Fault Detection and Isolation System for a Loop Type Low Voltage DC Microgrid Using Segment Controller

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***Abstract-* A fault detection and isolation scheme for low-voltage dc-bus microgrid systems is presented in this report. Unlike traditional ac distribution systems, 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 isolate the faulted section so that the system keeps operating without disabling the entire system. To achieve these goals, a loop-type dc-bus-based microgrid system, which has a segment controller between connected components, is proposed. The segment controller consists of master and slave controllers that monitor currents and control the segment separation, which include solid-state bidirectional switches and snubber circuits. The proposed system can detect faults on the bus regardless of fault current amplitude or the power supplys feeding capacity. The proposed concepts have been verified by MATLAB/Simulink simulations and experiments on hardware test bed with PV panel and a battery is used to provide the DC power supply to the dc-bus.**

***IndexTerms-* LVDC, Loop type, Segment Controller, MATLAB/Simulink, Microgrid.**

I. INTRODUCTION

In last few years, electrical sector has witnessed many distributed power systems being added to meet increasing demand. Most of these added systems belong to the renewable energy sources. Solar photovoltaic systems and wind turbine systems have been among the most favored energy sources utilized for this approach [1-4]. Distributed power systems have several advantages as it provides relief of transmission and distribution, is eco-friendly, has better efficiency in both economical and generation way and has very high quality of power. Every country is trying to increase their renewable energy sector in an exponential way to make provisions for a green environment [5-7].

Micro-grid is a system consisting of small to medium scale energy sources and equivalent loads which can be connected to main supply grid. Generally, they have two operation modes: stand-alone (islanded) mode and grid-connected mode. Microgrid systems can be divided into ac-bus and dc-bus systems, based on the bus to which the component systems are connected. The advantage of the ac-bus-based microgrids is that the existing ac power grid technologies are readily applicable [8-10]. However, problems with the ac grid issues, including synchronization, reactive power control, and bus stability, persist [11,12].

To solve these problems, DC-bus-based microgrid systems are becoming a strong solution [13-15]. These systems are small and are localized. This makes transmission losses almost negligible. The size and cost of these systems are less as compared to typical ac-dc-ac systems. A conceptual diagram of the dc-bus microgrid is shown in Fig. 1.

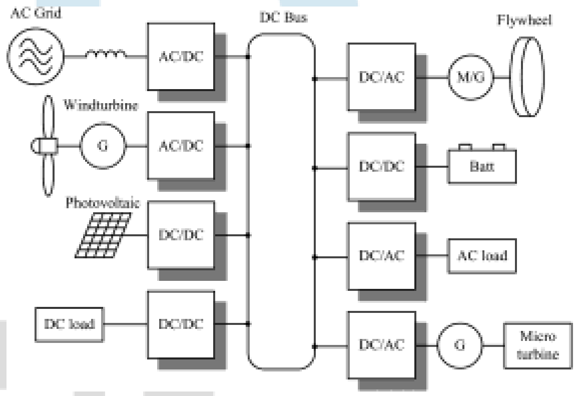

Fig. 1. Conceptual diagram of a dc-bus microgrid system

One of the major problems in a dc microgrid system is its protection. Locating afault in a dc-bus microgrid system, breaking of a dc arc and underdeveloped dc protective equipment and challenges regarding the same are few of the major concernsin this area. Also, there are less norms, standards and guidelines in this aspect.To overcome these problems, this project proposes a fault detection and isolationscheme for a dc-bus microgrid system [16-18]. A loop-type system with segment controller is proposed in this paper. A MATLAB/Simulink based model is developed to verifythe proposed algorithm while a test-bed of hardware setup is used to demonstratethe effectiveness of the system.
Section I is followed by introduction to LVDC systemin section II. Section III proposes the protection system for the problems identified in section II. Section IV presents MATLAB model and its simulated results while hardware results are presented in section V. Section VI concludes the paper.

II. LOW VOLTAGE DC-BUS MICROGRID

Compared to high-voltage dc (HVDC) systems, the low-voltage dc (LVDC) system is a relatively new concept in electric power distribution. For small-scale systems, LVDC microgrids have many advantages over traditional ac distribution systems. For both ac and dc microgrids, power-electronic converters are required to connect a variety of sources and loads to a common bus. Using a dc bus requires fewer stages of conversion. Furthermore, the cables for the ac and dc power systems are chosen based upon the peak voltage of the system, and the power delivered by an ac system is based on the rms values, while the dc power is based on the constant peak voltage. Hence, the dc system can deliver √2times that of an ac system with the same cable. And dc systems do not suffer from the skin effect. Therefore, the dc system can utilize the entire cable, thus decreasing losses.

Problems arise with dc microgrids when a system needs reliable and versatile protection. AC systems have plenty of experience and standards when it comes to system protection. DC systems do not have either of these advantages. The switchgear in dc systems must be very robust to handle the dc arc that is created during the interruption of fault currents. The protection devices commercially available for low-voltage dc-bus systems are fuses and circuit breakers (CBs). Traditional ac CB mechanisms, which rely on the natural zero crossing of the ac current to open the circuit, are inadequate to interrupt dc currents. More important, the fault persists because the operating time of the CB increases. Allowing a fault current to persist on a microgrid bus could be catastrophic.

Because the microgrid systems need to be multiterminal, voltage-source converters (VSCs) must be used to interface different subsystems to bus. When a fault occurs on the dc side of a VSC system interfacing the ac source, the insulated-gate bipolar transistors (IGBTs) lose control and the freewheeling diodes become a bridge rectifier feeding the fault. The challenge of protecting VSC systems is that the fault current must be detected and extinguished very quickly as the converter’s fault withstand rating is generally only twice the full-load rating.

III. PROPOSED PROTECTION SCHEME

A. Proposed Controller

This paper proposes a novel protection scheme for the dc-bus microgrid system. Instead of shutting down the whole system or limiting the bus current, the proposed scheme detects the fault and separates the faulted section so that the rest of the system keeps operating. The loop-type dc bus is suggested for the proposed scheme to make the system robust under faulted conditions. The entire loop will be divided into a series of 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. 2. The protection system is shown only in segment A, and controllers on other segments are omitted.

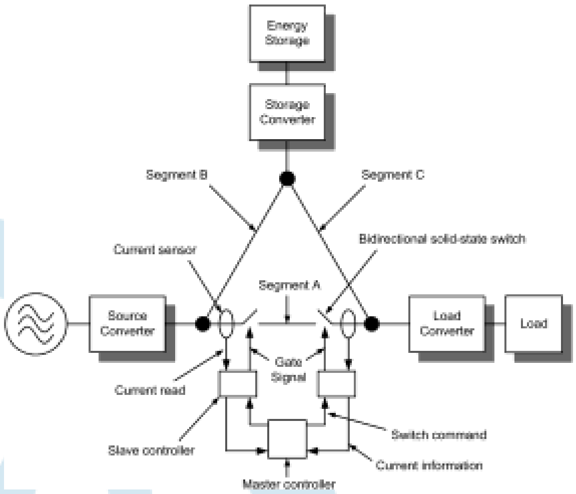

Fig. 2.Conceptual diagram of the proposed protection scheme. Protection controllers in segment B and C are omitted.

The proposed protection system consists of one master controller, two slave controllers, and freewheeling branches between each line and ground. The slave controllers read the current at each end of the bus segment connecting two components and send it to the master controller. They also operate the bidirectional solid-state switches on the bus segment and the freewheeling branch according to the commands from the master controller. During 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.

B. Fault Detection and Isolation

The master controller monitors the difference of two current readings of slave controllers in a segment

$$i_{diff} = i_{in} - i_{out} \quad \ldots \quad (1)$$

wherei_{in} and i_{out} is the line current at each end of the bus segment. When the difference exceeds the threshold, the controller sends the appropriate commands to slave controllers so that the faulted segment can be separated from the system. Because the proposed system uses the differential relaying principle monitoring only the relative difference of input and outputcurrent of a segment, it can detect the fault on the bus regardless of fault current amplitude or power supply's feeding capacity.Once the faulted segment has been isolated, 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. The implementation of the proposed scheme is shown in Fig. 3 which shows the configuration of segment A.

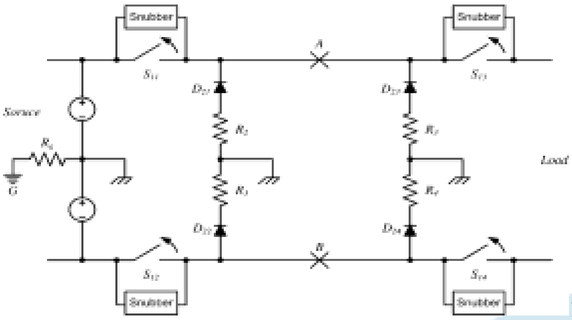

Fig. 3.Implementation of the proposed protection scheme. Arrows denote the switching action when a fault is detected.

IV. SIMULATION STUDY AND RESULTS

A computer simulation using MATLAB/Simulink has been performed for a microgrid system that consists of three typical energy devices: a source, a load, and energy storage. They are connected as shown in Fig. 4. Stiff dc power sources are assumed so that a constant fault current is fed by the sources without a voltage drop. A 240V bipolar dc bus with 200 m bus cable segments and a fault at the middle (100 m) of the bus is simulated.

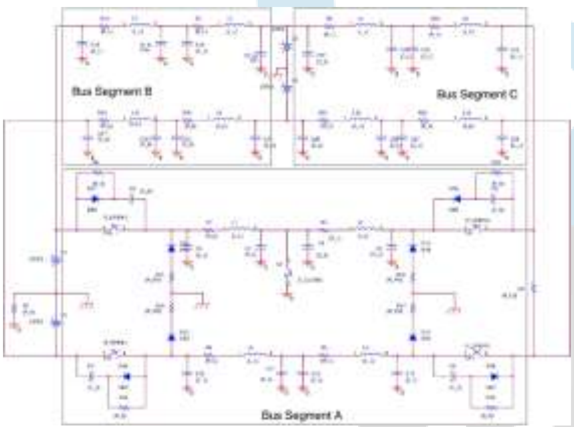

Fig. 4.Simulation circuit for the line-to-ground fault in the three-node microgrid system that contains two sources and a load. A fault is simulated in the segment between source 1 and load.

Simulation parameters can be found in Table I.

Table I. Simulation Parameters

DC Bus	
Bus Voltage	240V
Cable cross-section area	241.9mm^2
Unit Resistance R_u	121mΩ/km
Unit Inductance L_u	0.97mH/km
Unit Capacitance C_u	12.1nF/km
Segment Length l	200m
Fault Location d	100m
Ground Resistance R_G	0.5Ω
Freewheeling Resistance R_{fw}	1Ω
RCD Snubber Circuit	
Resistance R_s	10Ω
Capacitor C_s	10μF

Results

A positive line-to-ground fault in the middle of the bus segment A is simulated at 1ms. Fig. 5 shows the source-andload-side current of a line-to-ground fault with and without protection. It is seen that current from source has been increased to180 A after 0.5 msec. The fault current magnitude depends on the impedance of the fault path. The currents at each end of thesegment which had been identical before fault show clear difference after fault. Line-to-line fault current will be higher becausethere is no resistance to limit it. Therefore, fast detection and isolation are critical.

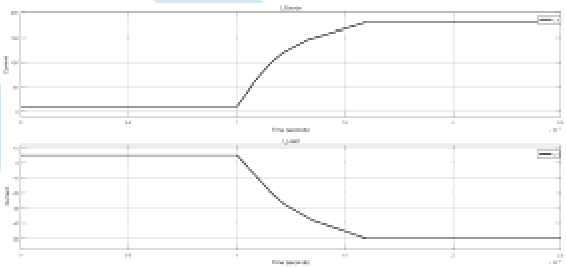

Fig. 5. Source-side current (top) and load-side current (bottom) for a line-to-ground fault without protection

Fig. 6 shows the load voltage without protection on the top side and current in the free-wheeling path on the bottom.

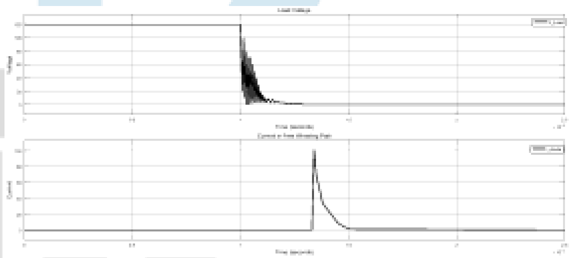

Fig. 6. Load voltage without protection (top) and current in a freewheeling path in the proposed scheme (bottom)

It has been assumed in the simulation that the segment controllers can detect it and open/close solid-state CBs in 250 μs.Considering the speed of current microcontrollers and switching devices, fast interruption in this speed range is feasible. Fig. 7 also shows that the fault currents are extinguished when the faulted segment is separated.

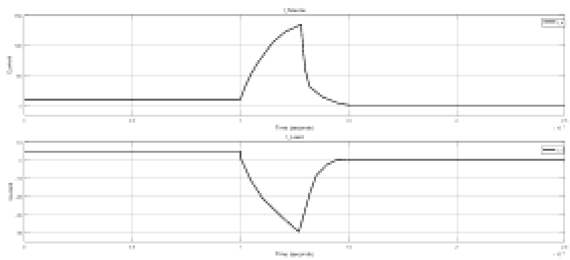

Fig. 7. Source-side current (top) and load-side current (bottom) for a line-to-ground fault with protection

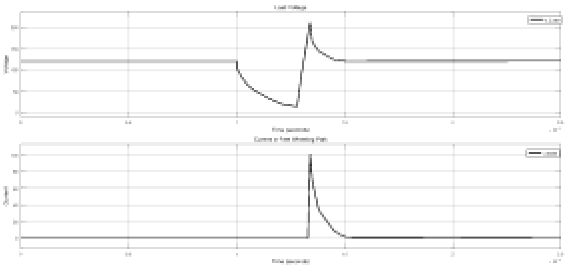

Fig. 8. Load voltage with protection (top) and current in a freewheeling path in the proposed scheme (bottom)

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 quicklyrestored after the faulted segment has been separated.

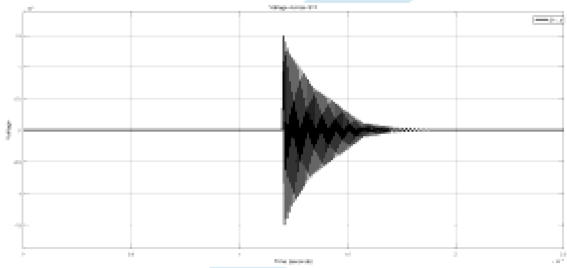

Fig. 9. Voltage across switch at turnoff without the snubber

Fig. 10 and Fig. 11 shows the voltage transient across the solid-state CB S_{13} without and with the snubber circuits, respectively. It also shows the fault extinction in the freewheeling path. The voltage transient at turnoff due to the line inductance and high di/dt 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.

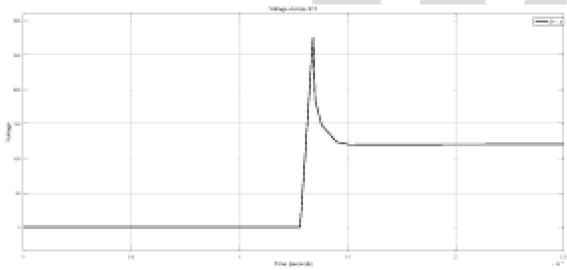

Fig. 10. Voltage across switch at turnoff with the snubber

The protective devices in bus segments B and C have been omitted in this simulation because the proposed protective scheme that detects the difference in net current flow will not be triggered if there is no fault in the bus. This can be verified by the currents flowing into and out of the intact bus segment C shown in Fig. 11. Even with the transient caused by the fault on the bus segment A, the incoming and outgoing currents of segment C are identical. The proposed scheme that detects the current difference is robust to common-mode noise and transient due to a fault.

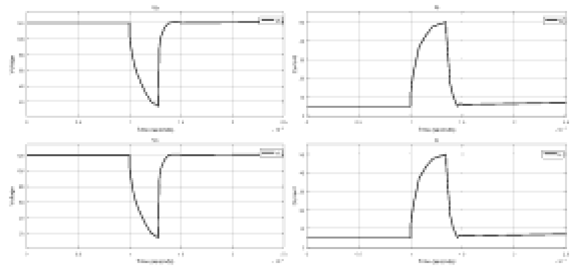

Fig. 11. Voltage of bus segments B and C (top) and currents of segment B and C (bottom)

V. HARDWARE DEVELOPMENT AND RESULTS

The basic block diagram of the hardware setup is shown in Fig. 12.As shown in figure, the hardware consists of following blocks:

1. Sources from solar panel and battery.
2. Two IGBT blocks along with their drivers.
3. One fault IGBT block along with its driver.
4. Load arrangement.
5. A micro-controller assembly connected to a LCD display.

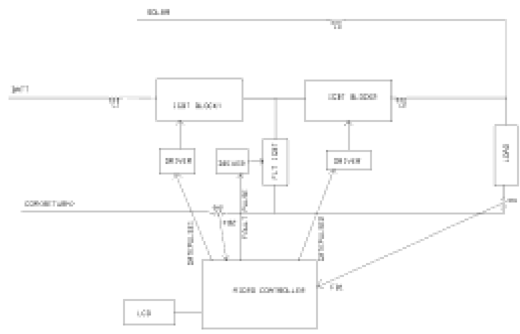

Fig. 12. Block Diagram of the System

The main objective here is to isolate the faulted section by detection of the fault using a segment controller used in the algorithm. The hardware workbench photograph is shown in Fig. 13.

Fig. 13. Photograph of Hardware Kit

Results

The results derived from the hardware kit are given in Fig. 14 to Fig. 19. Fig. 14 shows currents in the system without protection while Fig. 15 shows current in the free-wheeling path.

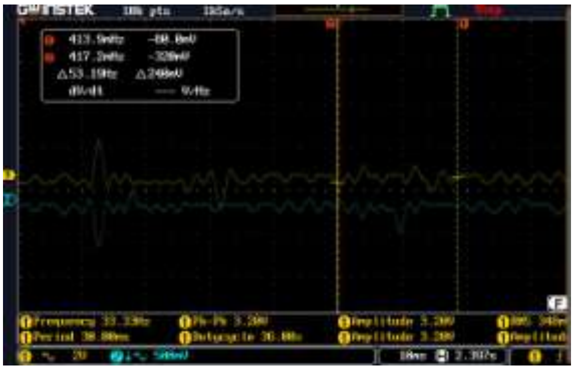

Fig. 14. Source-side current (top) and load-side current (bottom) without protection

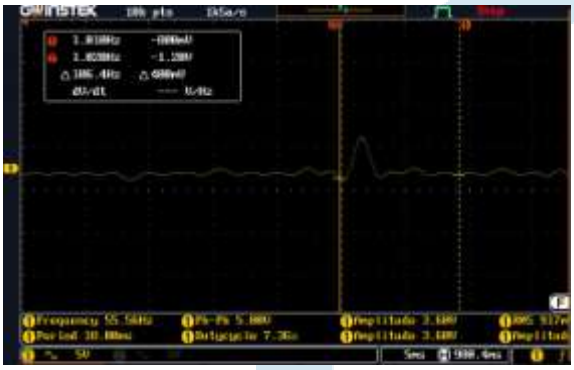

Fig. 15. Current in free-wheeling path

Fig. 16 shows voltage across IGBT V_{CE} without protection. We can see oscillations in the same due to lack of protective measures.

Fig. 16. IGBT collector-emitter voltage V_{CE} without protection

Fig. 17 shows currents in the system with protection while Fig. 18 shows the graph of load voltage with protective circuit in action.

Fig. 17.Source-side current (top) and load-side current (bottom) with protection

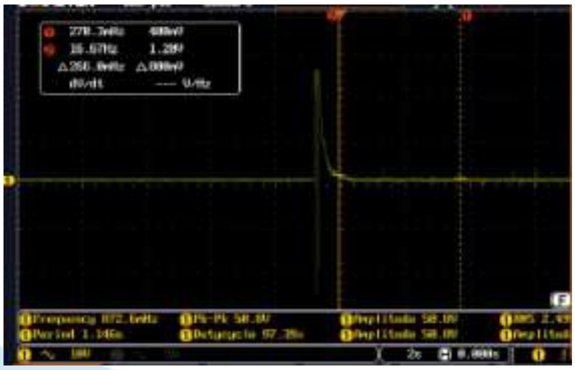

Fig. 18.Load Voltage with protection

Fig. 19 shows voltage across IGBT V_{CE} with protection. We can see that oscillations in the graph have been reduced due to protective circuit.

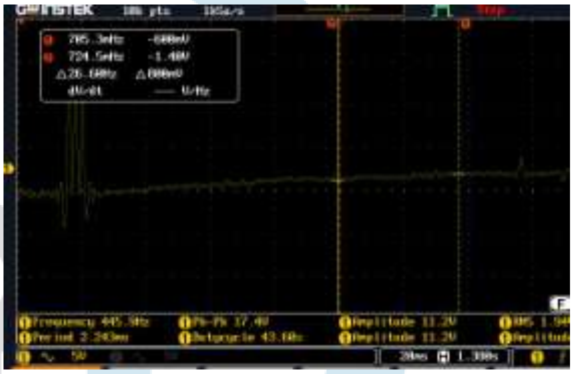

Fig. 19. IGBT collector-emitter voltage V_{CE} with protection

VI. CONCLUSION

In this paper, a fault detection and isolation scheme for the low-voltage dc-bus microgrid system was presented. 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 and the freewheeling branch has been proposed.

The proposed protection concepts have been validated by computer simulations and experiments. A prototype system with a segment controller that consists of master and slave controllers has been tested on an actual hardware test bed and it has shown successful fault detection and isolation capability. The DC source using a battery and a PV panel was considered in this setup.

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