under the prevailing regulatory environment. A benefits analysis approach has been developed and is demonstrated by two examples, Boston Bar and Holme Rd. A second TB expected in late-2015 will develop an actual roadmap for microgrid development.

Presentations from the annual International Microgrid Symposiums and other information can be found at: http://microgrid-symposiums.org .

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