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Adaptive Protection Scheme for Low-Voltage DC-Bus Microgrid Systems

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Abstract— *Adaptive Protection Scheme for low-voltage dc-bus microgrid systems is presented in this paper. Unlike traditional ac microgrids, protection has been challenging for dc systems. The goals of the proposed scheme are to detect the fault in the bus between devices and to separate the faulted section so the system keeps operating without disabling the entire system. To achieve these goals, a loop-type dc-bus-based microgrid system, in which differential protection scheme is proposed that include solid-state bidirectional switches and snubber circuits. The proposed scheme can detect faults on the bus regardless of fault current amplitude or the power supply's feeding capacity. The proposed concepts have been proved by MATLAB/Simulink simulations.*

Keywords— DC Distribution system, solid-state switch, fault locations, protection systems**.**

1. INTRODUCTION

Recently, many distributed power systems (or so called microgrids) have been researched and developed, particularly to meet the demand for high penetration of renewable energy resources, such as photovoltaic systems and wind turbines. The energy policy of many governments in the world competitively rises the requirement of the penetration of renewable energy resources and distributed generation (DG). For example, in the U.S., California is attempting to rise the usage of renewable generation up to 33% by 2020 [1] and Colorado has set specific needs for DG from eligible renewable energy resources [2].

Currently and due to advances in control and power electronics technologies, dc has been increasingly used particularly for long high voltage dc (HVDC) transmission lines to present a cost effective solution for transferring power over long distance with better power flow controllability. At distribution levels in today's public power systems, dc power systems are not widely used yet, and their applications are limited to specific areas such as electric traction systems due to the wide usage of dc motors, auxiliary installations in power plants and substations, and for aircraft power systems and electric ships due to the better controllability of dc [3]. Lately, LVDC distribution systems have been considered as one of the efficient energy technologies for powering different sized data centers [4], [5].

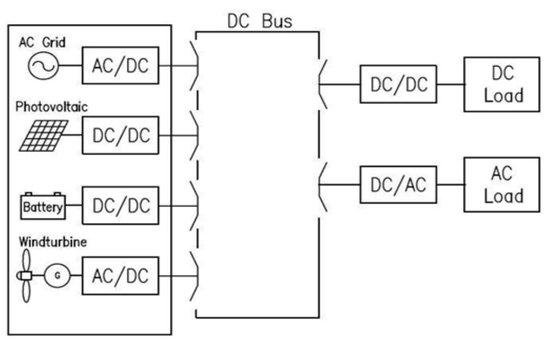

Fig. 1 Diagram of a dc-bus microgrid system.

The microgrid system is a small-scale distributed power system containing distributed energy sources, AC loads, and DC loads, and it can be easily integrated with the renewable energy resources [6]–[7]. Because of the distributed nature of the microgrid approach, the connection to the central dispatch can be omitted or minimized so that the power quality to sensitive loads can be enhanced. In general, they have two operation modes: grid-connected mode and stand-alone (islanded) mode.

Microgrid systems can be divided into ac-bus and dc-bus systems, depend on the bus to which the component systems are connected. The ac-bus-based microgrids has an advantage is that the existing ac power grid technologies are easily applicable. However, problems with the ac grid issues, including reactive power control, synchronization, and bus stability, still persist.

DC-bus-based systems can become a feasible solution because microgrids are small, localized systems where the transmission losses are negligible. Furthermore, they do not have the drawbacks of ac systems, and system cost and size can be minimized compared to the typical ac-dc-ac conversion arrangement because dc power is generally used in the power-electronics devices as a medium. A diagram of the dc-bus microgrid is shown in Fig. 1.

While the advantages of dc microgrids are considerable, the protection of dc distribution systems has suffer from many challenges, such as locating a fault within a microgrid, breaking a dc arc, dc protective equipment, and certainly the lack of experience, standards, and guidelines [8]. This paper presents an adaptive protection scheme for a low-voltage dc-bus microgrid system. The goals of the proposed scheme are to detect the fault in a bus segment between devices and then to separate the faulted section so the system continues to operate without disabling the entire system. To accomplish these goals, this paper proposes a loop-type dc-bus-based microgrid system which has a segment controller between connected components.

2. LOW-VOLTAGE DC-BUS MICROGRID

The low-voltage dc (LVDC) system is a comparatively new concept in electric power distribution systems compared to high-voltage dc (HVDC) systems. For small-scale systems, LVDC distribution systems have many advantages over traditional ac distribution systems. For both ac and dc microgrids, power-electronic converters are needed to connect an assortment of sources and loads to a common bus. Using a dc bus needs fewer stages of conversion [8]–[10]. Moreover, the cables for the ac and dc power systems are chosen depend on the peak voltage of the system, and the power delivered by an ac system is based on the root mean square (rms) values, while the dc power is based on the constant peak voltage. So, the dc system can deliver $\sqrt{2}$ times more power than of an ac system for the same cable. And the skin effect phenomenon does not appear generally in dc systems. Subsequently, the dc system can utilize the whole cable, thus reducing losses [9], [11].

When a dc system needs reliable and versatile protection, problems increase with dc microgrids. AC systems have plenty of experience, guidelines and standards when we talked about system protection. DC systems do not have these advantages. The switchgear devices in dc systems must be very robust to handle the dc arc which is created during the interruption of fault currents. Fuses and circuit breakers (CBs) are the protection devices which commercially available for low-voltage dc-bus systems [8].

AC circuit breakers which have a mechanical operating mechanism that is able to clear the fault in several tens of milliseconds, are conventional fault current interrupters in distribution systems [15]. AC CBs interrupt the fault current during a zero crossing of the current waveform. However, DC fault currents do not cross zero point. Moreover, DC systems require a comparatively faster protection system capable of operating in several milliseconds to prevent any damage to the Voltage source converters (VSCs) [13,14,16]. In general, VSCs are utilized to interface individual sources to the dc bus as any microgrid should have multiple terminals. If the insulated-gate bipolar transistors (IGBTs) used in a VSC, VSC will lose control when a fault occurs on the dc bus and the freewheeling diodes act as a bridge rectifier feeding the fault. So, the challenge associated with protection of VSC systems is that the fault current must be detected and cleared very quickly as the converter's fault withstand rating is generally only twice the full-load rating [12]. So that conventional AC CBs are not suitable for fault current interruption in DC systems. Different types of solid-state and hybrid DC breakers have been proposed by researchers [17,18]. However, because of the technical and economic issues associated with these CBs, fault current interrupters are still one of the main challenges in the evolution of DC systems.

3. FAULTS IN DC DISTRIBUTION SYSTEMS

3.1 POSSIBLE FAULTS

Two types of faults are commonly encountered in dc systems: 1) line to line fault and 2) line to ground fault that can be seen in Fig. 2. A line-to-line fault occurs when the positive and negative lines are short-circuited. A line-to-ground fault occurs when either the positive or negative line is short-circuited to ground. While line-to-line faults usually are characterized as low fault impedance, the line-to-ground faults often have both high and low fault impedance [8]. The line-to-ground faults are the most common types of faults in industrial distribution systems such as data center [19].

VSCs may experience internal switch faults that can cause a line-to-line fault. This is a terminal fault for the device that cannot be cleared; in most cases, it needs to be changed. Hence, dc fuses would be a proper protection measure for this kind of fault. In ac systems, the ac-side CB will trip for these faults.

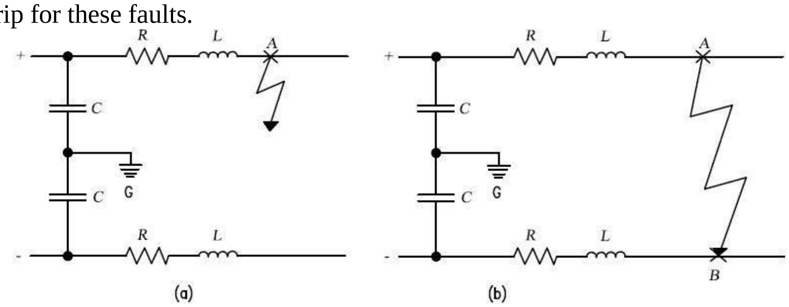

Fig. 2 DC system faults: (a) line-to-ground fault and (b) line-to-line fault.

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3.2 DC Fault Currents

When a fault occurs in a segment, the line current will be divided into load current and fault current

$$i_{line} = i_{load} + i_{fault} \qquad (1)$$

The load current will not change if the source and load keep the same, while the amplitude of the fault current depends on the fault location and resistance of the fault current path. If the impedance of fault path is low (e.g., a line-to-ground fault with solid ground), the current polarity at the receiving end could be reversed, preventing the load from being supported at all. The fault current from the power source and bus capacitors can be given as follows:

$$i_{fault}(t) = \frac{V_s}{R_{eq}}\left(1 - e^{-\frac{R_{eq}}{L_{eq}}t}\right) + \frac{V_s}{R_c} e^{-\frac{t}{R_c C_{eq}}} \qquad (2)$$

where V_s is the line voltage, R_{eq} and L_{eq} are the equivalent resistance and inductance including source, line and ground component, and R_c and C_{eq} are the equivalent series resistance and capacitance of bus capacitors, respectively. The time constant of the dc fault current is quite small because the line resistance of the dc system is negligible compared to ac power systems that have high reactance in the line. The bus voltage will collapse, depending on the capacity of the power supply and energy-storage device in the bus, and the grounding impedance [19].

3.3 Current Protection Techniques

The common practice in dc power systems is not to install any protection on the dc side, and to detect the fault, the ac CBs that link the ac and dc systems are opened [20], [21]. A handshake method was suggested in [21] to isolate and locate the faulted segment: however, this method completely de-energizes the dc system until the fault is removed and the systems can be re-energized. It works for HVDC and medium-voltage dc (MVDC) transmission systems where the dc system is a link between the ac systems and loads. However, this method can create unnecessary outages in LVDC microgrids where multiple sources and loads are connected to a common bus. Protection techniques such as overcurrent [8], [9], [11], current time derivatives [8], undervoltage and directional protection [9] have been reported for LVDC distribution systems and dc shipboard power systems, but the dynamics of voltage and current on a faulted segment, especially when it is separated has not been extensively investigated.

Due to the limitations of fuses and traditional ac CBs in dc systems, a solid-state CB has become a valid option for dc power system protection. There are several alternatives for solid-state devices for the CBs, such as gate turn-off thyristors (GTOs), insulated-gate bipolar transistor (IGBTs), and insulated-gate commutated thyristors (IGCTs). GTOs offer a high-voltage blocking capability and a low on-state voltage, but suffer from slow switching speeds [22]. IGBTs are widely used in the low-voltage (1200 V) systems and their advantages include fast interruption time and high short-circuit current withstanding capability [23]. However, high conduction loss is their disadvantage [24]. IGCTs have the lower conduction losses of a thyristor with the turnoff capability of a transistor. The IGCT has high voltage and current ratings as much as IGBTs, and the conduction loss is relatively low [25]. In order for the microgrid bus to allow power flow in either direction, the solid-state CB needs to be bidirectional.

Fuses or molded case CBs (MCCBs) can be utilized on dc systems [8], but they have a drawback is that neither can be controlled autonomously. In the event of a fault, human intervention is required to re-energize the system once the fault has been removed from the system. Another way to protect the system from excessive fault current is to limit the bus current under fault conditions. The fault current limiters can be used in conjunction with CBs. The advantages of fault current limiting include ridethrough for temporary faults, safe operation of switchgear, and system cost down by switchgear capacity reduction. Several devices have been utilized to limit the fault current, such as superconductors [26], saturated inductors [27], and power-electronics devices [28].

4. PROPOSED PROTECTION SCHEME

4.1 PROPOSED SCHEME

This paper proposes a novel protection scheme for the dc-bus microgrid system. Instead of shutting down the entire system or limiting the bus current, the proposed scheme detects the fault and isolates the faulted segment so that the rest of the system keeps operating. To provide a reliable and continuous power dc system, loop-type DC bus is generally suggested for microgrid design. It has also been reported that the loop-type bus has good system efficiency particularly when the distribution line is not long [29]. The whole loop will be divided into several segments between subsystems. Each segment will consist of a section of bus (positive and negative lines or positive line and ground) and a segment controller. The conceptual diagram of the proposed protection scheme is shown in Fig. 3. The protection system is shown only in segment 1, and controllers on other segments are omitted.

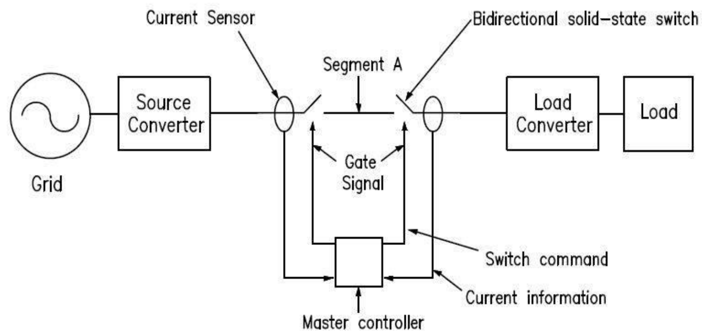

Fig. 3 Conceptual diagram of the proposed protection scheme for segment A.

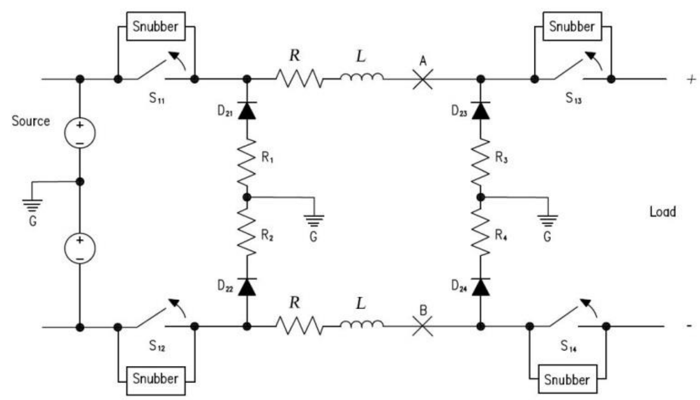

Fig. 4 Implementation of the proposed protection scheme. Arrows denote the switching action when a fault is detected.

The proposed protection system contains two current sensors, master controller, and two bidirectional solid-state switches. The current signals are measured by current measuring devices and monitored by the controller. They also operate the bidirectional solid-state switches on the bus segment according to the commands from the controller. In case of normal operations, the currents measured at each end of the bus segment should be nearly identical and the master controller sends commands to put the bus switches on normal positions.

4.2 Fault Detection and Isolation

The fault detection of DC bus needs to detect the fault as soon as the fault occurred, quickly identify the faulted line, and find out the fault type with simple judgment.

The controller monitors the difference of two current readings of current sensors in a segment

$$i_{diff}=i_{in} - i_{out} \tag{3}$$

Where i_{in} and i_{out} is the line current at each end of the bus segment. The implementation of the proposed protection scheme is shown in Fig. 4 which shows the configuration of segment 1 in Fig. 3. Semiconductor-based bidirectional switches S_{1x} and diodes D_{2x} are used for segment separation and fault current freewheeling, respectively. In normal operations, switches are closed and diodes are open. When the difference current exceeds the threshold, the controller sends the appropriate commands to bidirectional solid-state switches so that the faulted segment can be isolated from the system and switches are opened. Diodes are conducting at the same time to form a freewheeling path for fault currents so that the switches can open and the fault current can be extinguished through resistors.

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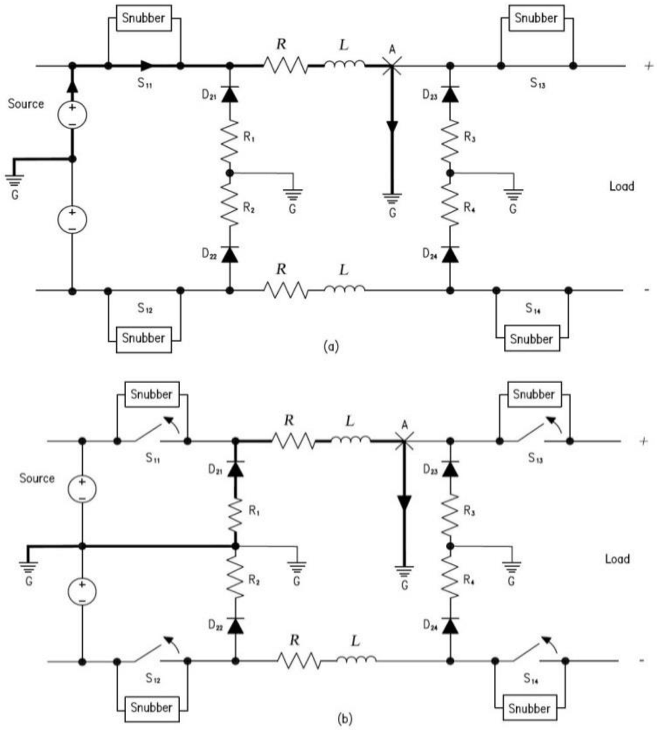

Fig. 5 Fault current and operation of the proposed protection scheme. (a) Line-to-ground fault between point A to G. (b) Isolated line-to-ground fault.

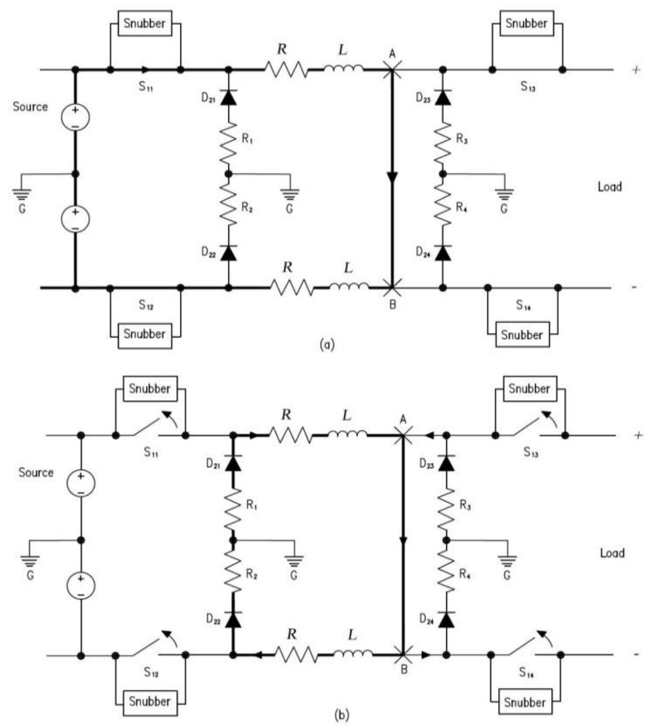

Fig. 6. Fault current and operation of the proposed protection scheme. (a) Line-to-line fault between point A and B. (b) Isolated line-to-line fault.

Because the proposed scheme uses the differential relaying principle monitoring only the relative difference of input and output current of a segment, it can detect the fault on the bus regardless of fault current amplitude or power supply's feeding capacity and

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it can determine also the fault type after i_{diff} exceeds the threshold, the controller will compare it quickly with differential currents of the other line of the same section and the lines of nearby sections. For line-to-ground fault at point A, the magnitude of i_{diffp} of faulted positive line should be larger than the magnitude of i_{diffn} of negative line, and the magnitudes of i_{diffp} and i_{diffn} are much larger than the differential currents in nearby sections. On the other hand, when a line-to-line fault connects point A and B, the current differences i_{diffp} and i_{diffn} will increase with same amplitude and they are much greater than the differential currents in nearby sections. According to the simple comparisons, the fault type and faulted line can be quickly determined.

The line-to-ground fault and the line-to-line fault are shown in Fig. 5 and Fig. 6. It can be seen that the fault current is isolated and extinguished in the freewheeling loop.

Once the faulted segment has been determined and separated, the bus voltage will be restored and remainder of the system can continue to operate on the loop-type bus. Even with multiple faulted segments, the system can operate partially if the segments from some power sources to loads are intact. The possibility of the fault around the device connection point can be minimized if the segment controllers are installed as close to the connection point as possible.

4.3 Snubber Circuit

Snubber circuits are essential to protect the solid-state CBs from the voltage transient due to the bus cable inductance. It is more so especially in a loop-type bus where the line inductance exists on both sides of the CB. Although the fault current needs to be interrupted as quickly as possible, the high di/dt could make the transient voltage destructively high for the solid-state switches. There are a couple of snubber circuit topologies to suppress the overvoltage at turn-off due to line inductance, such as decoupling capacitor, discharge restricted decoupling capacitor, discharge-charge-type RCD snubber, and discharge-suppressing-type RCD snubber [30].

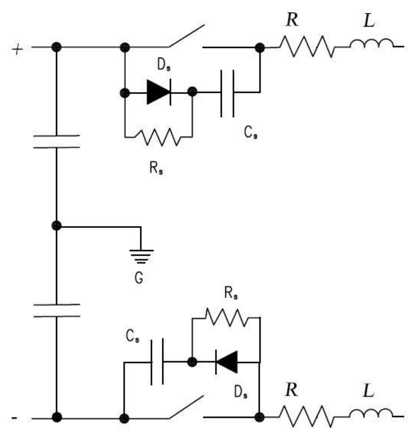

Fig. 7 Charge-discharge-type RCD snubber circuit.

It has been reported that the decoupling capacitor has low losses but also oscillation issues and RCD snubbers have higher losses but no oscillation problem and good for higher current applications [31]. Charge-discharge-type RCD snubber has been chosen for better voltage suppression performance as the solid-state CBs do not switch in high frequency. The charge-discharge-type RCD snubber is shown in Fig. 7. A case of source-to-load power flow has been considered. The capacitor in the charge-discharge-type snubber is fully discharged in normal operation when the switch is closed. When a fault is detected and the switch is trying to open, the diode D_s is forward biased and the snubber capacitor C_s is charged to absorb the energy stored in the line inductance L.

5. SIMULATION RESULTS

To explain the effectiveness of proposed protection scheme, microgrid with one power supply: AC supply, one DC load and one AC load is modeled on MATLAB/Simulink program. The Simulink model and its connections are shown in Fig.8. As claimed by some researchers in [14], the LVDC distribution system with a bus voltage around 380V is regarded as most effective and is highly recommended. Thus, the bus voltage V_{bus} between positive and negative lines is set to be 450V. Since three converters are connected to the bus, the loop-type bus is divided into 3 sections. The system parameters of each component of the system are listed in Table I.

The faults are simulated at points A and B that are located at both the end and the beginning of positive and negative lines of section 1. The performance of proposed method is studied for cases of different faults.

A line-to-ground fault is simulated on the positive bus at the point A, first at the end of section. It occurs at 0.12 s. Fig 9. shows the source- and load-side current of a line-to-ground fault with protection. It can be seen that the current from source increased to 1.7 KA. The fault current magnitude depends on the impedance of the fault path. The currents at each end of the segment which had been identical before fault show clear difference after fault. It has been assumed in the simulation that the segment controller can detect it and open/close solid-state CBs in 1ms, but because of delay time which is taken into account for temporary faults, solid-state CBs will open/close in 11ms.

TABLE I: SYSTEM PARAMETERS OF LOOP-TYPE DC Bus

Component	Data
DC bus voltage V_{bus}	450V
Grounding capacitor C_g	0.05μF
Rectifier capacitor C	1F
Bus length (section I)	60m
Bus length (section 2)	70m
Bus length (section 3)	60m
Unit resistance (cable)	0.6Ω/km
Unit inductance (cable)	0.5mH/km
Capacitor C_1	0.5F
Capacitor C_2	4.4mF
Capacitor C_3	0.5mF

Line-to-line fault is simulated at the points A with B, also at the end of section. In this case, fault current will be higher because there is no resistance to limit it. Hence, fast detection and isolation are critical. The source- and load-side current of a line-to-line fault with protection is shown in Fig. 10.

Considering the speed of switching devices, fast interruption in this speed range is feasible. Fig. 9 shows that the fault currents are extinguished when the faulted segment is separated. Fig. 11 shows the voltage across the AC load. The ground fault pulls the positive pole voltage to zero, and the bipolar dc bus will experience a voltage offset on the faulted pole. However, the load voltage is quickly restored after the faulted segment has been separated.

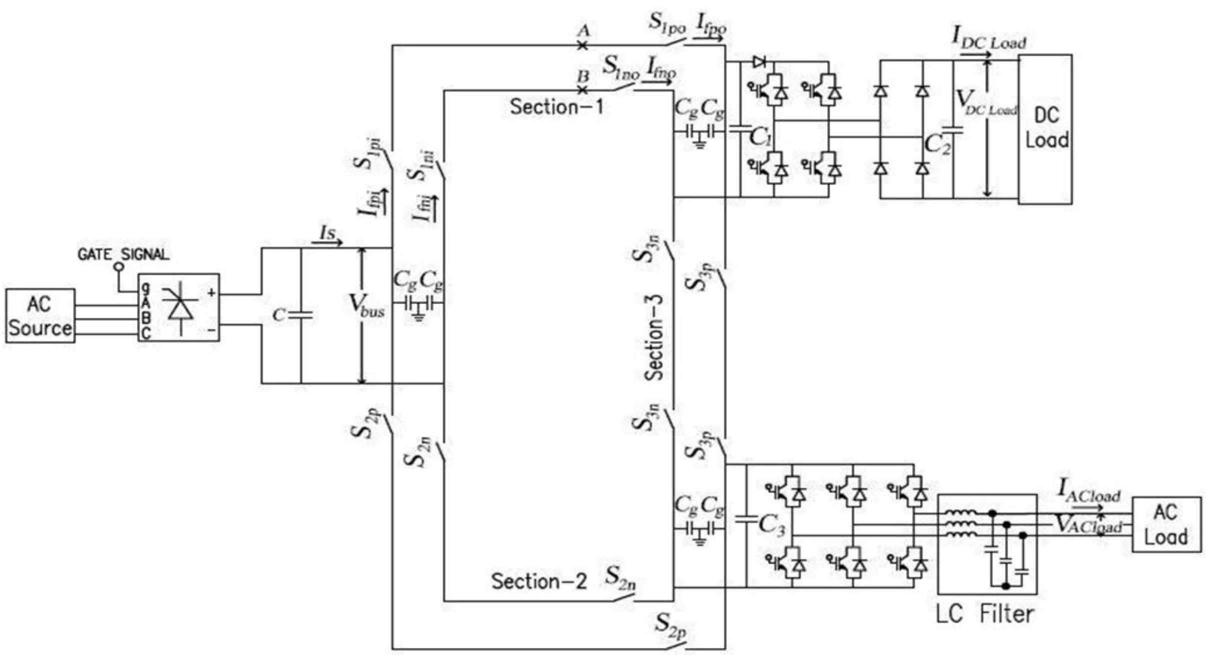

Fig. 8 Simulation model of DC distribution system which consists of one source, one DC load and one AC load.

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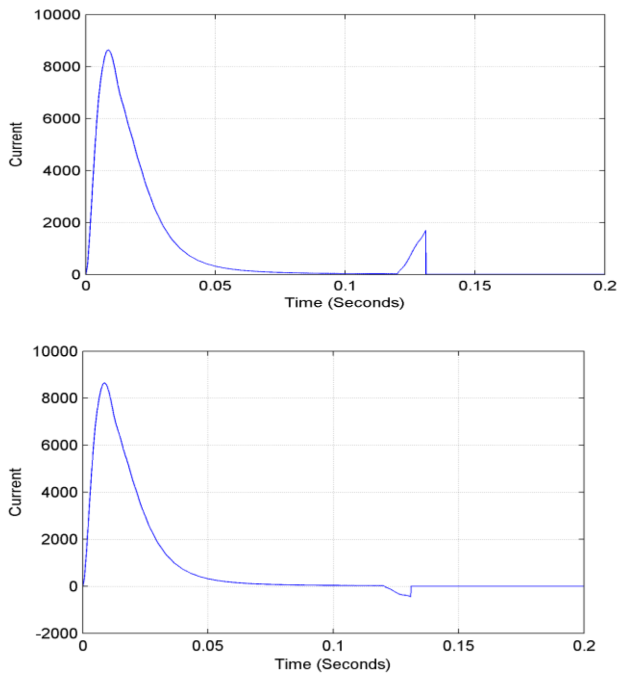

Fig. 9 Source-side current (top) and load-side current (bottom) at the end of section1 for a line-to-ground fault with protection.

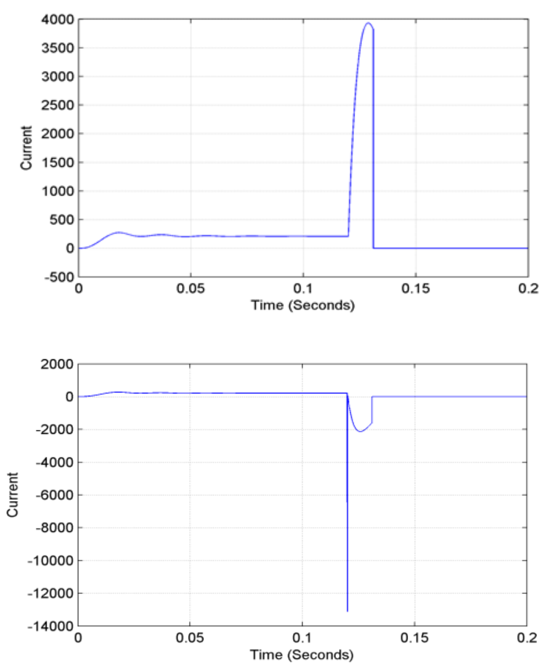

Fig. 10 Source-side current (top) and load-side current (bottom) at the end of section1 for a line-to-line fault with protection.

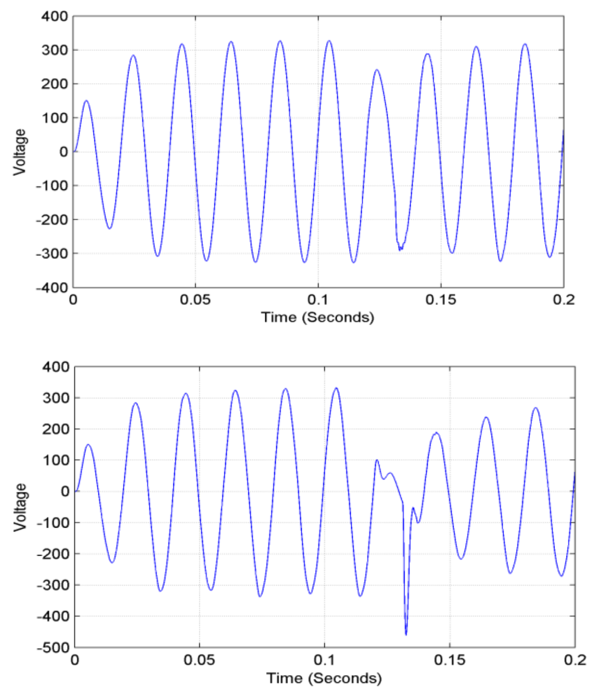

Fig. 11 Voltage of AC load with protection at the end of section1 for line-to-ground fault (top) and line-to-line fault (bottom).

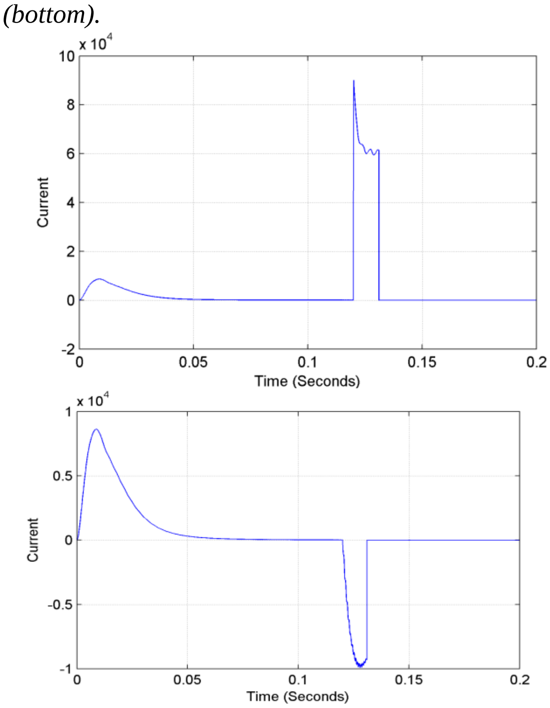

Fig. 12 Source-side current (top) and load-side current (bottom) at the beginning of section1 for a line-to-line fault with protection.

The voltage transient at turnoff due to the line inductance and high can be very high and it can easily damage the solid-state switch. It can also be seen that the voltage transient is suppressed by a snubber circuit at a tolerable level.

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Of course, if the faults are simulated at the beginning of the section, fault currents will increase because of segment impedance as shown in Fig. 12 for line-to-line fault.

As the fault current magnitude based on the impedance of the fault path, the line-to-ground fault is simulated with resistance to show its effect on the fault current. Fig. 13 shows the fault current with resistance value equals 0.1Ω we note that the fault current decreases for line-to-ground fault and this resistance make the voltage across the Ac load has less disturbance as shown in Fig. 14.

Fig. 15 shows the voltage transient across the solid-state CB with the snubber circuits. The voltage transient at turnoff due to the line inductance and high can be very high and it can easily damage the solid-state switch. It can also be seen that the voltage transient is suppressed by a snubber circuit at a tolerable level.

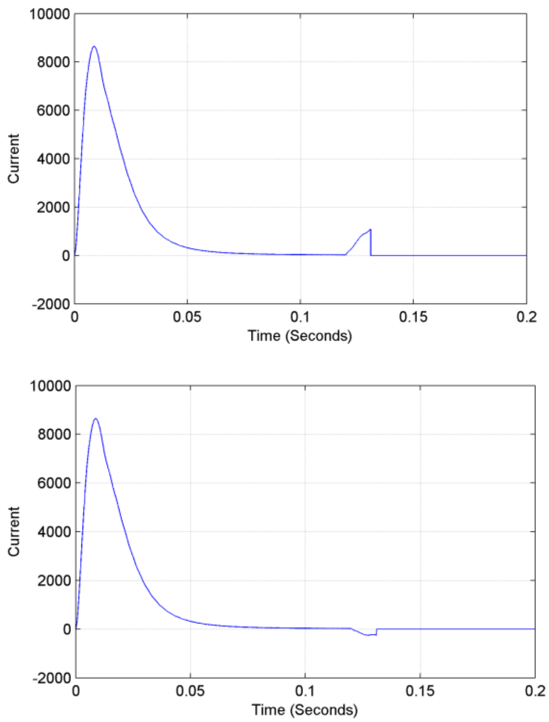

Fig. 13 Source-side current (top) and load-side current (bottom) at the end of section1 for a line-to-ground fault with resistance equal 0.1Ω.

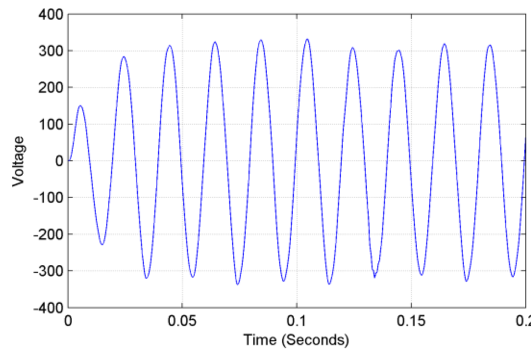

Fig. 14 Voltage of AC load with protection at the end of section1 for line to-line fault with resistance equal 0.1Ω.

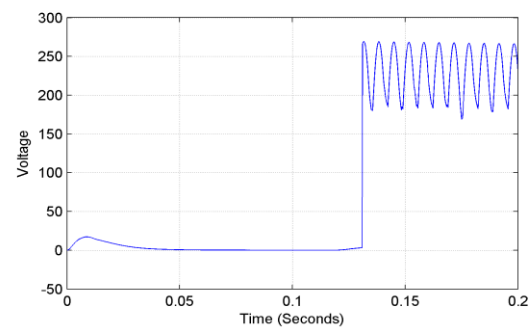

Fig. 15 Current in a freewheeling path in the proposed scheme (top) and voltage across switch S_{11} at turnoff with the snubber. (bottom).

6. CONCLUSION

This paper has presented a fault detection and isolation scheme for the low-voltage dc-bus microgrid system. The proposed protection scheme consists of segment controllers capable of detecting abnormal fault current in the bus and separating the faulted segment to avoid the entire system shutdown. A loop-type dc-bus-based microgrid system with segment controllers between connected components has been proposed. The proposed protection concepts have been validated by computer simulations. Line-to-ground and line-to-line faults have been simulated and we note that the fault current increases in line-to-line fault. The proposed scheme can be applied to dc power systems, such as Green Buildings, with sustainable energy resources and data centers with a server array.

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