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Structuring DC Micro-Grid for Integrating Renewable Energy in a DC Load Dominant Electrical Environment

Joydeep Sarkar, Pramod Yade
Dept. of Electrical Engineering, Sandip Institute of Engineering & Management, Nashik (MS)
Joydeep.sarkar@siem.org.in

Abstract: The present power system is established on the principle of alternating power that provides supply to the AC powered machine, but with the ongoing revolution in electronics industry, many smart devices are coming in the list of domestic goods, which are powered by DC. To provide DC, AC supply should be rectified and regulated. This process incurs much looses. Instead of this rectification process, a separate independent DC micro-grid can be designed for buildings or colonies to which the DC loads can be connected. In this review paper, we will structure this infrastructure which can be independently powered by renewable power generation methods which can directly generate DC power
Keywords: DC supply, Micro-grid, Solar Energy, Wind Energy, Rectification losses, DC-DC Conversion

Introduction

Our electric power system was designed to move central station alternating current (AC) power, via high-voltage transmission lines and lower voltage distribution lines, to households and businesses that used the power in incandescent lights, AC motors, and other AC equipment. Today's consumer equipment and tomorrow's distributed renewable generation requires us to rethink this model. Electronic devices (such as computers, florescent lights, variable speed drives, and many other household and business appliances and equipment) need direct current (DC) input. However, all of these DC devices require conversion of the building's AC power into DC for use, and that conversion typically uses inefficient rectifiers. Moreover, distributed renewable generation (such as rooftop solar) produces DC power but must be converted to AC to tie into the building's electric system, only later to be re-converted to DC for many end uses. These AC-DC conversions (or DC-AC-DC in the case of rooftop solar) also result in substantial amount of energy losses.

One possible solution is a DC micro-grid, which is a DC grid within a building (or serving several buildings) that minimizes or eliminates entirely these 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%. In addition, roof top photovoltaic (PV) and other distributed DC generation can be fed directly to DC equipment, via the DC micro-grid, without the double conversion loss (DC to AC to DC), which would be required if the DC generation output was fed into an AC system. This report describes the operation of DC microgrids, potential national benefits, barriers to deployment, and policy measures that could accelerate this deployment.

Microgrid

The DOE and the CEC jointly commissioned a report identified two "Points of Universal Agreement" of what constitutes a microgrid [1]:

- A microgrid consists of interconnected distributed energy resources capable of providing sufficient and continuous energy to a significant portion of internal load demand.
- A microgrid possesses independent controls, and intentional islanding takes place with minimal service interruption (seamless transition from grid-parallel to islanded operation)

Microgrid is a small-scale grid that is designed to provide power for local communities. A Microgrid is an aggregation of multiple distributed generators (DGs) such as renewable energy sources, conventional generators, in association with energy storage units which work together as a power supply network.
The main components of a microgrid are:

- Distributed generation sources such as photovoltaic panels, small wind turbines, fuel cells, diesel and gas micro-turbines etc
- Distributed energy storage devices such as batteries, supercapacitors, flywheels etc.
- Critical and non-critical loads
- Energy storage devices are employed to compensate for the power shortage or surplus within the microgrid.

They also prevent transient instability of the microgrid by providing power in transient. The transient power shortage in a microgrid can be compensated for by fast energy storage devices in the microgrid, or by the utility grid

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through a bidirectional power converter when operating in grid-connected mode. Typically, a Microgrid operates synchronously in parallel with the main grid. However, there are cases in which a Microgrid operates in islanded mode, or in a disconnected state. Integration of renewable energy into the utility grid can be at either the transmission level or the distribution level, depending on the scale of generation. Large renewable energy generation such as wind farms are directly interconnected to the transmission system. Small scale distributed generation is generally interconnected to the medium or low voltage distribution systems. This small network can be a residential building, commercial building, is a market or even a village. Micro-grids operate mostly interconnected to the higher Voltage Distribution network, but they can also be operated isolated from the main grid.

The flexibility of microgrids comprises important benefits, but their efficient implementation poses very challenging problems [4]:

- The benefits Micro-grids provide to power system operation and planning need to be quantified and in- corporated into an appropriate commercial and regulatory framework, so that a level playing field for all energy technologies can be established. In order to achieve the full benefits from the operation of Microgrids, it is important that the integration of the distributed resources into the LV grids, and their relation with the Medium Voltage (MV) network up- stream, will contribute to optimize the general operation of the system. The coordinated control of a large number of distributed sources with probably conflicting requirements and limited communication imposes the adoption of mostly distributed intelligence techniques.
- The design of Micro-source Controllers enhanced with advanced frequency and voltage control capabilities and possessing ride-through capabilities is essential for the stable operation of Micro-grids, especially in islanded mode of operation.
- The design of smart Storage and Load Controllers able to face the stringent requirements posed by the islanded operation and especially during transition from inter-connected to islanded mode is also crucial.

Structure of dc microgrid

DC microgrid is an efficient method to combine a system of high reliability and the possibility to reduce the losses in the system. It can eliminate DC/AC or AC/DC power conversion stage and thus has advantages in the stand of efficiency, cost and system size. DC microgrid is inspired by the absence of reactive power, possibility of an efficient integration of small distributed generation units and the fact that, internally, all the loads operate using a DC voltage [6]. DC micro-grid is suitable for home loads which are mainly of DC loads. This method eliminates the ac/dc interface. DC microgrid, also by one or more inverters is connected to the utility grid and industrial loads (AC loads). However, some references [7] have introduced a hybrid network that, the DC link and AC link is used. A DC grid within a building (or serving several buildings) can minimize or eliminates entirely these conversion losses. In the DC microgrid 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%.

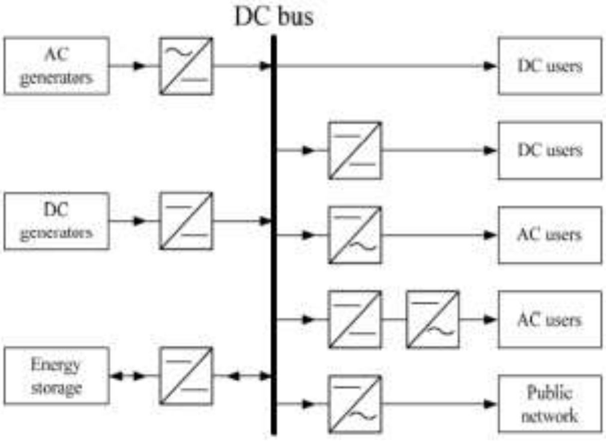

Figure 1 - DC bus structure

Roof top photovoltaic (PV) and other distributed DC generation can be fed directly to DC equipment, via the DC micro-grid, without the double conversion loss (DC to AC to DC), which would be required if the DC generation output was fed into an AC system. DC micro-grids can optimize the use of electronic devices, electrical storage, and distributed generation. The DC micro-grid concept represents a decentralization of the idea of the grid, and one that advances the goals of the current Smart Grid overhaul.

Factors	AC microgrid system with centralized storage	DC microgrid system with distributed storage
Sizing Issues	Hard to incrementally resize. Inverter losses can dominate with mismatch to load	Lack of inverter/central-storage makes it easy to incrementally add more generation
DC-AC/DC-DC conversion losses	30% due to central battery bank + inverter	10% daytime, 23% nighttime: due to 3 DC-DC conversion steps
Losses due to internal rectification and conversion in loads	> 25%	0% for DC and >25% for AC loads
End-to-end Efficiency	< 60%	85-77% for DC loads, < 63% for AC loads

Table 1- AC Microgrid vs. DC Microgrid (11)

The DC micro-grid begins to change the paradigm from a centralized generation and distribution system of power delivery to a system that is more flexible and more accommodating of the load that has come to be: one that is

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more electronic, more ubiquitous, and more essential to our economy and our environment. DC micro-grids can create power systems that are more efficient and more compatible with the fastest growing segment of the load today. [11]

Renewable energy penetration

Renewable energy based on Diesel-hybrid power systems are classified into two categories based on penetration level of renewable energy. These are summarised as follows [5]:

- *Systems with diesel generators as main power supply:* In these systems, diesel generators are designed to operate daily, along with renewable energy generators, to supply power directly to the load. The functions of renewable energy generators are to reduce fuel usage and generator mechanical servicing. Small batteries can be used in these systems to meet high load demand that lasts for a short duration only and the system batteries may be recharged by diesel generators.
- *Systems with renewable energy generators as main power supply:* In these systems renewable energy generators are designed to supply a high fraction of total energy demand. The functions of the diesel generator are to recharge the battery bank and to complement the renewable energy generator power supply when there is insufficient renewable resource. Due to the high penetration level of renewable energy, large battery banks are usually required in these systems.

The penetration level of renewable energy in a hybrid power system mainly depends upon local weather conditions and the customer's preference. With a given renewable energy penetration level, system components can be sized using various approaches.

Battery sizing for dc microgrid

An important concept in battery selection is that the amp-hour rating of a battery is discharge-rate specific. The greater the discharge rate, the less energy can be withdrawn from a specific battery.

Battery specification sheet of the battery used for DC storage at the DC Microgrid, we can see that a battery bank is rated around 10 amp-hours at the 20 hour rate, 8.5 amp-hours at the 5 hour rate, 4.5 amp-hours at the 1 hour rate, and 3.5 amp-hours at the 20 minute rate and so on. The reduction in amp-hour (Ah) capacity with increased discharge current is the first indicator that a high current discharge, such as 200 amps, will not result in an energy capacity, or Ah capacity, that has much correlation to the battery's rated capacity. Battery characteristics for 12V Batteries can be used for the selection process, with experimental evidences estimate the design predictions for required discharge rate and duration. The data can also be used to further illustrate the error in trying to select a battery for high discharge-rate applications using amp-hour capacity, rather than maximum discharge current. [12]. If one were to try to size the DC storage battery for a DC Microgrid using required energy capacity, the beginning point would be to calculate the energy required for a single discharge. For example, a discharge of 200A for 0.25 sec, that is 0.014Ah. One would then decide how many discharges in succession the battery must be capable of prior to being recharged. So, if we consider 100 discharges before recharge, we will design a battery with 1.4Ah capacity.

It is important to monitor temperature that the internal battery temperature is actually accessed. The preferred method is to measure the temperature of a negative battery terminal. An alternative method is to measure the side of the battery case, with the measurement being taken well below the level of the electrolyte inside the battery. With flooded batteries, this is relatively effective.

Volage control & converters

One of the key features to be incorporated in our DC microgrid is the distributed control of the grid-voltage. This allows for instantaneous signalling of power available in the source converter and enables on-the-fly power-sharing between the connected PMUs. The source-converter allows the voltage to operate in a range between 360-400 VDC and the PMUs have a controllable power-profile (load-line) based on internal parameters as well as information provided through digital communications. The PMUs are responsible for converting the grid voltage down to the level of household usage (12V) while presenting a controlled positive-impedance (load-line profile) to the grid in order to enable power-sharing between multiple units and maintain grid voltage.

The PMUs consist of the following functional blocks:

- A DC/DC converter that converts the voltage from the 360-400VDC grid distribution level to the 12V household battery level.
- Integrated scalable battery storage that enables the PMUs to store energy at the households and decouple power-draw from both grid-voltage and local usage, thus enabling the distributed stabilization of grid-voltage
- A communications block that enables sharing of usage information and remote management

A DC-DC converter is a critical device to connect each DC generation system to the DC bus. The operating point is determined by the combination of the aggregate load-line and the available power from the source converter. The base topology used for the PMUs is a Phase-shifted full bridge (PSFB) converter.

The Phase-shifted topology is a buck-derived topology and lends itself to analysis by using a PWM buck converter as an analogous circuit. However, the leakage inductance causes the small-signal behaviour to diverge from that of a buck converter. The impact of the leakage inductance is analogous to current feedback and has a damping effect on the circuit. For the purpose of understanding, assumptions done are the variation in current through the output inductor Lout, and the variation in voltage across the capacitors C_s and C_{out} are small compared to the nominal values of those quantities over a switching period.

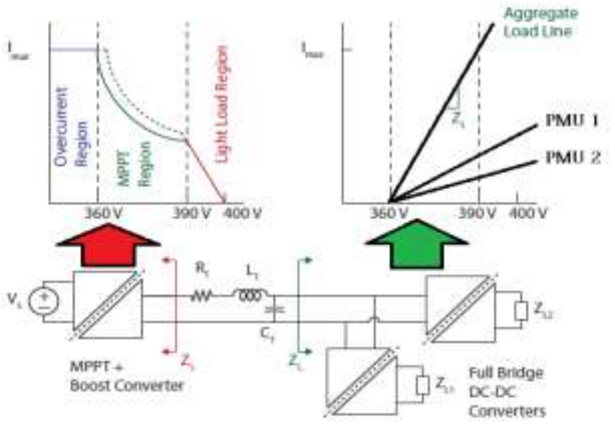


Figure 2- PMUs connected to a single source converter [13]

The steady-state operating point of the converter as given in reference [13],

$$I_l = \frac{I_s \cdot V_{out} \cdot n}{D_{nom} \cdot V_{out} - I_s \cdot R_l}$$

$$V_c = \frac{V_{out}^2 \cdot n}{D_{nom} \cdot V_{out} - I_s \cdot R_l}$$

The current feedback effect caused by the leakage inductance makes the effective impedance of the PMU on the grid always positive.

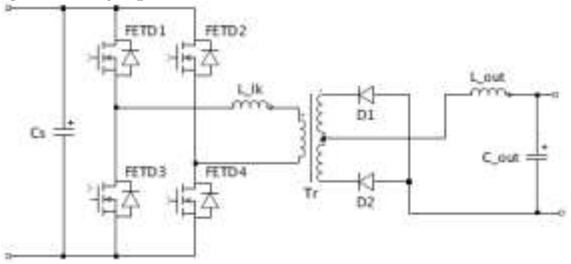


Figure 3- Phase-Shifted Full-Bridge DC-DC converter [13]

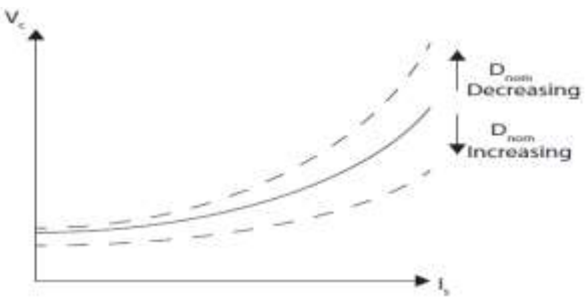


Figure 4 Open loop characteristic of Converter [13]

CONTROL OF DC MICROGRID

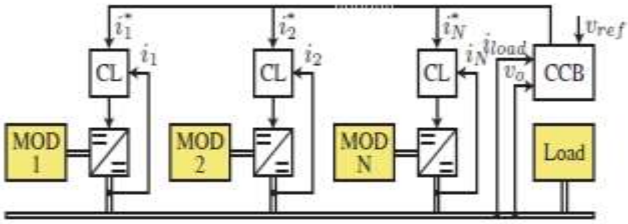
Microgrid control must insure that [14]:

- new distributed generation and storage systems can be added or removed from the microgrid seamlessly
- equal and stable current sharing between parallel power converters (i.e. sources) is enabled
- output voltage fluctuations can be corrected
- Desired power flow from/to the microgrid together with technically and economically viable operation is enabled.

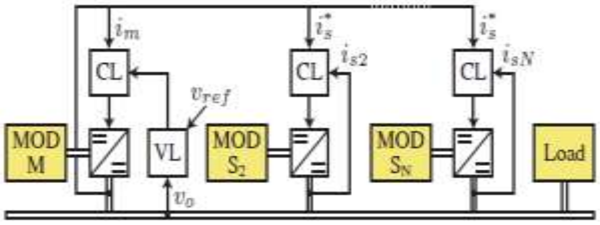
There are a fairly large number of methods for paralleling power converters (PCs). From the viewpoint of the operating mechanism to current sharing and output voltage level management, control methods are classified into two basic categories:

(i) active load sharing
(ii) Droop control methods.

In active load-sharing technique, there is a need for inter-communication link. Although these links limit the flexibility of the microgrid and degrade its redundancy, both tight current sharing and low-output-voltage fluctuations can be achieved.



(a) Centralized control of a DC microgrid



(b) Master-slave control of a DC microgrid

Figure 5- Active Load Sharing Control [14]

In droop control method, the absence of critical communications between the modules improves the reliability without restricting the physical location of the modules. The droop method is based on a well-known concept in large-scale power systems, which consists of drooping the frequency of the AC generator when its output power increases. The droop method achieves higher reliability and flexibility in the physical location of the modules since it only uses local power measurements.

A microgrid control is often implemented in a hierarchical manner, with three control loops:

- Tertiary loop manages the power flow from/to the microgrid,
- Secondary loop corrects output voltage fluctuations
- Primary loop performs current sharing control between power converters.

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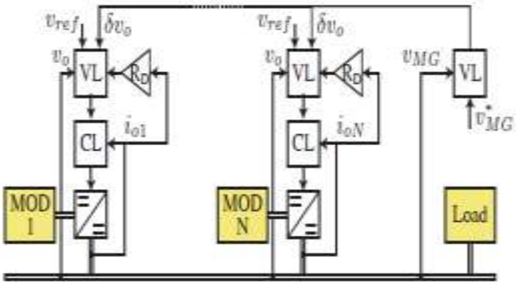

Figure 7.2 Droop Control Method [14]

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- Equal and stable current sharing between parallel power converters (i.e. sources) is enabled
- Output voltage fluctuations can be corrected
- Desired power flow from/to the microgrid together with technically and economically viable operation is enabled.

Advantages & Problems

The DC micro-grid has the following advantages over the AC micro-grid [5]:

- No need of synchronizing with the utility grid
- No reactive power requirement
- Disturbance on grid does not affect DC bus voltage of DC microgrid directly as the stored energy of DC capacitor and the voltage control of AC/DC converter.
- DC microgrid has fault-ride through capability. [8]
- Number of converters used in the DC bus is lower than the AC bus.
- In connected energy system combining multiple using DC bus, inject THD less into the network.
- In DC microgrid because, AC loads connected to the DC bus this opportunity exists in a condition that is generation power more than load, especially in islanded mode, some non-critical loads out of orbit and was feeding sensitive loads [9].
- Microgrid losses in DC micro-grid are 15% lower than the AC Micro-grid.
- Power transmission in DC system is higher
- In DC microgrid voltage affected by the active power therefore, it is simple to control [10].

There are some drawbacks to put dc micro- grid to practical use as follows [9]:

- It is needed to construct private dc distribution lines for dc micro-grid.
- The protection in dc system is more difficult than the AC system's because there is no zero crossing point of voltage in DC system.
- The loads adapted for dc power supply are required for high system efficiency.

Conclusion

A DC microgrid is a distribution network collecting a wide range of distributed generation systems, mostly non-conventional renewable energy DC sources and DC storage systems with local loads, which can be disconnected from the upstream network under emergency conditions or as planned. It can eliminate DC/AC or AC/DC power conversion stage and thus has advantages in the stand of efficiency, cost and system size. The system can supply high-quality power to loads in those conditions.

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