Direct Current Smart Micro-grids for Distributed Generation with Renewable Sources

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Abstract

The wide diffusion of renewable energy sources encourage the distribution of electrical energy by the so called Distributed Generation, where large power plants are substituted by small-scale environmentally friendly technologies. Moreover micro-grids are considered which concept assumes a cluster of loads and micro-sources operating as a single controllable system that provides both power and heat to its local area. This influences the operation of distributed generation. This research paper deals with the distributed generation evolution, considering the technologies for generation from renewable sources, up to the smart micro-grids, i.e. in domestic applications where direct current micro-grids are considered and smart micro-grid concept is introduced.

Keywords

Distributed generation; Micro-grid; Smart grid; Renewable energy.

Introduction

In the very first electricity supply systems, generators were built very close to the loads to be supplied, and so relatively simple networks could be employed to connect the two together. The limitations of this approach became apparent as the demand for electricity grew and the concept of a unified electricity grid became established. Distributed generation - in the following indicated as DG - became almost extinct in the period to 1990. The primary reason for this was that the economies gained by building larger power stations outweighed the additional costs of transporting the electricity - via the transmission system - to consumers.

Nowadays and in the near future, renewable sources will increase their share in the electricity generation system. The renewed interest in the DG is strictly connected to diffusion on a huge scale of those sources because of their well-integrated territorial nature.

One of the fundamental benefits of DG remains the significant reduction in the transportation costs. The precise potential for efficiency gains and emission savings varies depending on the generation technology and the location of the generation unit.

Almost every participant in discussions about DG defines the term “Distributed Generation” differently. At one end, DG could include only small-scale, environmentally friendly technologies - such as photovoltaic (PV), fuel cell, micro-turbine, or small wind turbines - that are installed on and designed primarily to serve a single end user’s site. At the other end, DG could encompass any unit generation built near consumers load regardless of size or energy source. The latter definition could include large cogeneration facilities capable of exporting hundreds of megawatts [1].

In general, any technology that produces power outside of the utility grid - typically in the range of 3 kW to 50 MW - through generation units located within the electric distribution system or near the end user, can be defined as Distributed Generation [2]. They are connected in parallel to the electric utility or stand-alone units. The European Union defines as “DG plant” all the generation plants connected to the distribution grid.

The diffusion of DG in the electric generation led to improvements for the electric network giving the opportunity to reduce overloads of transmission lines, improving the energy security and stability of the electricity grid, and the integration of renewable sources can be utilized for ancillary services too [3]. In the meantime there are advantages in terms of reliability and power quality thanks to the introduction of innovative apparatuses like the power electronic transformers [4-7]. These aspects are widely demonstrated with reference to some of the primary DG applications and are reported in recent literature [8].

There are many kinds of DG technologies that include fossil-fuelled devices as well as those that use renewable fuels [9-15].

The aim of this research paper was to provide a review on the electrical energy distributed generation, where large power plants are substituted by small-scale environmentally friendly technologies, has been presented before treating the micro-grids that can be considered conceptually as a cluster of loads and micro-sources operating as a single controllable system that provides both power and heat to its local area. This concept provides a new paradigm for defining the operation of distributed generation. In this research paper was analysed and investigated the distributed generation evolution, considering the technologies for generation from renewable sources, that leads to the smart micro-girds that are a good technical solution for future in residential applications where direct current micro-grids have been considered evidencing the advantages of DC micro-grids, enclosing features and advantages proper of a smart architecture.

The Electricity Generation from Renewable

High fossil fuel prices combined with concerns about the environmental consequences of greenhouse gas emissions encourage the development of alternatives to fossil fuels, specifically nuclear power and renewable energy sources. Renewable energy is the fastest growing source of electricity generation.

Renewable energy sources have positive environmental and energy security attributes. Total generation from renewable resources increases by 3.0% annually, and the renewable share of world electricity generation grows from 18% in 2007 to 23% in 2035.

Generation from renewable energy sources in the United States i.e. increases in response to requirements in more than half of the 50 States for minimum renewable generation or capacity shares: the share of generation coming from renewable energy sources grows from 8.5% in 2007 to 17.0% in 2035 [16-19].

The growth of non-hydropower renewable energy sources in OECD Europe is encouraged by some of the world’s most favourable renewable energy policies: the European Union has set a binding target to produce 20% of total amount of electricity generation from renewable sources by 2020.

Renewable generation in Non-OECD Europe and Eurasia, almost entirely from hydropower facilities, increases relatively slowly, largely as a result of repairs and expansions at existing sites.

There are many differences between OECD and Non-OECD Countries regarding the mix of renewable and fossil fuels used for electricity generation. In OECD nations, the majority of economically exploitable hydroelectric resources already have been captured. As a result, most renewable energy growth in OECD Countries comes from non-hydroelectric sources, especially wind and biomass.

The contribution of wind energy, in particular, has grown swiftly over the past decade - from 18 GW of net installed capacity at the end of 2000 to 159 GW at the end of 2009 - a trend that continues into the future [16-19]. Almost 80% of the increase worldwide is in hydroelectric power and wind power. Solar is the faster growing source in both OECD and Non-OECD Countries, this evolution is presented in table 1 [16-19].

Table 1. OECD and Non-OECD net renewable electricity generation by energy source

Region	2007	2015	2020	2025	2030	2035	Average Annual Change 2007-2035 [%]
OECD							
Hydropower	1246	1384	1460	1530	1585	1624	0.9
Wind	144	525	671	803	846	898	6.8
Geothermal	37	57	61	66	73	80	2.8
Solar	6	85	104	107	114	122	11.6
Other	195	253	318	398	456	485	3.3
Total OECD	**1628**	**2303**	**2614**	**2904**	**3074**	**3208**	**2.5**
Non-OECD							
Hydropower	1753	2305	2706	3061	3449	3795	2.8
Wind	21	157	231	312	388	457	11.7
Geothermal	21	41	47	52	68	80	5.0
Solar	0	10	23	33	39	44	21.7
Other	40	141	196	255	317	389	8.4
Total Non-OECD	**1628**	**2654**	**3203**	**3714**	**4263**	**4764**	**3.5**
World							
Hydropower	2999	3689	4166	4591	5034	5418	2.1
Wind	165	682	902	1115	1234	1355	7.8
Geothermal	57	96	108	119	142	160	3.7
Solar	6	95	126	140	153	165	12.7
Other	235	394	515	653	773	874	4.8
Total World	**3462**	**4958**	**5817**	**6618**	**7336**	**7972**	**3.0**

Solar power can be economical where electricity prices are especially high, where peak load pricing occurs, or where government incentives are available. The use of energy storage - such as hydroelectric pumped storage, and batteries - and a wide geographic dispersal of wind and solar generating facilities mitigate many of the problems associated with intermittence production of these sources and make those technologies a great value to the electric system.

In Non-OECD Countries, hydroelectric power is expected to be the predominant source of renewable electricity. Strong growth in hydroelectric generation is expected in China, India, and a number of nations in Southeast Asia, including Malaysia and Vietnam. In Canada, hydroelectricity provided 59% of the nation’s electricity generation in 2007. Mexico’s current renewable generation energy mix is split largely between hydroelectricity (73%) and geothermal energy (19%). In Brazil, the South America region’s largest economy, hydropower provided almost 85% of electricity generation in 2007. India’s federal government is attempting to provide incentives for the development of hydropower across the nation. The United States net installed capacity of wind power increased by 39%, equal to nearly 10 GW, in 2009 alone [20, 21].

In five OECD European Countries (Germany, Denmark, Portugal, Ireland and Spain) wind power covers more than 10% of the installed power and provides more than 5% of electric energy demand. To Germany, Denmark and Spain belong more than 72% of the wind power installed all over Europe [20, 21].

Although hydroelectric projects dominate the renewable energy mix in Non-OECD Asia, generation from non-hydroelectric renewable energy sources, especially wind is also expected to grow significantly. The most substantial additions of electricity supply generated from wind power are centred in China. At the end of 2008, China completed installation of its 10^{th} GW of wind capacity, achieving its 2010 target a full year ahead of the schedule set out by the National Development and Reform Commission [20-23].

In figure 1 is presented annual worldwide installed PV capacity from 2000 to 2010 in MW (source: EPIA). Figure 2 illustrate the evolution of global cumulative installed capacity worldwide in MW (source: EPIA).

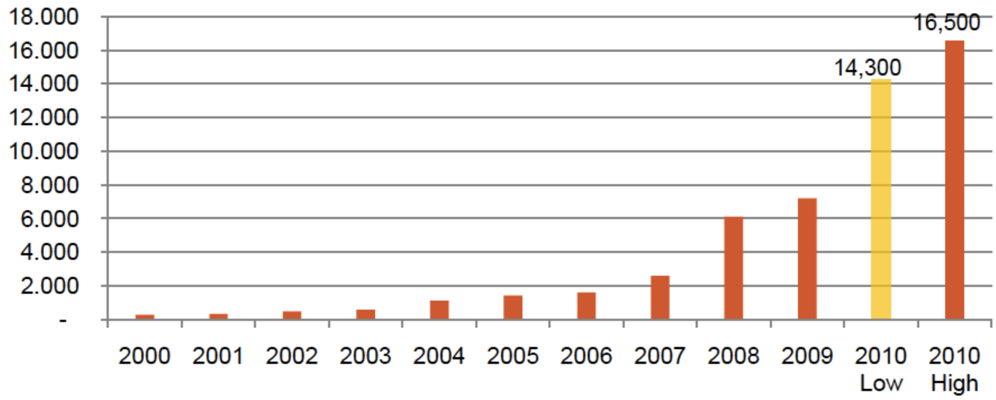

Figure 1. *Annual worldwide installed PV capacity from 2000 to 2010 in MW (source: EPIA)*

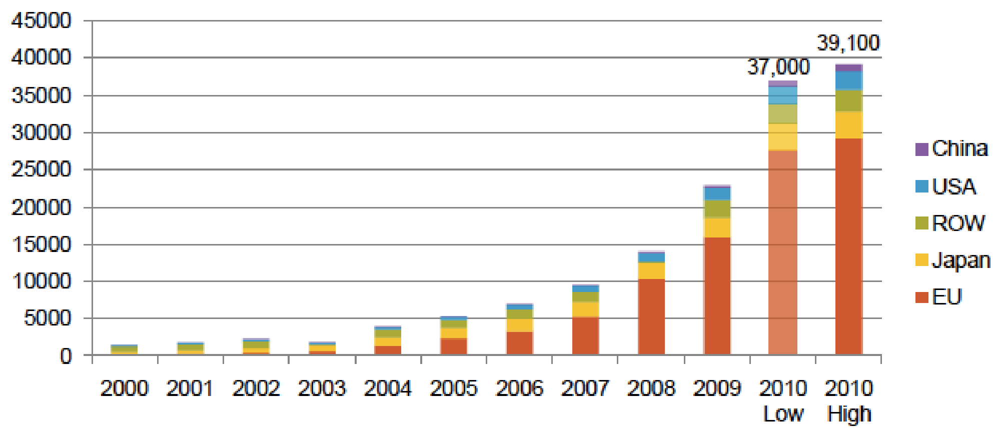

Figure 2. *Evolution of global cumulative installed capacity worldwide in MW (source: EPIA)*

Micro-grid Concept

DG technologies consist primarily of energy generation and storage systems placed at or near the point of use. Distributed energy encompasses a range of technologies including fuel cells, micro-turbines, photovoltaic and other energy generation technologies.

Energy storage technologies produce no net energy but can provide electric power over short periods of time. They are used to correct voltage sags, flicker, and surges that occur when utilities or customers switch suppliers or loads. They may also be used as an uninterruptible power supply (UPS). As such, energy storage technologies are considered to be a distributed energy resource.

DG also involves power electronic interfaces, as well as communications and control devices for efficient dispatch and operation of single fuel-fuelled and renewable technologies generating units, multiple system packages, and aggregated blocks of power.

The concept of Micro-grid had been introduced into the power system firstly by Consortium for Electric Reliability Technology Solutions (CERTS) [24-27].

As defined in [27] the micro-grid is assumed as a cluster of loads and micro-sources units, typically micro-turbines, PV panels, and fuel cells that are placed at customer sites. These sources are low cost, low voltage and have high reliable with few emissions, and are interfaced by means of power electronics to provide the control and flexibility required by the micro-grid concept. Correctly designed power electronics and controls insure that the micro-grid can meet its customers as well as the utilities needs [28-31]. This concept provides a new paradigm for defining the operation of distributed generation of electric energy.

Micro-grid is practically a small-scale power grid realized by integrating distributed generation, distributed storage, loads and control devices which can satisfy different levels of loads to the customer side.

The micro-grid is operated both in the grid-connected mode and in islanded mode. In normal conditions, the micro-grid is connected to a utility grid, operates in parallel with the utility grid, and exchanges power according to a power balance between supply and demand in the micro-grid. However, the micro-grid disconnects the utility grid and transfers into the islanded operation when a fault occurs in the upstream power grid. In the islanded mode, the micro-grid is operated like an isolated island.

To the utility the micro-grid can be thought of as a controlled cell of the power system. For example this cell could be controlled as a single dispatch able load, which can respond in seconds to meet the needs of the transmission system. To the customer the micro-grid can be designed to meet their special needs; such as, enhance local reliability, reduce feeder losses, support local voltages, provide increased efficiency through use waste heat, voltage sag correction or provide uninterruptible power supply functions to name a few.

A micro-grid is defined smart if 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. A Smart micro-grid do not only supply power but also information and intelligence, the smartness consists in employing innovative technology, products and services together with intelligent monitoring, control, communication, and self-healing technologies that enable new energy services and energy efficiency improvements to better plan and run existing electricity grids, to control generation.

AC Micro-grids

A micro-grid generally consists of a static transfer switch, single or multiple Distributed Energy Resources (DER) units, distributed critical and non-critical loads, a power management system, and protection devices [32]. A typical configuration of an AC micro-grid is illustrated in figure 3 [33].

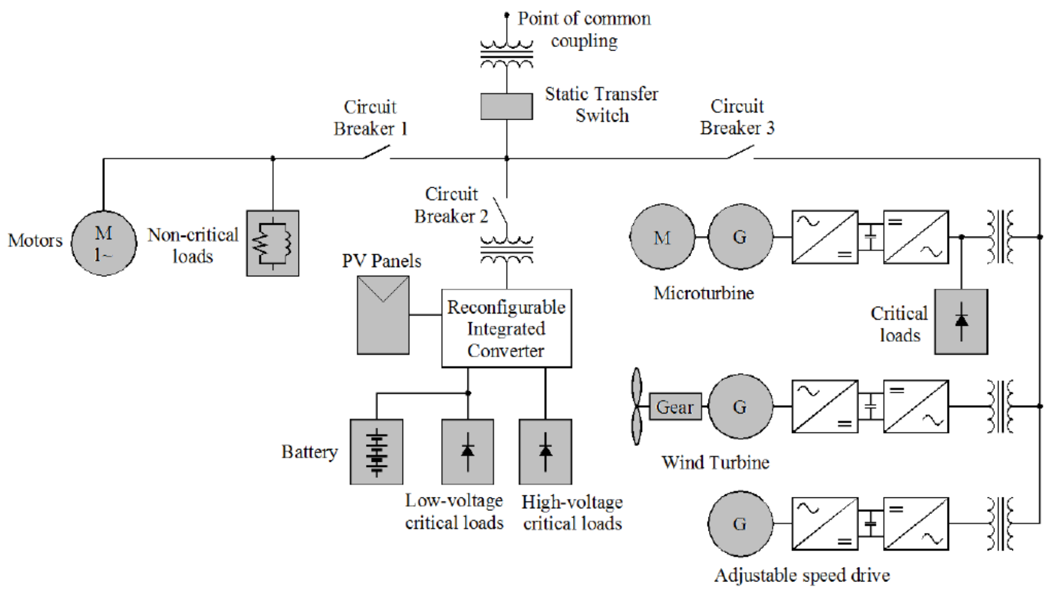

Figure 3. *Configuration of a typical AC micro-grid*

In the micro-grids, DER units can be distinguished by their interface characteristic as the conventional rotary DER units and electronically-coupled DER units.

Conventional rotary DER units are interfaced directly through the rotating generators, which comprise fixed speed wind turbines, micro-turbines, and small hydro engines [34]. In contrast, the electronically-coupled DER units utilize the power electronics converters to match the requirements of grid connection. The electronically-coupled DER units mainly involve the variable speed wind turbines and other renewable energy source based DG units, internal combustion engines, and distributed storage units.

Since the prime energy sources can produce either DC or AC voltages, the general topologies of electronically-coupled DER units consequently fall into two categories.

For wind turbine and internal combustion engine generation systems the output is in AC, whereas the photovoltaic (PV) and fuel cell (FC) power systems produce DC voltages.

The output voltages form those energy resources are then converted by means of a power electronics converter to the voltages that are compatible to the micro-grid.

For PV and FC power systems, a single-stage power conversion system features the simplest configuration, whereas is compromised by the bulky and expensive low frequency transformer. On the other hand, a multiple stage power conversion system is widely used. The commonly used two-stage topology consists of a DC-DC converter with or without a high frequency galvanic isolation transformer - as in figure 3 - and a DC-AC converter. The DC-DC converter performs maximum power point tracking functionality to capture the maximum power from the energy sources, while the DC-AC converter is controlled to follow grid requirements. Definitively, the types of output power from the prime energy sources determine the topologies of power electronics interfaces within the micro-grids.

Distributed generation units based on renewable energy source – as photovoltaic generators and fuel cells - produce DC power. Such power must be converted to AC to tie into the building's electric system and to be re-converted only later to DC for many end uses. In fact, electronic devices - such as computers, florescent lights, variable speed drives, and many other household and business appliances and equipment - need direct current DC input. Hence, all of these DC devices require conversion of the building's AC power into DC for use, and that conversion typically uses inefficient rectifiers. These AC-DC conversions - or DC-AC-DC in the case of rooftop solar generator - result in substantial energy losses.

Today's consumer equipment and tomorrow's distributed renewable generation development require us to rethink the model of our electrical power system.

One possible solution is a DC micro-grid means as a DC grid within a building - or serving several buildings - that minimizes or eliminates entirely the conversion losses. In the DC micro-grid system, AC power converts to DC when entering the DC grid using a high efficiency rectifier, which then distributes the power directly to DC equipment served by the DC grid. On average, this system reduces AC to DC conversion losses from an average loss of about 32% down to 10% [32]. In addition, roof top photovoltaic and other distributed DC generation can be fed directly to DC equipment, via the DC micro-grid, without the double stage converter or the bulky transformer which would be required if the generation output was fed into an AC system.

Another benefit of DC micro-grids is the superior compatibility of the DC power with electricity storage. During every major grid blackout - or brown-out, as periods of insufficient power production are called - several studies demonstrate that further development of grid scale power storage would vastly improve the stability of the grid. Fortunately, adding DC storage to a DC micro-grid is easier compared to the complications of integrating DC storage in the AC domain where additional hardware is required. Moreover, the battery total power equals the sum of its parts: 1000 small battery banks each having 10 hours of capacity to run a laptop needing 100 W equals 1 MWh just as if it came from a giant battery owned by the utility. Furthermore, power from the distant battery would suffer other losses the local battery would not. These include inversion losses (going from the DC in the battery to the AC of the grid), transmission and distribution losses - estimated to be i.e. in USA 7 to 11% by the U.S. Department of Energy - and finally rectification losses when it gets to electronic load. Collectively, these losses could add up to as much as 41% of the energy ultimately delivered to a DC device [35]. On the other hand, using distributed batteries connected to a DC network maximizes the battery's power by avoiding the conversion of its output.

Considering a set of DC building loads we have the opportunity to integrate - at higher efficiency - other renewable energy generators that are intrinsically DC sources such as solar PV, small wind turbines, or fuel cells. Unlike an AC system, these various DC elements can work in concert without regard to matching phases. In a DC system, only the voltage needs to be considered, whereas AC systems require each element to have identical wave shapes - or be synchronized - to operate. This coordination is achieved through an inverter, which provides the well-known problems linked to weak link in distributed generation systems.

DC micro-grid can also simplify and raise the efficiency of how plug-in hybrid electric vehicles and electric vehicles connect to the grid. Moreover, because DC power has no phase to match, the connection to the vehicle is simplified, providing a more efficient path to its DC battery. As a system, the DC micro-grid also creates more possibilities for the vehicle's stored or generated power by enabling either high efficiency on site use, or the more marginal economics of sending the power to the grid.

Power supplies currently on the market impose losses on the power going to the device, typically 15% to 40%. This range of losses in a DC micro-grid can be readily lowered to 10% to 15% by using a higher efficiency conversion for multiple loads. This topology will persistently win out due to the superior economics of bulk conversion versus converter at every point-of-use.

The potential percentage savings for the residential sector's addressable load, as calculated in 2006 and reported in [35], is 25.32% corresponding to a reduction i.e. in the total U.S. load of 2.98%. Addressable load refers to load that can be connected to a DC micro-grid. Therefore, given a suitably robust generator and ample storage, we could have quite an efficient local grid network that uses solar PV and integrates electrical storage at higher efficiencies than are possible in a conventional AC system.

The Smart Micro-grid Concept

The Smart Micro-grid (SM) is a residential smart grid communicative system that manages power between the AC utility grid, storage devices, and on-site renewable generation units - such as solar panels and wind turbines - while maintaining a unique level of user comfort. The SM is conceived starting from the concept of DC micro-grid, enclosing features and advantages proper of such architecture. The interface with the AC utility grid is also provided in order to guarantee benefits for both the user and the grid through an automated approach to the demand-response problem.

Using the communication abilities of the smart grid, modern power electronics, renewable energy, and on-site storage devices an intelligent micro-manage of the power demand of a house is achievable.

By enforcing time-of-day (TOD) rates, the utility can get demand response from their residential customers, making them more aware of their power consumption and more likely to reduce it during peak times. If notified of the higher rates ahead of time - with phone calls or emails - the consumer can make informed decisions and consciously reduce their loads. Several organizations have tested this theory with pilot programs but most have had only moderate success [36, 37]. A more tried method takes control of out the customers’ hands.

The peaks in power mostly coincide with the peaks in price, meaning the consumer is charged more during these periods. If the loads are managed to stay off the grid during these peak times, consumers could save money and produce at the same time an improvement in the operating of the utility grid. Selected loads - such as water heaters - could be turned on and off automatically during the peak by an intelligent management system. For time-independent loads, this type of work can be easily done with programmable switches. In very simple cases, this does not affect homeowner comfort. For example an oversized water heater acts like an energy storage device, charged only once a day when it is convenient for the utility. The same amount of energy is consumed but with no excessive strain on the grid.

However, most loads, such as air conditioning and consumer electronics, are more complicated and can take into account ambient temperature, the habits of the user, and more. In addition, on-site energy storage devices should be used - considering the TOD rates changing, the fluctuation of renewable energy source and the varying weather conditions - to maximize the benefits.

These saving methods work well for shifting the peak, however they can quickly become difficult for the consumers. With SM system, these power usage decisions can be made automatically based on unique homeowner and utility settings.

To summarize, the system has the following features:

- Programs load schedules based on user preference;
- Interfaces the renewable based DC distributed generation units and storage devices to AC grid;
- Supplies power even when grid is down (islanding);
- Sells excess to utility company (where it is convenient);
- Allows users feeding from utility grid;
- Prepares house with weather forecasts;
- Communicate with other homes in its networks.

The SM development includes several different fields of study as power electronics of the circuitry, utilization of renewable energy, home energy storage, load control algorithms, communication methods and business cases.

The affirmation of SM system is strictly connected to the development of flexible-high efficiency integrated power converter architecture capable to achieve the technical standards imposed and absolve - through proper control and management algorithms - the functions defined.

Conclusions

A key element is that communications among micro-sources are unnecessary for basic operation. Each inverter is able to respond to load changes in a predetermined manner without communication of data from other sources or locations, which enables plug and play capabilities. Plug and play implies that a micro-source can be added to the micro-grid without changes to the control and protection of units that are already part of the system.

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