Chapter 2
AC and DC Microgrid with Distributed Energy Resources

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Abstract Renewable power generation and the prospect of large-scale energy storage are fundamentally changing the traditional power grid. Arising challenges occur in terms of energy management, reliability, system control, etc. Microgrid, as an active subsystem of modern power grid, has revealed its promising potential in dealing with intermittent clean power generation and emerging energy storage, partially brought by electrical vehicle batteries. In this chapter, the concept of microgrid is introduced. The main focus is placed on the basic issues of control, operation, stability, and protection of DC microgrids.

2.1 AC Microgrid

The arising concerns on environment and sustainable energy issues have promoted the development of distributed renewable power generation and the emerging of microgrid [1]. Since renewable power sources are naturally dispersed, it is very difficult for the power system to manage a countless, yet still growing, intermittent distributed power generation in a traditional way. In order to effectively manage distributed generation sources, load, and possibly energy storages, a systematic view has to be taken. By integrating all these distributed units together, a micro power system is formed from the distribution side, hence the nomination of microgrid. Given that distribution power system is formerly considered as load-only, the inclusion of generation and storage units in microgrids is fundamentally changing the control and operational structure of traditional power system.

As traditional power system is based on AC, microgrids are considered to be naturally AC based at early stage. A three-phase AC bus is commonly employed as the point of common coupling (PCC) [2]. PCC is normally set as the only power interface between a utility grid and the microgrid. The schematic structure is shown

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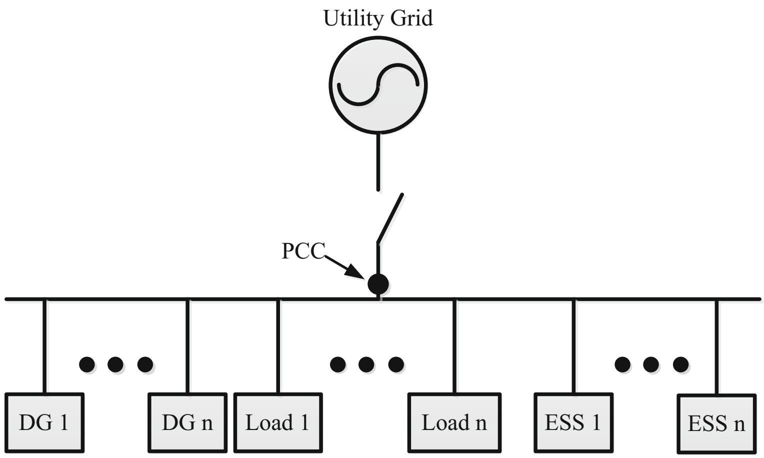


Fig. 2.1 AC microgrid

in Fig. 2.1. A microgrid can be either operated in grid-connected condition or in some situations, switched to the stage of isolation, i.e., islanding operation [3]. A fast switch can be placed in between PCC and utility grid as the cutoff point between the microgrid and utility grid.

Comparing with traditional power grid, the emergence of DGs and ESSs is the major difference. In a microgrid, renewable DGs and ESSs are interfaced with power electronics converters with distributed control [4].

Renewable DGs extract power from natural environment, blowing wind, or sunshine for instance, and try to maximize the power extraction and integration to the grid. In this sense, the actual power generated mainly depends on instant natural conditions. Therefore, the renewable DGs are generally considered to be nondeterministic from the grid operator's view. The only exception occurs when renewable power must be curtailed or switched off, however, at a certain cost.

ESSs are considered to be a controllable bidirectional source in a microgrid. A high-performance power electronics interface enables an ESS to provide instant support to power grid in addition to storage energy management. This special feature can be employed to cope with the problem caused by intermittent renewable DGs. For example, the EV charging station can use its battery as an energy buffer to absorb intermittent power to avoid voltage instability and discharge it in peak hours to reduce the demand on spinning reverse. It has to be pointed out that a vehicle battery with a one-direction charger is not necessarily an ESS system. A charging-only battery system, though controllable, behaves more like a controllable load in distribution power system due to its lack of discharging capability. However, a vehicle battery, or more likely a group of vehicle batteries in a charging station, with bidirectional "chargers" under certain control can play the role of ESS in a microgrid.

A coordinating scheme, either distributed or centralized, is usually designed to combine all the above-mentioned DGs, loads, ESSs, and relays together to form a subsystem. This feature also defers from a passive distribution power system with isolated DGs and ESSs. A digital secondary control system is commonly used to supervise, manage, and monitor the whole system [5]. Additional communications and energy management schemes might be applied with relevant supervisory control and data acquisition (SCADA) system of higher power system hierarchy.

2.2 Introduction to DC Microgrids

2.2.1 DC Distributed Sources

The idea of DC microgrid emerged soon after the concept of microgrid was proposed [6]. It is commonly designed for a distributed DC power source connecting intermittent renewable power sources, energy storages, and DC loads. This is due to the fact that many renewable power sources, e.g., directly driven wind generation and photovoltaic system, and energy storage systems, e.g., battery and super-capacitor, normally have DC links at their interface converter stages [4].

2.2.2 The Configuration of DC Microgrids

By connecting all the DC links of the sources and loads, a DC microgrid is formed, as is demonstrated in Fig. 2.2. Unlike the idea of AC microgrids, a DC microgrid does not directly connect to the prevalent three-phase AC utility grid but via a bidirectional DC/AC converter for common integration.

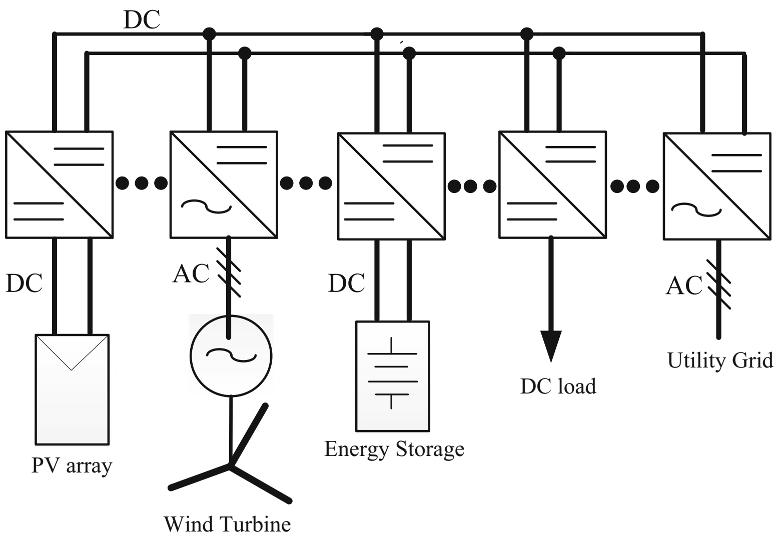


Fig. 2.2 DC microgrid

2.2.3 Comparison of AC and DC Microgrids

(a) Conversion efficiency

DC microgrids are considered to boast its efficiency advantage over AC counterparts in isolated operation mode when energy storage is involved in power flow due to fewer conversion levels. Typically for a PV-to-battery charging case, the power flow in an AC microgrid has to go through DC generation-AC distribution-DC storage process with DC/AC and AC/DC conversions. However, the power flow in a DC microgrid skips the AC stage, thus eliminating the losses brought by DC/AC and AC/DC conversions. One potential additional loss in DC microgrid is on the load side. Additional DC/AC conversion losses may apply if interface convertors are placed between the DC bus and the local AC loads. As a result, the total conversion efficiency between DC and AC microgrids depends on the trade-off between reduced conversion and additional conversion losses.

(b) One-off cost on converters

A common DC/AC converter is normally used for interfacing the DC microgrid to AC utility grid whereas in an AC microgrid, DC/AC converters have to be equipped with every distributed source. As the power rating of the common DC/AC converter in a DC microgrid is normally less than the total power rating but greater than any of the individual unit rating in AC counterparts, the one-off manufacturing and installation cost is reduced in DC microgrids due to higher per-kilowatt cost on converters of lower power ratings.

(c) Transmission/distribution efficiency

A significant feature of DC transmission is that there is no reactive power concern. As a result, the transmission loss caused by reactive current in AC systems is eliminated. In addition, a constant DC current tends to produce less copper loss on power line than AC over the same line resistance when delivering the same amount of real power.

(d) Power supply reliability

One promising feature of microgrids is that it can provide uninterrupted power supply during utility grid outage, which is often referred to as "seamless" switch during islanding operation.

For the AC microgrid system, it is difficult to determine when to switch the energy storage converter to islanded (isolated) mode since there is a contradiction between potential low-voltage ride-through (LVRT) grid code requirement and seamless switch.

Even though the present IEEE 1547 standard does not demand distributed sources to carry out voltage ride through during voltage dip and require renewable sources be tripped for voltage deviations, and the PCC switch of an AC microgrid can be designed and implemented to such requirement accordingly at this stage, it is doubtful that if it is appropriate in future. The reason is that a voltage dip caused by transmission level tends to cause low voltages over a vast area of distribution systems. The instant and simultaneous trips of AC microgrids along with its DG sources can potentially cause further transient event after the fault. It is better to maintain the generations and possibly loads to avoid severe power imbalance after a grid fault.

A possible case in future is that the utility grid operator would require the distributed sources or microgrids stay connected for a predefined period of time, say a few hundred of milliseconds, before disconnection when voltages stay above a small percentage of nominal, say 15 %, during voltage sag. This could be demanded in a distribution system with high penetration of renewable generations. It is to ensure that a temporary fault would not cause further undesirable disconnection of other distributed generations [7]. That is to say, for a grid-connected AC microgrid, a predefined seam might be required by the grid operator if the voltage drop is not sufficiently low. Therefore, the energy storage system, as is directly coupled with AC utility grid, cannot restore the local voltage by switching to the voltage regulation mode immediately after a voltage dip is detected. Furthermore, the prevalent implementation of instant voltage detection approach, digital phase-locked loop (PLL), either for single or three phase, can cause further delay in voltage detection process [8, 9], which is another unfavorable aspect for seamless transition during islanding operation.

For a DC microgrid not directly coupled with the AC utility grid, the energy storage system on the DC side can take over or facilitate the DC voltage regulation immediately after an abnormal DC voltage variation, say 20 % dip, is detected. It can help to suppress the undesirable variation to a predefined level in a reacting time of milliseconds. This reaction can take place regardless of the operation mode of the common DC/AC converter and whether there is a utility fault or not [10–12]. In addition, enhanced operational control technique [13] may be applied to further improve DC power quality to cater specific power quality standards, MIL-STD-704F for instance, during transients. These features make the DC microgrid to provide a better quality "seamless" power supply to cater commercial [11] and industrial [12] consumers' needs.

(e) Controllability

A good feature of DC power systems is that a constant DC voltage would ensure the stability of the system. As a result, DC voltage regulation is the only essential concern to maintain a stable DC power system. For an AC power system, however, not only the voltage (amplitude) but also the frequency (angle) must be regulated and both regulations must be performed simultaneously. Furthermore, as the AC utility grids are three-phase systems, sophisticated techniques shall be employed to cope with unbalanced components which predominantly come from the vast adoption of single-phase DGs and loads in low-voltage power system. All these fore-cited factors indicate a better controllability for DC microgrids over AC.

(f) Protection arrangement

Protection is currently the major advantage of AC microgrid over DC. For AC protection theory and equipment have been maturely developed and the zero-crossing nature of AC current enables AC circuit breakers to distinguish arc easily. However, zero-crossing does not naturally happen in a DC system. Thus sophisticated technique has to be implemented resulting in higher costs for DC circuit breakers.

(g) Load availability

As power system is predominantly AC based, electric equipment is prevalently designed for standard AC power supply. However, DC load has huge potential. Digital equipment such as computers, routers, LEDs, and TV sets are naturally more compatible with DC power supply. In addition, motor drives including EVs are likely to have DC links. A common DC bus would help to greatly reduce its cost on the rectifying side. The relevant loads, such as converter-fed electric fans, pumps, and air conditioners, can be designed for DC power supply instead of AC with manufacturing cost lowered and efficiency boosted.

The comparison of AC and DC microgrid is generalized in Table 2.1.

Table 2.1 DC microgrid

Microgrid type	AC	DC
Conversion efficiency	Low: Multiple AC/DC and AC/DC conversions have to be used when interconnecting renewable sources and storages	High: AC/DC and DC/AC conversions between renewable sources and storages are reduced
Cost on converters	High: DC/AC converter has to be invested for each of the renewable sources and storages	Low: Reduced conversion stage means less converters are required
Transmission efficiency	Low: Additional loss due to reactive current	High: Loss associated with reactive current eliminated
Power supply reliability	Difficult-to-guarantee seamless transition after a utility fault	A guaranteed smooth transient DC power supply with limited voltage variation
Controllability	Difficult: Both voltage and frequency regulation needed; unbalance compensation needed in a three-phase system	Simple: No frequency, reactive power, or phase unbalance concern
Load availability	High: Available loads are dominantly designed with AC power supply	Low but with great potential: Digital and converter-based loads are highly compatible to DC
Protection	Mature arcing technique with cost-effective circuit breaker and well-developed protection system	High-cost circuit breaker with protection theory and equipment under development

2.3 The Control and Operation of DC Microgrids

2.3.1 Principles of DC Microgrid Operation

As is seen in the previous section, a DC microgrid consists of a number of terminals to achieve certain functions, which are power generation, grid connection, energy storage, and power consumption. DC capacitors which help to maintain system DC voltage are located at each of the terminals. DC lines are set to connect every terminal to form a DC network.

2.3.1.1 The Definition of DC Terminals [13]

DC microgrid terminals can be categorized into four basic types in terms of their functions. They are grid connection, power generation, load consumption, and energy storage.

If we further analyze how the terminals can affect a DC power grid, we can generalize the terminals, in terms of their contributions to system operation stability, into two groups which are named as power terminal and slack terminal.

- Power terminals are defined for those DC terminals that are either outputting or absorbing power on their own merits, which behave as “selfish” terminals.
- Slack terminals are defined for those DC terminals that are actively balancing the power flow within the DC grid, which behave as “generous” terminals.

Care must be taken that the determination of which fore-cited group a certain DC terminal belongs to is based on its instant behavior. Therefore, for a certain DC terminal, it is possible that its category can be switched from one to the other. For instance, the utility grid-side DC/AC converter, normally operating as slack terminal, accommodates the power surplus and deficit within the DC grid. When the surplus exceeds the power rating, the DC/AC converter has to operate at its maximum power (current) point and consequently loses the capability of balancing power and becomes a power terminal.

Obviously, in order to maintain the power balance, there must be at least one slack terminal within the DC microgrid, for the “selfish” power terminals are not capable of balancing the power on their own.

2.3.1.2 Control of DC Microgrids: Central Control and Autonomous Control

One original idea of DC microgrid control scheme was centrally control based [14], which stems from traditional power system control. By using a central controller, the real-time sampling and detections are collected from all the terminals to a general central controller as is illustrated in Fig. 2.3a. The central controller

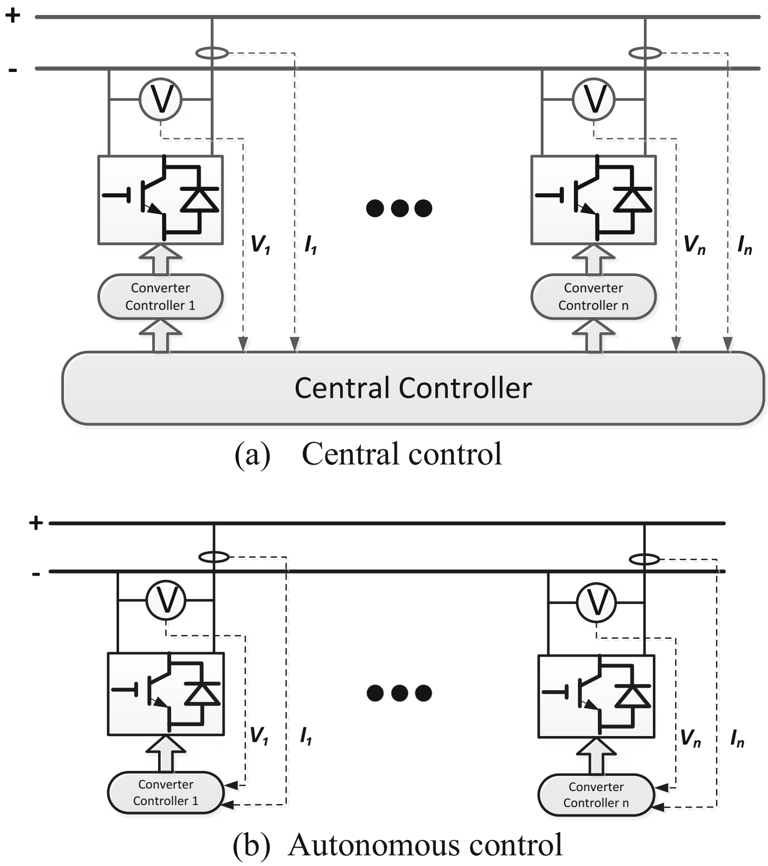


Fig. 2.3 (**a**) Central control. (**b**) Autonomous control

possesses the detected information and manages to output instant orders to each terminal. This idea was soon found unfeasible and unreliable for an expanded DC network with increasing number of DC terminals. Unlike traditional large-scale AC power systems, a DC microgrid does not have significant inertia. The DC voltage can typically drop to zero or rise to double in a few mini-seconds if a steady power mismatch is not addressed. As a result, an extremely high bandwidth and reliable communication channels are demanded in this case. Central control scheme demands duplex communications on the loop of high-bandwidth control between each terminal and the central controller, which would greatly increase the cost and, more importantly, the extra communication system degrades the reliability as unpredictable consequences would occur if there is a communication failure, a packet losing for instance. The overall reliability of a centrally controlled DC microgrid is generally difficult to guarantee as a failure on the central controller on the communication channel may result in system collapse.

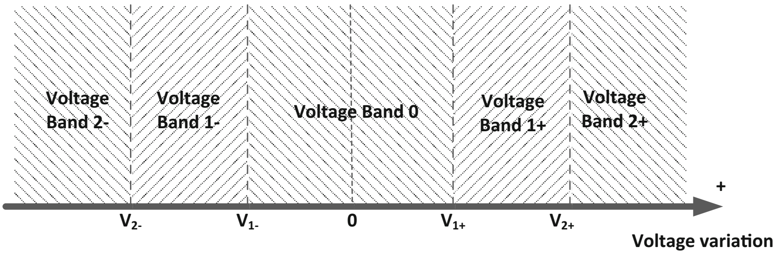
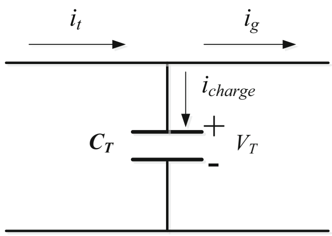


Fig. 2.4 Voltage band definition for autonomous DC microgrid control scheme

Fig. 2.5 Voltage variation-based DC microgrid control scheme



In order to avoid such high communication demand of central control, autonomous control was proposed for DC microgrid control at primary control level, which is illustrated in Fig. 2.3b. Autonomous control is based on local detections only and therefore the primary controls of terminal converters can be incorporated in a "plug-and-play" and expandable manner without the need for communications. With autonomous control methods, the terminal cooperation scheme shall be specially designed and embedded into terminal controllers.

For autonomous control, voltage variation-based technique can be implemented [15–17] which does not need additional communication channel but local voltage detection, hence better reliability and lower cost. Droop control is normally employed throughout voltage variation-based autonomous control scheme. A typical voltage banding scheme is demonstrated in Fig. 2.4, where specific control strategies are determined by which band the local DC voltage detection belongs to [17], and its relevant control is locally embedded within each DC terminal.

2.3.1.3 The Principles of DC Voltage Control [13]

Figure 2.5 shows the basic DC terminal model. The terminal voltage would rise when the capacitor charging current is positive and drop when negative. In other words, voltage variation of a DC microgrid can indicate whether the system power flow is effectively balanced.

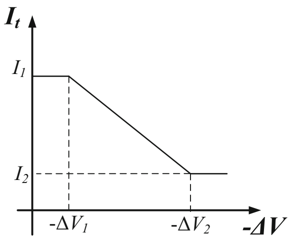


Fig. 2.6 DC voltage droop

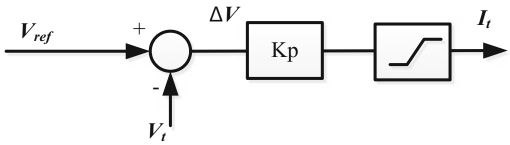


Fig. 2.7 DC voltage droop control block

The charging current i_{charge} is subjected to

$$i_{\mathrm{charge}} = i_{\mathrm{t}} - i_{\mathrm{g}} \tag{2.1}$$

where i_{t} is the terminal current and i_{g} the DC grid current. Once the grid current is given, the charging current can be regulated by controlling the terminal power. Droop control, as is shown in Fig. 2.6, is widely used in the implementation to determine how much current a slack terminal shall be given on a real-time basis. Linear current-voltage control is imposed when the voltage variation is between and ΔV_1 and ΔV_2. Saturation current/voltage is normally added for power rating or control band switching concern.

The corresponding control diagram of droop control can be generalized as a proportional with saturation control shown in Fig. 2.7, where the voltage variation can be calculated with the reference voltage V_{ref} and the detected terminal voltage V_{t} and K_{p} refers to the gain of the droop.

2.3.1.4 Operational Criteria

In order to determine the specific control strategy in each operational status, the operational criteria of a DC microgrid is set up in three groups in terms of priority as the following:

- Reliability—of the first priority

  Reliability concerns operational stability and equipment safety, which ensures that the facilities within the microgrid, such as capacitors, power electronics devices, transmission lines, and energy storage systems, are not damaged and are in normal operation. As the reliability is primarily for safety concern, once a DC microgrid is in operation, the criteria of reliability shall be obeyed at all time.

- Function ability—of the second priority

  Function ability concerns satisfactory anytime plug-and-play power supply, maximum renewable power generation, and state of charge (SOC) management of energy storage. As the function ability is proposed for the basic function demand from microgrid customers, it shall be fulfilled upon the state when reliability is ensured.
- Optimization—of the least priority

  Optimization concerns the optimal but not essential operation attributes for a microgrid. Examples are utility grid support, power smoothing, and internal voltage variation suppression.

  During system operation, conflicts among groups of criteria may occur under certain circumstances. The criteria of the lower priority shall be subjected to the higher. One typical example is when the microgrid is operating during islanding operation, load shedding shall be carried out when the load power consumption exceeds the real-time total power supply capability, where the anytime power supply function ability shall give way to the safety criteria to avoid system instability.

2.3.1.5 Autonomous Control Strategy of DC Microgrid [17]

Since the control schemes of the terminals within a DC microgrid can be determined by DC voltage variation, autonomous control for an entire DC microgrid can be established. Assuming that the voltage difference among the terminals is negligible, a certain range of operational voltage can be set and divided into a number of bands. In order to ensure the power balance, certain combination of terminals is assigned into each band acting as slack terminals. Based on the voltage band defined in Fig. 2.4 and the fore-cited control criteria, a typical autonomous voltage control scheme can be established, which is demonstrated in Fig. 2.8.

As is shown in Fig. 2.8, a control structure of three levels within 5 V bands is established by injecting slack terminals into each of the voltage bands. The control levels are:

Level 0: Level 0 control corresponds to voltage band 0, where the system is in normal grid-connected operation. The DC voltage is maintained by utility grid-connected DC/AC converter (GVSC)—the slack terminal.

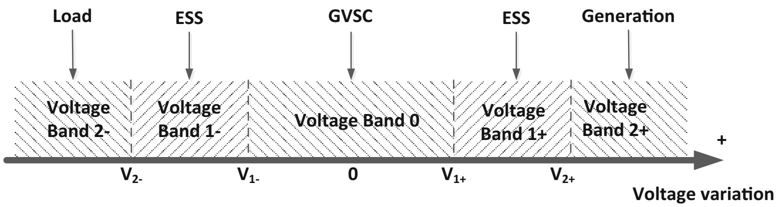


Fig. 2.8 Autonomous voltage control

Level 1: Level 1 control corresponds to voltage band 1+ and 1−, where the G-VSC fails to regulate the DC voltage within band A and energy storage system (ESS), the slack terminal(s), starts to take the place.

Level 2: Level 2 control corresponds to voltage band 2+ and 2−, where both GVSC and ESS cannot maintain DC voltage within band A and an emergency control is performed. Load shedding is carried out in band 2− and generation curtailing in band 2+. Please note that since load shedding is normally an on/off process, it cannot possibly maintain the DC voltage within band 2− but to push the voltage back to band 1−. If the voltage goes below band 2− or above 2+, protection measures shall take place.

It is possible that multiple slack terminals are selected within one band and cooperation strategy is essential in such situation.

2.3.1.6 Enhanced Droop Control for DC Microgrids [13]

Droop control is normally performed in voltage regulation, though it has a number of drawbacks. One obvious fact is that there is always a static error. Another undesirable feature is that the system might be subjected to lack of phase margin when the droop gain is too large for a relatively large control period. In order to correct the undesirable features of droop, enhanced control strategies are proposed for practical implementations.

Adding an integral controller paralleled with the proportional forms a PI controller, as is shown in Fig. 2.9a, which is normally employed by GVSC within a DC microgrid to eliminate static voltage error during AC grid-connected operation. Care must be taken that no more than one PI regulation can be implemented within a DC microgrid simultaneously to avoid conflicts between each other.

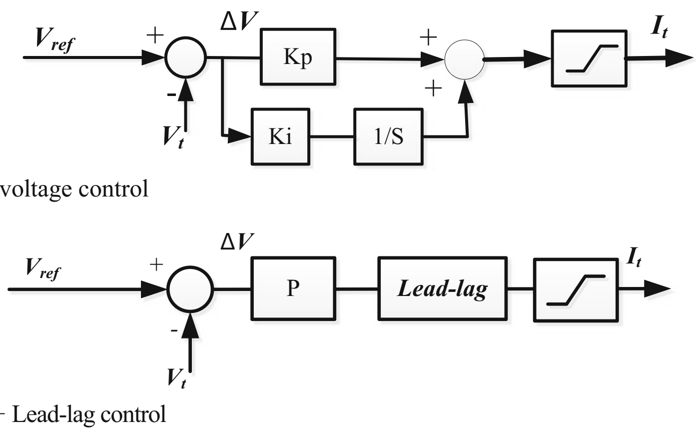


Fig. 2.9 Enhanced droop control. (**a**) PI voltage control. (**b**) P + lead-lag control

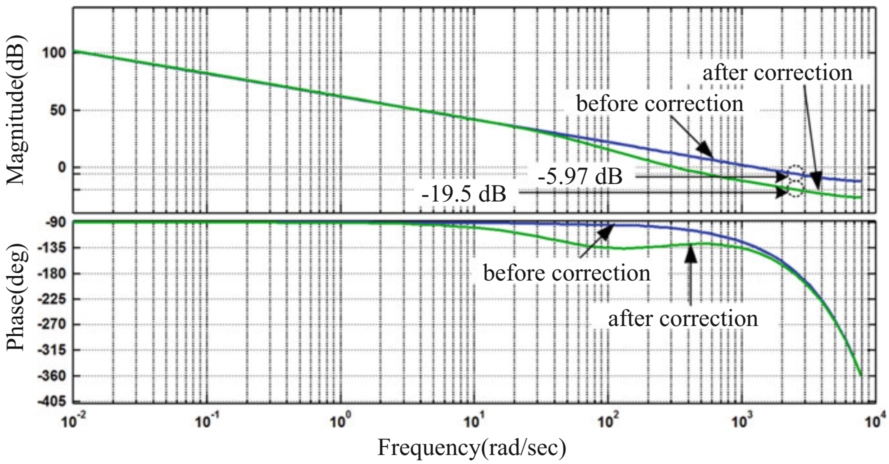


Fig. 2.10 Lead-lag correction

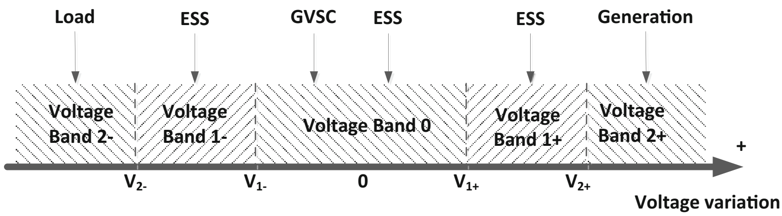


Fig. 2.11 Enhanced operational control

Lead-lag controller is also well employed when a large droop gain is required with a low control frequency, typically 2.5–5 kHz. A lead-lag controller is added to the droop controller to correct the dynamic behavior by increasing phase and gain margin; one example is shown in Fig. 2.10.

2.3.1.7 Enhanced Operational Control of DC Microgrid and Power Smoothing

In order to enhance the output power exchange with the utility grid, ESS can be injected into the voltage band 0 in Fig. 2.8 as Fig. 2.11 shows.

By setting the gain much larger than the GVSC, the ESS can effectively share most of the power fluctuation of higher frequency, hence smoother output power from the GVSC to the utility grid. Besides, the total bandwidth of voltage regulation can be increased, which means that the DC voltage variation can be further suppressed for the same power variation. As the gain can be considerably large, a lead-lag controller shall be added to the ESS controller in the form of Fig. 2.9b.

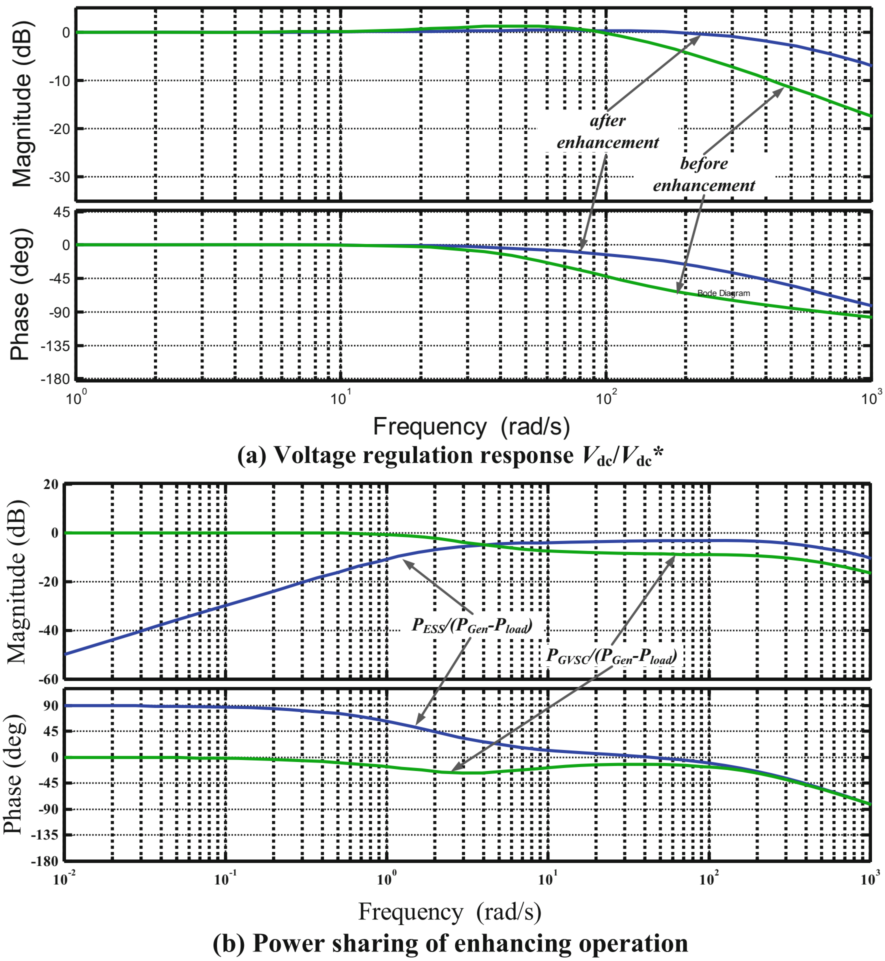


Fig. 2.12 Close loop Bode plot for enhanced voltage control. (**a**) Voltage regulation response $V_{dc}/V_{dc}*$. (**b**) Power sharing of enhancing operation

Such a voltage regulation and frequency-based power sharing strategy can be assessed by close-loop Bode plot, which is illustrated in Fig. 2.12.

2.3.1.8 Hierarchical Control Scheme with Low-Bandwidth Communication

The major drawback of the fore-cited autonomous control scheme is that a static voltage variation cannot be avoided when the DC system is operating in a certain voltage band other than band 0. Besides, it is also difficult to achieve accurate power sharing among slack terminals in an autonomous manner. A communication

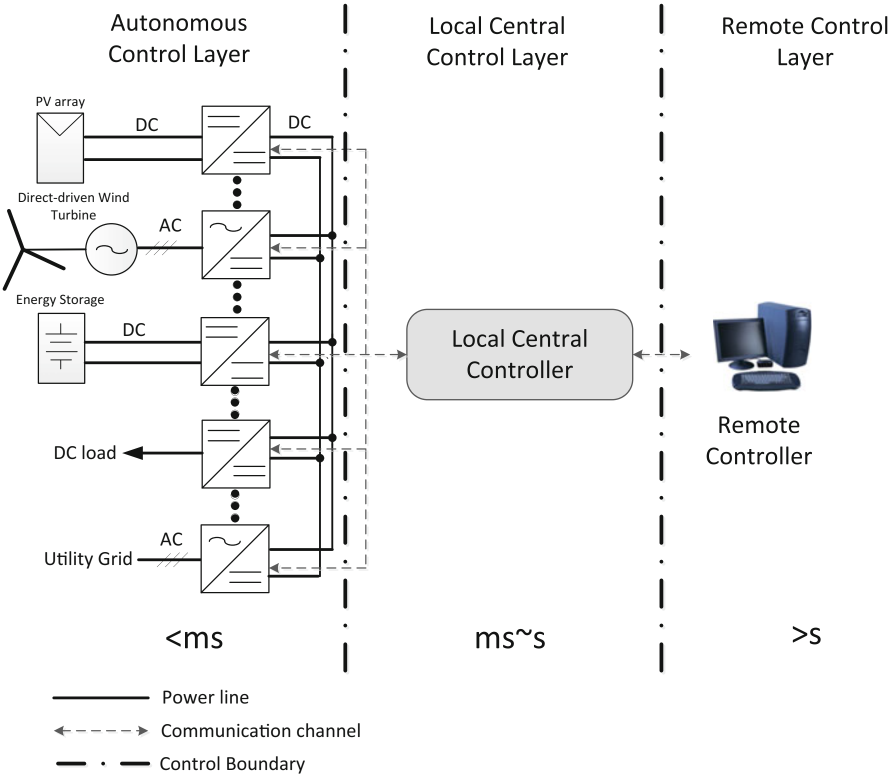


Fig. 2.13 Three-layer DC microgrid control system

network is therefore employed to optimize voltage profile in various timescales, hence a hierarchical control system [18]. A hierarchical microgrid control system can be typically divided into three layers in terms of the control cycle. They are autonomous control layer, local central control layer, and remote control layer, which are demonstrated in Fig. 2.13. As is shown in Fig. 2.13, the fore-cited autonomous primary control scheme is performed by each of the terminal converter in the autonomous control layer. The instant control feedbacks are based on each local voltage and current detections. The control cycle of this layer is normally less than a millisecond. Meanwhile, local central controller collects the current and voltage information from each terminal and provides optimized parametric amendment orders to current and voltage control. A secondary power sharing and voltage adjustment can be performed in this layer [19]. And the overall energy management can also be carried out in this layer if applicable. The control cycle of local central controller is typically between tens of milliseconds to a few seconds depending on communication baud rate and system scale. The remote controller layer allows the system operator or higher but slower level control to access the database uploaded by local central controller and manage the energy management strategy based on a cycle of a few seconds to a few minutes. The local central control layer is a desirable redundancy for optimization to the autonomous control layer and similar case is the remote control layer to the local central controller.

2.4 Stability of DC Microgrids

2.4.1 Small Signal Model and Stability Assessment

2.4.1.1 Virtual Impedance Method

In order to assess the dynamic performance of a DC system, an appropriate linearized model shall be established for small signal analysis. As is cited in previous sections, the DC microgrid system consists of power terminals and slack terminals. Slack terminal control can actively affect system dynamic performance. A single-slack terminal DC system model can be established with the slack control modeled as virtual impedance in S domain using virtual impedance method [20]. The modeling scheme is demonstrated in Fig. 2.14, where Reg(s) refers to the linear transfer function of the slack terminal control, including both open-loop voltage regulator RegV(S) and close-loop current regulator RegI(S).

The transfer function can be given by

$$\mathrm{Reg}(S) = \mathrm{RegV}(S)\mathrm{RegI}(S) \tag{2.2}$$

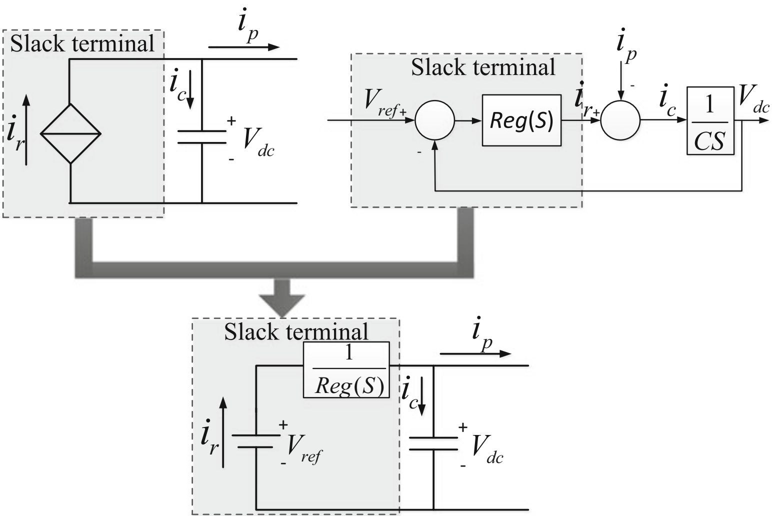


Fig. 2.14 Single-slack terminal DC microgrid modeling using virtual impedance concept

A high-bandwidth current regulation transfer function can be simplified and modeled as a first-order delay process as

$$\mathrm{RegI}(S) = \frac{1}{1 + T_c S} \tag{2.3}$$

where T_c is the implemented control cycle. RegV(S) is the linearized open-loop voltage regulator which can be a P control, P with lead-lag control or PI control as is cited in previous sections.

With a simplified model as Fig. 2.14 shows, transfer functions or state space can be established and then system stability can be analyzed with known assessing technique such as phase/gain margin analysis and root locus. One example of single-slack terminal analysis in terms of variable PI regulator band width is shown in Fig. 2.15 using close-loop root locus and open-loop marginal analysis.

For a DC microgrid with multiple slack terminals and complex topology, S-domain model can be set up based on single slack terminals connected to each other via line impedances. By using Thevenin's equivalent from any of the terminal sides, the multiple-terminal system can be transformed into a simplified model in the same form in Fig. 2.14. This process is shown in Fig. 2.16 and then the same stability assessing technique applies.

2.4.1.2 Impacts of Constant Power Load on System Stability

The DC loads in a system are not necessarily linear load. Their behaviors vary and can have significant impact on a DC microgrid operation and stability. One of the commonly seen and severe cases is the constant power loads (CPLs) [17].

Static Consideration of a DC System with CPL

As is previously cited, droop-based control is normally used in autonomous control level. A basic concern about the impact of CPLs is whether they are compatible with droop control. A basic example is demonstrated in Fig. 2.17a where a droop-controlled slack terminal is supplying a CPL R_{CPL} with a cable resistance of R_L. The static characteristic of the simple circuit is shown in Fig. 2.17b with two droops and the CPL considered [17].

The DC voltage at the load terminal is

$$V_{dc} = V_{ref} - \left(R_{eq} + R_L\right) I_{dc} \tag{2.4}$$

where R_{eq} is the equivalent slack terminal virtual resistance and per-unit values are used in all the expressions in this section.

As is shown in Fig. 2.17b, the CPL characteristic is given as

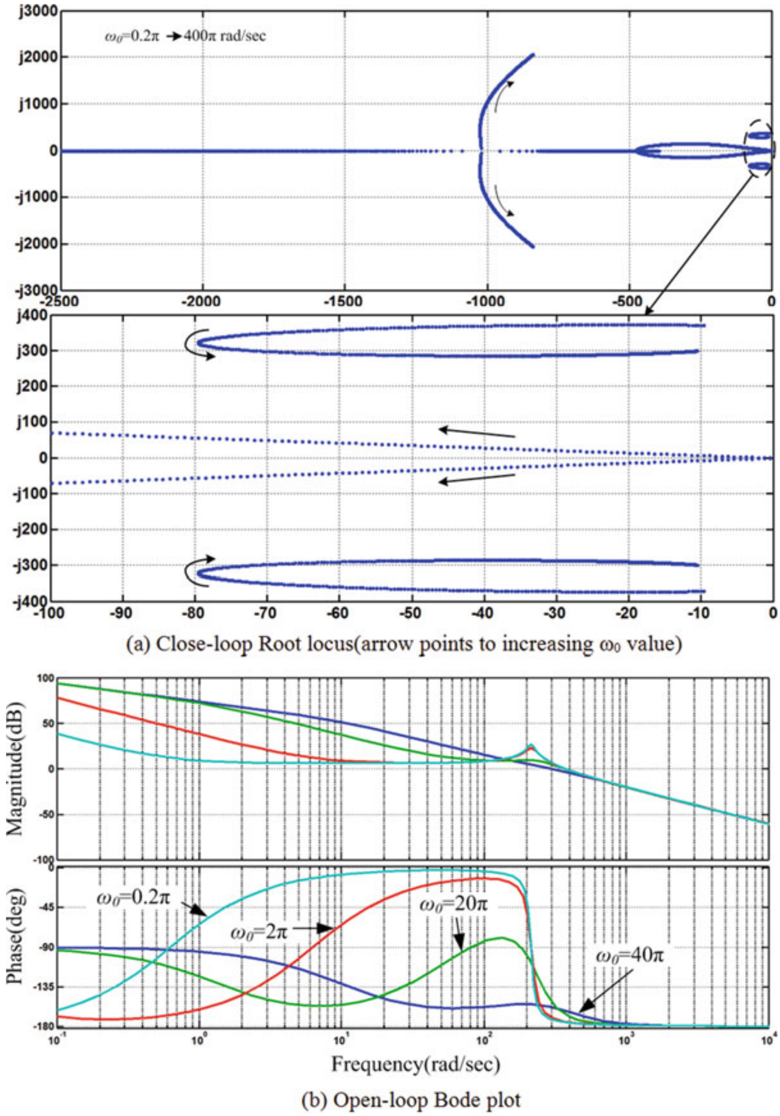


Fig. 2.15 Stability assessment of single slack terminal. (**a**) Close-loop root locus (*arrow points* to increasing ω_0 value). (**b**) Open-loop Bode plot

$$V_{\mathrm{dc}} \cdot I_{\mathrm{dc}} = \text{constant} = P_{\mathrm{L}} \tag{2.5}$$

where P_{L} refers to the load power.

In order to ensure a stable system operation, the characteristic curves of the slack terminal and the load must share a cross point on the V–I plane, using per-unit value

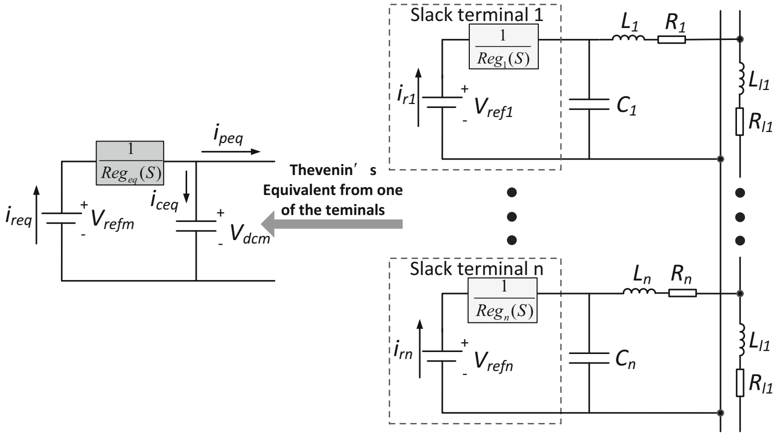
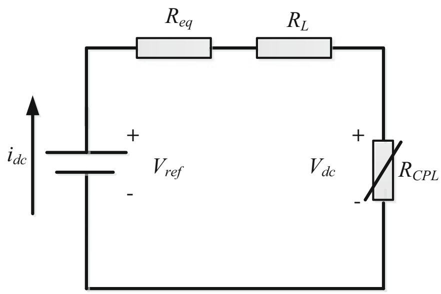
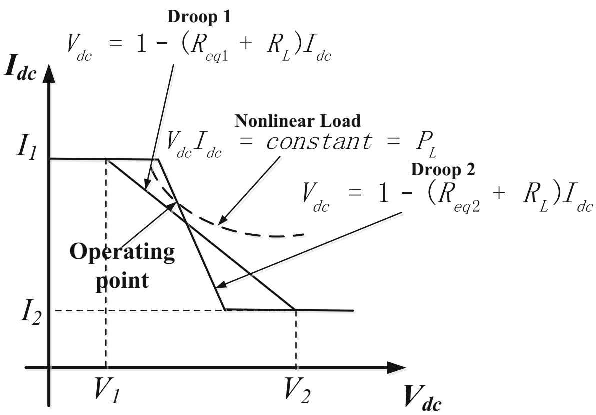


Fig. 2.16 DC microgrid modeling with multiple slack terminals

Fig. 2.17 Simple DC system with one slack terminal and one CPL. (**a**) Circuit diagram. (**b**) V–I characteristics with different droop



(a) Circuit Diagram



(b) V-I characteristics with different droop with the superscript of "*" and assigning $V_{dc}* = 1$. The operating voltage can be calculated by combining (Eqs. 2.4 and 2.5) as

$$\frac{V_{dc}* = 1 \pm \sqrt{1 - 4\left(R_{eq}* + R_L*^L\right)P_L*}}{2} \tag{2.6}$$

To ensure the existence of the operating point, the following condition must be met:

$$R_{eq}* + R_L* \leq \frac{1}{4P_L*} \tag{2.7}$$

Obviously, Droop 1 does not meet the conditions whereas Droop 2 does in Fig. 2.17b. And the operating point can be given as

$$(V_{dc}*, I_{dc}*) = \left(\frac{1 + \sqrt{1 - 4\left(R_{eq}* + R_L*\right)P_L*}}{2}, \frac{2P_L*}{1 + \sqrt{1 - 4\left(R_{eq}* + R_L*\right)P_L*}} \right) \tag{2.8}$$

Droop can be selected with the guidance of (Eqs. 2.7 and 2.8).

Small Signal Modeling of a CPL with Virtual Impedance Method

By differentiating the equation of $V_{dc} = P_L/I_{dc}$ on both sides, the small signal virtual impedance on a given point can be obtained as

$$R_{CPLeq} = \frac{dV_{dc}}{dI_{dc}}\Big|_{I_{dc}=I_{dc0}} = -\frac{P_L}{I_{dc}^2}\Big|_{I_{dc}=I_{dc0}} \tag{2.9}$$

where I_{dc0} refers to the equilibrium point current. Therefore, when the operational analysis point, that is, V_{dc} and I_{dc}, has been determined, this equivalent virtual resistance can be incorporated into the fore-cited S-domain analytical circuit based on virtual impedance concept.

Dynamic Consideration of a CPL Within a DC Microgrid

In a DC power system, though the static characteristic matches the needs from CPL, there is still a chance that severe oscillation would be caused due to its dynamic behavior caused by the negative resistance brought by CPL. Such oscillation is more likely to happen with larger line impedance, smaller terminal capacitance, and larger constant power load.

In order to prevent undesirable oscillation, damping measurement shall be taken into consideration at the designing stage. The damping implementation varies. However, the damping methods can be generally categorized into two kinds—slack terminal side damping [19–21] and power terminal side damping [22–24]. The power terminal damping methods superimpose an extra damping control into the CPL control, hence a modified and more stable CPL behavior for the global system concern. Such power terminal side method can possibly result in a trade-off of the modified load performance but more adaptive to a system with multiple CPLs and possible reconfigurations [24]. Slack terminal damping methods, on the other hand, superimpose the damping control into the normal voltage control to provide extra damping to the DC system without compromise to load behavior; yet the drawback is that it is case sensitive to system configuration and variable sources and loads may increase the difficulty to ensure its robustness.

2.5 Protection of DC Microgrids

Comparing the protection of traditional AC systems, the theory and implementation of the newly evolved DC microgrid protection are far from maturity. In this section a few issues concerning DC microgrid protection are discussed.

2.5.1 Introduction to DC Faults

The faults within a DC microgrid can occur at terminal units and on any point of the network. The terminal units are DC/DC converters, grid-connected VSC, loads, utility AC grid, or other converters. Network fault concerns those occurring at the DC buses, transmission lines, or feeders.

For converter and AC-side fault, the fault current can normally be limited by the inductive filters along with switching devices.

The DC network faults can further be divided into two types: line breaking and short fault [25].

(a) Line breaking

A line breaking fault will possibly change the system topology and power flow of a DC microgrid. Typically in a radial topology, a breaking fault would essentially intersect the grid into two sub-grids, which is illustrated in Fig. 2.18. The instant autonomous control scheme will continuously be performed within each of the sub-grid. The terminal unit will remain in the operational voltage band shown in Fig. 2.4 as long as there is at least one slack terminal surviving for each sub-grid. Otherwise, the DC system voltage will divert and protection must take place by blocking all the converter sources and tripping the loads. Actually, the system behavior of a DC microgrid after a line

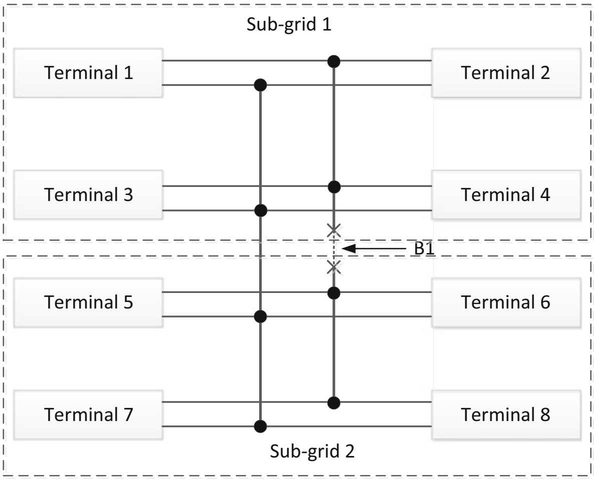


Fig. 2.18 Line-breaking fault in a DC microgrid

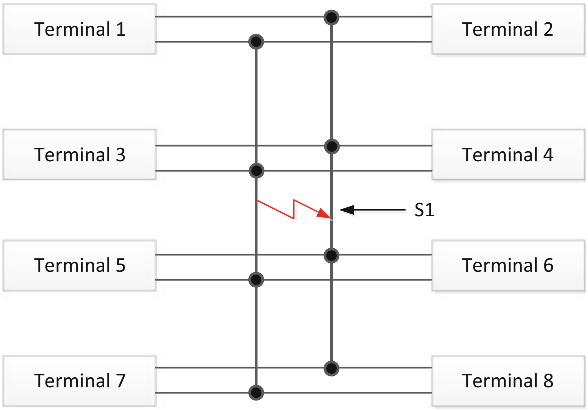


Fig. 2.19 Bus fault in a DC microgrid

break seems more like a mode switch and can be handled with predefined autonomous control scheme and voltage protection.

(b) DC short faults

As the DC side impedance is very low, a DC short fault will produce a huge current surge draining into the faulty point in a very short time, typically milliseconds. If a bus fault happens at the point of S1 shown in Fig. 2.19, the current will increase drastically.

Simulation results shown in Fig. 2.20 are given from the GVSC converter side, where it can be seen that the fault current across the faulted cable can rise up to 20 p.u. in 5 ms.

(c) DC arc faults

Arc faults refer to the situation that an electric circuit is maintained via an arc when two conductor ends are very closely located with dielectric medium in between [26–30]. Such situation results from the cause that the

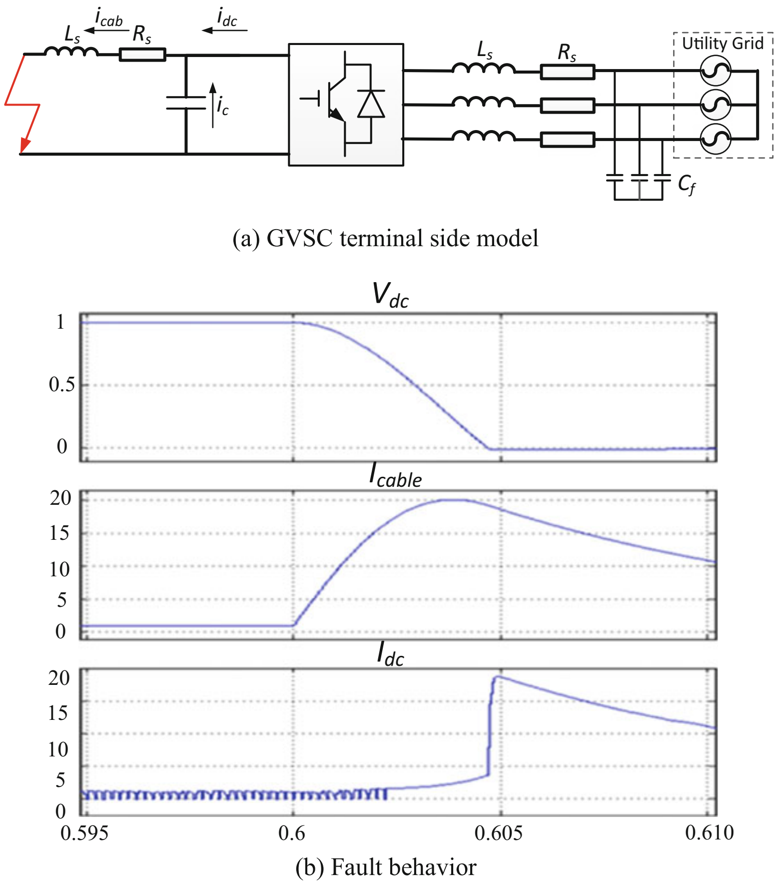


Fig. 2.20 DC fault behavior from GVSC side. (**a**) GVSC terminal side model. (**b**) Fault behavior

high-temperature arc ionizes the dielectric medium. The arc current is usually not very significant comparing with normal power rating but is able to accumulate high temperature at the faulty point. A lasting arc fault may further damage the adjacent equipment and cause more severe fault event. There are mainly two kinds of arc faults—series and parallel, shown in Fig. 2.21a, b. A series arc fault is more common in a DC system. It can be caused by unintentional conductor discontinuity within DC lines or by a loose contactor that slightly separates the connections, etc.

In order to prevent damage caused by arc fault, the arc fault of a DC microgrid should be detected. However, the detection of DC arc fault, especially a series arc fault, in a DC microgrid is difficult. The reason lies on the fact that the behavior of an arc fault is similar to small nonlinear impedance, causing limited changes to system currents and voltages [26–29]. Reports show that the behavior includes a static resistive characteristic along with high frequency, typically a few kHz, chaotic noise as well [26, 27]. It is still

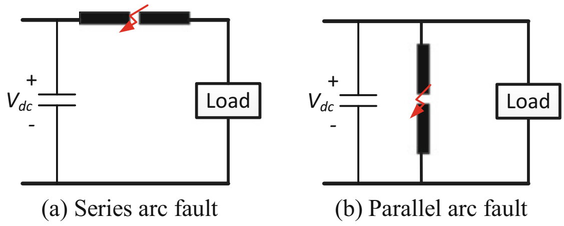


Fig. 2.21 DC arc fault. (**a**) Series arc fault. (**b**) Parallel arc fault

difficult to establish an explicit analytical model to find out its exact signature due to its chaotic behavior and random causes.

2.5.2 DC Circuit Breaking

The key issue of DC protection device is to interrupt fast-increasing DC fault current. There are generally two types of DC current interruption methods, that is, current breaking and current limiting.

Fuse [25] is the most common circuit-breaking device with a fuse link and arc-quenching component. A fuse breaks its circuit by melting when a certain root mean square current goes through, which means that it can be applied in either DC and AC circuit. A fuse uses its heat-absorbing material to break the circuit and quench the arc. The heat-absorbing material is normally silica sand, connecting to conductor links within a ceramic cartridge. The selection of fuse mainly depends on its voltage and current-time ratings. For the DC applications, a shorter current rising time (typically a few milliseconds) rather than a steady large current will result in a quicker melting process and better arc quenching [31]. A quick melting fuse with light overcurrent handling ability is desirable for a DC fault. The major drawback of fuse is that it is nonreversible. Fuse can be applied as the main protection device in small-scale DC microgrid or as the backup device in a relevant large system.

Molded case circuit breaker (MCCB) is the most commonly used low-voltage circuit breaker. Unlike fuses, MCCBs are reversible. An MCCB is able to interrupt current within a time of a few tens of milliseconds under a rated voltage of hundreds of volts and with an interruption current of tens of kilo amperes [32]. MCCB can be used as the main protection device in low-voltage small-scale DC microgrid system.

The idea of current limiting is to insert a device of current-sensitive impedance into DC circuits. The inserted impedance can be resistive or inductive. The value of the inserted impedance is very low when normal current goes through and tends to rise drastically when large fault current passes through, hence limited rising rate of the DC fault current. With the assist of current limiter, the DC current can be interrupted with relevant "slower acting" switchgear. The DC circuit breaker can therefore make the fault current to commutate to the axillary resonant circuit and force a zero-current point to allow arc extinguishing.

2.6 Conclusion

Microgrid, as a promising new power management system, is proposed for accommodating growing distribution generation and energy storages; for example, electric vehicle charging stations can act as an ideal storage resource in microgrids. Distributed renewable generations, energy storage systems, and local loads are key elements of a microgrid. DC microgrid is specially designed for distribution power systems dominated by those generations, storages, and loads that have DC links.

In this chapter, the hierarchical structure of DC microgrids is introduced. With autonomous voltage control scheme at primary control level, a DC system can well operate autonomously. Secondary and higher control levels enable further optimization on accurate power sharing, voltage restoring, and energy management. Virtual impedance method is introduced for assessing DC power system dynamics.

DC microgrids have significant advantages in terms of converter cost, distribution efficiency, power supply reliability, and controllability compared to AC ones, whereas the difficulty in DC protection is the major weakness.

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