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AC and DC Microgrids: A Review on Protection Issues and Approaches

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Abstract – Microgrid is a convenient, reliable, and eco-friendly approach for the integration of Distributed Generation (DG) sources into the utility power systems. To date, AC microgrids have been the most common architecture, but DC microgrids are gaining an increasing interest owing to the provision of numerous benefits in comparison with AC ones. These benefits encompass higher reliability, power quality and transmission capacity, non-complex control as well as direct connection to some DG sources, loads and Energy Storage Systems (ESSs). In this paper, main challenges and available approaches for the protection of AC and DC microgrids are discussed. After description, analysis and classification of the existing schemes, some research directions including coordination between AC and DC protective devices as well as development of combined control and protection schemes for the realization of future hybrid AC/DC microgrids are pointed out.

Keywords: AC microgrids, DC microgrids, Hybrid AC/DC microgrids, Protection challenges, Protection schemes

1. Introduction

Most recently, there have been growing concerns associated with gradual depletion of fossil fuel resources, environmental pollution and global warming. These challenges have led to a new type of generation at users' site by applying small DG sources [1, 2]. The DG sources which enhance the reliability and power quality of the network can either be non-renewable (such as fuel cells, gas turbines, microturbines, reciprocating engines, etc.) or renewable sources (such as wind turbines, photovoltaic systems, small hydro power, etc.) [3].

The integration of distributed generators has created the concept of microgrid which is defined as a collection of DG sources, loads and ESSs that cooperate with each other to act as a single-controllable entity with respect to the grid [4]. The total generation capacity of DG sources installed in a microgrid can be a few hundred kilowatts to a few megawatts. Under normal conditions, microgrid is connected to the main grid (grid-connected mode) and imports or exports power from or to the main grid. Once a fault occurred at the main grid, it is disconnected via a Static Switch (SS) at the Point of Common Coupling (PCC) and is transferred to the islanded mode. After the fault clearance, the microgrid is reconnected to the main grid [5, 6].

Microgrids should have two significant features: peer-to-peer and plug-and-play. The former means that the operation of microgrid is not influenced by the availability of a specific component such as a master controller or a central storage system. The latter enables DG sources to be installed at any location in the microgrid without restructuring of protection scheme. This capability reduces the possible engineering errors and facilitates the installation of new DG sources in the microgrid [7].

Notwithstanding many benefits provided by microgrids, there are some technical challenges which need to be resolved by power system researchers and engineers. One field which requires more attention is the protection. The significant challenge associated with the protection of microgrid is that the magnitude of short circuit currents in islanded mode of operation is too low [8]. The reason is that the power electronic interfaces required for the connection of DG sources to the microgrid are designed to limit their output current to protect their semiconductor switches [9]. Hence, fault detection strategies for the islanded operating mode should be based on low short circuit currents. In fact, a desirable microgrid protection scheme should not only possess the general features such as sensitivity, selectivity, speed of response and security level, but also ponder the number of installed DG sources and the fault current contribution of each of them in the islanded operating mode [10, 11].

In recent years, many studies have been conducted to design and model effective protection strategies for different structures of microgrids. In this paper, the pivotal challenges in protection of AC and DC microgrids are discussed, and the existing methodologies against these challenges are introduced and classified.

The remainder of this paper is as follows: Sections II and III discuss the main protection challenges and approaches in AC and DC microgrids, respectively. In Section IV, the conclusion is reported and some research directions for protection of future hybrid AC/DC microgrids are suggested.

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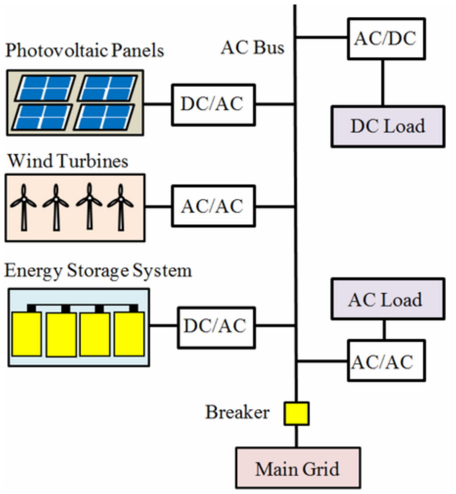

Fig. 1. Structure of a typical AC microgrid

2. Protection Challenges and Approaches in AC Microgrids

To date, AC system has been the most popular architecture which is used for the majority of microgrid research projects. Since the design and modeling of AC systems are much simpler than DC ones, a large number of microgrids around the world have been developed based on this technology [12]. The structure of a typical AC microgrid is shown in Fig. 1. As can be seen from the figure, different types of DG sources, ESSs and loads can be connected to the microgrid AC bus, either directly or indirectly by means of converters [13].

2.1 Protection challenges in AC microgrids

Most conventional distribution systems operate radially, where power flows unidirectionally from large power plants to the customers. In such systems, since the magnitude of short circuit current is proportional to the fault location, the protection is done by overcurrent-based protective devices [14]. Also, the time-graded coordination between them enables upstream devices to operate as backup for downstream ones [15]. In recent years, the emergence of microgrids has changed the structure of distribution systems from passive networks into active ones. This change disturbs the operation of the overcurrent-based strategies such that they would no longer have the ability to protect new structures [16, 17].

As mentioned earlier, the fault current contribution of inverter-based DG sources in a microgrid is limited (only 2 to 3 times the maximum load current) due to the low thermal capability of their power electronic devices. Therefore, the protective devices of a microgrid containing inverter-based DG sources would operate very slowly or may not be triggered at all in case of a fault event during islanded mode. In addition, the considerable difference between the magnitudes of short circuit current in grid-connected and islanded modes makes single-setting traditional overcurrent relays unable to protect dual-mode operating microgrids [18, 19]. Therefore, the protection of AC microgrids including inverter-based DG sources is not possible using traditional overcurrent protective devices and some new techniques should be devised.

2.2 Protection approaches for AC microgrids

As discussed earlier, the traditional overcurrent-based strategies have not the ability to protect AC microgrids and subgrids due to the drastic difference between magnitude of fault currents in grid-connected and islanded modes. In order to overcome the challenge, a number of strategies have recently been proposed in the scientific literature. In the following subsections, apart from introducing and categorizing the most relevant approaches proposed to date, the merits and demerits of each category are discussed.

2.2.1 Adaptive protection

According to [20], Adaptive protection is defined as an online system which modifies the preferred protective response to a change in system conditions through an externally generated signal. Adaptive protection schemes can be classified into three main categories including overcurrent, differential and symmetrical components.

a) Adaptive overcurrent schemes

In adaptive overcurrent schemes [21-24], a central protection unit is used to periodically store and update three distinct tables namely event, fault current and action tables. Event table lists all possible configurations of the microgrid along with the respective status of DG sources. Subsequently, in accordance with each configuration, the fault current measured by each relay for all possible fault locations is stored in the fault current table. Also, for each set of configurations, action table lists the relay settings for each type of fault along with its time delays. Finally, the central protection unit is able to issue the proper tripping signals to the respective relays based on the status of these three tables in each period. Moreover, in case a relay fails to trip, its upstream or downstream relay (based on action table) operates after a predetermined period of time and provides the secondary protection. Likewise, if a fault takes place in the main grid, the closest microgrid relay to the main grid interrupts the fault current provided by microgrid DG sources, and then the microgrid is transferred to the islanded mode [25]. However, adaptive overcurrent protection strategies suffer from some challenges including: (a) necessity to consider all possible configurations of a microgrid with regard to different locations and types of faults. (b) complicated analysis of short circuit currents in a large microgrid with many radial and looped feeders. (c) costs associated with installation of a communication infrastructure.

b) Adaptive differential schemes

Differential protection schemes operate based on comparison between the measured currents by relays installed at both ends of a protected element (such as busbar, line and transformer). In case a fault occurs in the protected element, the difference between these measured currents exceeds a threshold value and the relays trip to isolate the faulted element from the rest of network. In addition, backup protection can be provided by setting the adjacent upstream and downstream relays of the protected element [22, 26].

In [27], a differential strategy using traditional overcurrent relays as well as communication links is proposed which is able to protect medium voltage microgrids including both inverter- and synchronous- based DG sources. Even though the economic issues are considered in the scheme, it is unable to provide protection during unbalanced loads.

Sortomme et al. designed another differential-based protection scheme applying digital relays and Phasor Measurement Units (PMUs) along with communication channels [28]. The scheme provides three levels of protection including instantaneous and comparative voltage relays. Additionally, the protection against High- Impedance Faults (HIFs) is presented in the scheme. Nevertheless, the suggested method is not economical, since PMUs are quite expensive.

In [29], a different protection scheme is introduced for microgrids including both radial and looped feeders. In the scheme, lines and busbars are protected by means of only differential currents, whereas the protection of DG sources is provided by over- and under-voltage, reverse power flow, and synchronism check relays. Although the developed methodology can provide a robust protection for both grid-connected and islanded modes, it still suffers from problems related to the unbalanced loads and switching transients.

Generally, the main drawbacks of differential protection approaches are: (a) need for communication system as a key element, while its failure endangers protection of microgrid. (b) deployment of costly synchronized measurement devices. (c) difficulties resulting from unbalanced loads and transients during connection or disconnection of DG sources.

c) *Adaptive protection schemes based on symmetrical components*

The offered protection schemes in the category substantially apply principles of symmetrical components and enable overcurrent-based strategies to protect micro-grids in both grid-connected and islanded modes. The main proposal in the area is put forward by Nikkhajoei and Lasseter in 2006 [30]. In their proposal, they make use of zero- and negative- sequence currents to detect and isolate, respectively, single-line-to-ground and line-to-line faults in islanded mode of operation. However, their devised solution has not the ability to protect microgrids during HIFs. Furthermore, the operation of their protection scheme requires communication links.

In [31], a microprocessor-based relay along with a protection strategy is designed. The strategy which is able to protect low voltage microgrids against both solid and high-impedance faults, operates by applying zero- and negative- sequence components. The main feature of the strategy is that it does not require communication links. However, the proposed method is not capable of protecting microgrids including mesh feeders.

The authors of [32] developed another protection scheme based on only positive-sequence components. In their proposed scheme, they use a designed Microprocessor-Based Relay (MBR) along with PMUs and a digital communication system to protect microgrids including both radial and looped feeders against different types of faults. The designed MBRs have the ability to update their pickup values after any change in the structure of microgrid, thereby protecting microgrids against subsequent faults. Even though the offered protection scheme remedies the drawbacks of the previous works, it is not economical due to the high price of PMUs.

The main issues related with the implementation of the above-mentioned schemes are: (a) necessity to extensive communication infrastructure in some proposals that may fail at some point, jeopardizing the whole microgrid protection. (b) inability to provide protection for looped microgrids (c) high costs associated with deployment of PMUs.

2.2.2 Distance protection

Distance protection scheme which offers a high selectivity is another way to protect AC microgrids. The installed distance relays in the scheme are responsible for calculation of impedance using the measured voltage and current at their location, by which they are able to detect the fault occurrences. Prior to fault occurrence, the measured impedance value is high because it includes the load impedance, while in case of a fault event on the network lines, the value becomes equivalent to only line impedance and decreases. As a result, the fault in each zone can be detected and located by comparison between the measured impedance values before and after the fault [33].

The typical time settings for a three-zone distance protection scheme are depicted in Fig. 2. According to the figure, Zone 1 protects 80% of the line length of AB without any tripping time delay. Zone 2 is set to not only protect whole Line AB, but also provide protection for 20% of its adjacent line (Line BC) with tripping time delay t_1. Also, 100% of both Lines AB and BC plus 25% of Line CD are protected with tripping time t_2 through Zone 3 [34].

The main study in this category is accomplished by Dewadasa and his research group in references [35, 36]. In

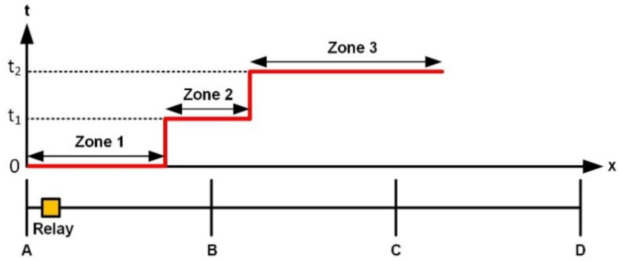

Fig. 2. Time settings for a three-zone distance protection scheme

their offered protection scheme, new admittance relays are developed based on characteristics of inverse time tripping. The developed relays have the ability to provide protection in their forward and inverse directions against different kinds of faults. However, some shortcomings of this methodology include: (a) errors resulting from fault resistance in measured impedances by relays (b) complications associated with impedance measurements in short lines.

2.2.3 Pattern recognition schemes

In reference [37], a new microgrid protection scheme is developed by applying a time-frequency transform which has the ability to protect radial and looped microgrids against different types of faults in both grid-connected and islanded mode. In the developed scheme, first, S-transform is used to extract the spectral energy contents of the fault current signals, measured at both ends of each line. Subsequently, fault patterns are registered by differential energy computations. Based on the predetermined threshold values (in accordance with each type of fault) on differential energy, the protection scheme is able to detect and isolate the faulted line. With regard to the indicated simulation results, the differential energy can be a suitable criterion, since it remarkably varies for a faulty phase in comparison with healthy ones. Moreover, the developed strategy is immune to the noise and less sensitive to synchronization errors.

3. Protection Challenges and Approaches in Dc Microgrids

DC microgrids can not only enhance the efficiency of the network by decreasing the number of power converters for DC-based DG sources and ESSs, but also provide higher power quality and transmission capacity in comparison with AC ones [38]. In addition, the structure of a DC microgrid is such a way that it does not require synchronization and control of reactive power [39-41]. The structure of a typical DC microgrid is shown in Fig. 3. As shown is Fig. 3, the connection of different types of DG sources, ESSs, and loads to the microgrid DC bus can be done directly or indirectly through power converters.

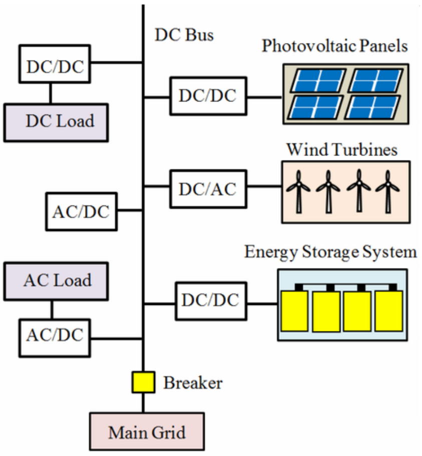

Fig. 3. Structure of a typical DC microgrid

3.1 Protection Challenges in DC Microgrids

In spite of numerous merits provided by DC microgrids, protection of such systems suffers from several challenges. Some challenges such as limited fault current contribution of inverter-based DG sources in islanded mode or inability of single-setting overcurrent relays in protection of dual-mode microgrids are common between AC and DC microgrids. Nevertheless, protection of DC ones is also influenced by two additional issues, i.e., grounding and lack of natural zero-crossing current.

3.1.1 Grounding

Basically, there are two types of faults in DC microgrids, namely, Line-to-Ground (LG) and Line-to-Line (LL). Even though the latter has typically low fault impedance and causes severe damage to the network, the former is considered as the most frequent fault type in DC microgrids which is greatly affected by the grounding system [42,43].

The most important objectives in design of grounding system for a DC microgrid are to facilitate fault detection and to minimize the corrosion phenomenon resulting from DC stray currents (leakage of DC current from conductor to the ground) [44-46].

Detection of faults in a solidly grounded system is simple because of its low grounding resistance, but the level of DC stray current in such systems is high which cause severe corrosion. Conversely, ungrounded systems are the best choices for the reduction of corrosion phenomenon, but fault detection in such systems is challenging due to the low level of fault currents. Hence, the protection of DC microgrids and minimization of corrosion are two contradictory objectives which are influenced by the type of grounding system.

3.1.2 Lack of natural zero-crossing current

Although operation of circuit breakers in both AC and DC microgrids is accompanied by an arc phenomenon,

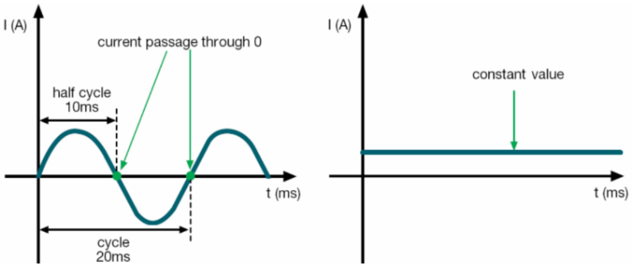

Fig. 4. Existence and lack of natural zero-crossing current in AC and DC microgrids

mechanism of AC circuit breakers, relying on the natural zero-crossing of the AC currents, enables them to distinguish the arc within the half cycle after tripping. However, due to the lack of natural zero-crossing in DC currents, the interruption of currents in a DC microgrid is a major problem which not only causes a serious hazard for personnel safety, but also results in the contact erosion of circuit breakers, thereby decreasing their lifetime [47-50]. The existence and lack of natural zero-crossing current in AC and DC microgrids are shown in Fig. 4.

Currently, the commercially available protective devices for DC systems are fuses and Circuit Breakers (CBs) [51, 52]. Fuses, which are frequently used in low impedance systems, operate on the principle of melting down a metal wire when too much current flows through it. They must be selected based on the time-current and voltage ratings of system in which they operate. They can function in either AC or DC systems. However, use of fuses in DC systems necessitates accurate calculation of the network time constant due to its direct influence on the fuse operation [51]. More precisely, if the network time constant is less than 2.5 ms, the fuse metal wire is quickly melted and the current is interrupted; In contrast, a large network time constant (more than 6ms) increases the melting time, and hence, the arc cannot be extinguished rapidly [53]. Additionally, transient overcurrents in a DC network may cause fuse malfunction. Consequently, fuses are not suitable options for protection of DC microgrids, but they still can be used as backup protective devices.

Molded-Case Circuit Breakers (MCCBs), consisting of a quenching chamber, contacts, and a tripping device (thermal-magnetic or electronic), are additional choices for interruption of fault currents [54]. Such circuit breakers are designed to operate once their instantaneous trip is exceeded. However, the final opening of the contacts does not happen unless the peak current lasts for a specific period of time [55]. In the microgrid, some loads and sources are interfaced with microgrid through power electronic devices. These power electronic devices often require line-to-line or line-to-ground filter capacitors. In case of a DC fault incident, the capacitors swiftly discharge into the fault point and lead to large peak currents for a short period of time, and hence the adequate force for completely opening of contact may not be generated [56]; in particular, contacts in a highly inductive system may weld closed during the fault [57]. For this reason, employment of circuit breakers is not an ideal solution for interruption of fault currents as well.

3.2 Protection approaches for DC microgrids

Although the majority of offered protection schemes for AC microgrids can be designed compatible with DC ones to overcome the common challenges, provision of a robust scheme for DC ones necessitates addressing the challenges associated with grounding and lack of natural zero-crossing current. The following subsections review the main proposed approaches, attempting to resolve these challenges.

3.2.1 Reconfigurable grounding systems

As mentioned in Subsection III.A.1, protection of DC microgrids and minimization of corrosion are two contradictory requirements which are affected by grounding system. In fact, best fault detection and minimum corrosion cannot be achieved in a certain grounding system. Hence, some alternative solutions have recently appeared in technical literature which try to ponder both of these requirements by applying reconfigurable grounding systems. More precisely, in such grounding systems, the network normally operates in ungrounded mode to minimize corrosion phenomenon resulting from high stray currents, but in case of sensing an unacceptable level of touch voltage (potential difference between energized device and the feet of a person in contact with the device), it automatically transfers to the grounded mode. However, it switches back to the ungrounded mode after clearance of abnormal operating condition.

The most basic structure of a reconfigurable system, referred to as diode grounded system, is shown in Fig. 5(a) [58]. As shown in the figure, diode grounded system contains a direct metallic connection of the negative bus to the earth by means of a diode circuit. In case a certain threshold voltage is reached, the current is allowed to flow through diode circuit to get dissipated in order that the personnel safety is ensured. However, due to the fact that

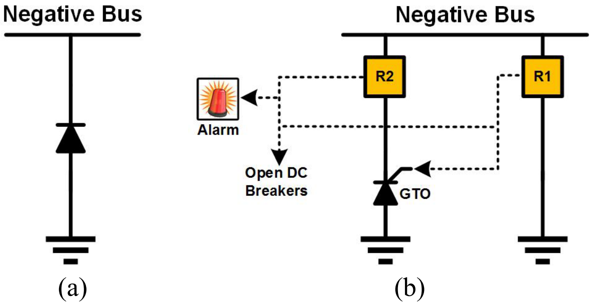

Fig. 5. Structures of reconfigurable grounding systems: (a) Diode grounded system; (b) Thyristor grounded system

corrosion cannot be entirely obviated by dint of diode grounded systems, they necessitate regular maintenance.

In order to possess an active control over the grounding instances, thyristor grounded system was developed in [44]. In the proposed system, as displayed in Fig. 5(b), an overvoltage relay (R1) continuously monitors the difference between negative bus and ground voltage magnitudes and triggers the thyristor gate once it exceeded a predetermined value. Furthermore, the system is equipped with a current sensor (R2) in order to check the status of the flowing current. If the level of sensed current was lowered, the system can be switched back to the ungrounded mode. Otherwise, a positive to ground fault event is the most probable reason that DC breakers must be swiftly opened. Moreover, the status of system can be reported to the environment via alarm signal. The salient feature of the thyristor grounded system in comparison with diode one is that it sustains the system ungrounded, unless a dangerous voltage is sensed; therefore, the thyrsitor grounded system considerably minimizes the stray current and its negative consequences.

3.2.2 DC Current Interruption Approaches

As discussed before, protection of DC microgrids by means of fuses and circuit breakers has some performance restrictions due to their inherent large time constants and time delays, respectively. In order to overcome the limitations, Tang and his colleague presented a new current interruption approach for Multi-Terminal DC (MTDC) grids and navy shipboard DC Zonal Electric Distribution (DCZED) systems by means of electro-mechanical switches. In their proposed approach, they split the network into several zones and make use of no-load switches to cease the fault currents [59, 60]. More precisely, once a fault was recognized in a zone, converters supplying the network de-energize the bus(s), and subsequently the faulted zone is isolated by no-load switches. Finally, the rest of network is re-energized to continue its operation. The main problem with the proposed approach is that it entirely shuts down the network after the fault detection which may not be necessary.

An alternative approach was proposed using Solid State Circuit Breakers (SSCBs) at DC terminals of Voltage Source Converters (VSCs) or on the downstream side of DC/DC converters [61, 62]. The approach can be implemented by different solid state switches such as Gate Turn-Off (GTO) thyristors, Insulated-Gate Bipolar Transistors (IGBTs), and Insulated-Gate Commutated Thyristors (IGCTs). However, employment of each of the switch topologies has its own merits and demerits [61]. SSCBs are also equipped with a parallel combination of a snubber circuit and Metal-Oxide Varistors (MOVs) to dissipate power during the interruption of fault currents. Notwithstanding advantages of SSCBs, some of their demerits make them disputable. Contrary to mechanical contacts, the maximum operating voltage and current of SSCBs are limited in order to protect their switching devices. However, in practice, their capacity can be enhanced via series and parallel connection of IGBTs. Moreover, Overrating of SSCBs leads to exponential increase of costs.

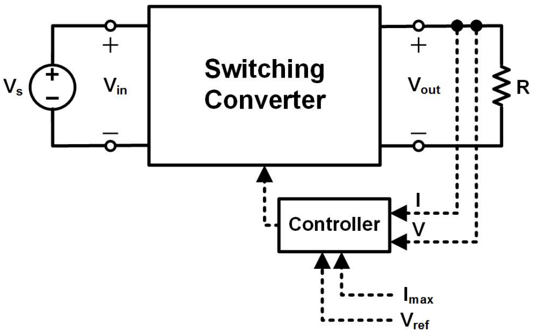

Fig. 6. A switching converter which can be controlled in voltage and current modes to provide fault current limitation and interruption

In [63], Baran and Mahajan presented a new scheme to limit and interrupt the fault currents through controlling the duty cycle of converters. Fig. 6 provides an example of switching converter which can be controlled in voltage and current modes to provide fault current limitation and interruption. Once a fault incident was detected on the downstream side, proper protection commands are issued to actively limit the fault current or to turn off the converter switches. In case of a switch hard turn-off command, the current from the primary side is rapidly ceased, whereas the load side current is interrupted after the stored energy in the output inductor was dissipated by freewheeling through the converter freewheeling diodes. But in case a current limiting command issues, the fault current is limited to an acceptable value or driven to zero, and then interrupted.

In 2009, Salomonsson et al. presented an approach based on proper selection of protective devices corresponding to the fault withstanding capability of each network component [64]. According to their research, ultrafast hybrid CBs are proposed for protection of power electronic devices in order to quickly interrupt the current flowing from their sensitive switching devices including IGBTs and diodes. On the contrary, regular CBs are suggested to protect batteries, since they can withstand drastically large currents without damage. Moreover, they also applied fuses and MCCBs for protection of network feeders. To be more precise, they claimed that MCCBs should install closer to the loads due to their capability in simultaneous interruption of currents in both positive and negative poles, whereas fuses are more suitable to be installed closer to the buses, since their magnetic sensing provides good selectivity.

Three years later, a new type of solid state breakers, termed as z-source breaker, was introduced [65]. The breakers are able to automatically commutate a main-path

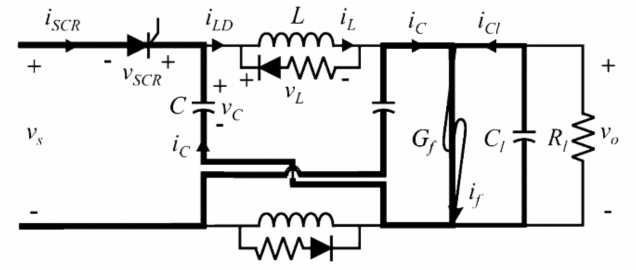

Fig. 7. Structure of a z-source breaker

Silicon-Controlled Rectifier (SCR) during a fault by means of a z-source LC circuit. In spite of swift operation of the z-source circuit breakers, their resonant circuit is strongly dependent on the fault characteristics as well as the parameters of upstream and downstream components. In addition, voltage oscillations resulting from resonant circuit may lead to overvoltage on other network components. The structure of a z-source breaker is depicted in Fig. 7.

In [66], Fletcher and his research group proposed unit protection approach against non-unit ones which often overlook the high sensitivity of the network response to the fault impedance. Also, they attempted to identify the means by which the fast and effective protection system operation is achieved, whilst seeking to minimize installation costs, against a set of very strict operating requirements. Finally, they presented a flexible design framework for unit protection of DC microgrids with a high selectivity as well as considering optimum operating speed and total cost of the system. In addition, the results of the study indicated that their proposed protection scheme provides a better fault discrimination in comparison with previous studies.

The authors of [48] developed a new protection scheme for low voltage DC-bus microgrids to isolate the smallest possible faulted area such a way as to allow the rest of network maintains operating. In their offered strategy, they make use of a loop-type DC bus along with segment controllers, consisting one master and two slave units, between the loop components. First, the master unit receives the values of current measured by the slave units, and then issues the proper disconnection commands to the bus switches depending upon the difference between these values.

4. Conclusion and Future Directions

Penetration of microgrids is currently growing around the world, since they offer less environmental impact, low running cost as well as high reliability and power quality. Hybrid AC/DC microgrids are composed of independent AC and DC subgrids, in which all AC- and DC-based DG sources and loads are connected to the buses directly or indirectly through power electronic interfaces. The aim of this paper was to provide a review on key issues and existing approaches for the protection of AC and DC microgrids.

With regard to the analysis of the wide range of technical publications presented in the previous sections, protection of future hybrid AC/DC microgrids necessitates simultaneous development of several fields. Coordination between AC and DC protective devices in hybrid AC/DC microgrids including Line-Commutated Converters (LCCs) is one of these fields. It is important, because a fault incident on the inverter AC system side in the case of LCC will cause commutation failure with temporary interruptions in the power transfer and stress in the converter equipment. Furthermore, it can result in significant DC current increase, and thus leads to additional heating of the converter valves and shortening their lifespan. Development of Combined control and protection schemes is another field which can be effective in resolving the following challenges: (a) self-healing which is an ability to provide fast recovery and resilience of the power system in response to the short circuit conditions. (b) Low-Voltage Ride Through (LVRT) which is defined as the capability of generators to stay connected in short periods of lower electric network voltage. (c) driving current to zero prior to its interruption by circuit breaker. However, development of combined control and protection schemes necessitates coordination with communication and information infrastructures.

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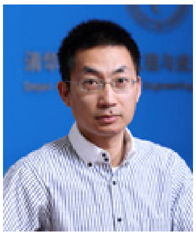

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