FAULT DETECTION IN DC MICROGRID SYSTEM

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Abstract—

A fault detection and isolation scheme for low-voltage dc-bus micro grid systems is presented in this paper. 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 micro grid 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 supply's feeding capacity. The proposed concepts have been verified by OrCAD/PSpice simulations and experiments on hardware test bed.

KEYWORDS — DC distribution, fault protection, micro grids, solid-state switch.

I. INTRODUCTION

Recently, many distributed power systems have been researched and developed, especially to meet the demand for high penetration of renewable energy sources , such as wind energy and solar .
The distributed power systems have advantages, such as the capacity relief of trans-mission and distribution, better operational and economical generation efficiency, improved reliability, eco-friendliness, and higher power quality. The energy policy of many governments in the world competitively increases the requirement of the penetration of renewable energy resources and distributed generation (DG). For instance, in the U.S., California is trying to increase the usage of renewable generation up to 33% by 2020 and Colorado has set specific requirements for DG from eligible renewable energy resources.

The micro grid system is a small-scale distributed power system consisting of distributed energy sources and loads, and it can be readily integrated with the renewable energy sources. Due to the distributed nature of the micro-grid approach, the connection to the central dispatch can be removed or minimized so that the power quality to sensitive loads can be enhanced. Generally, they have two operation modes: stand-alone (islanded) mode and grid-connected mode.

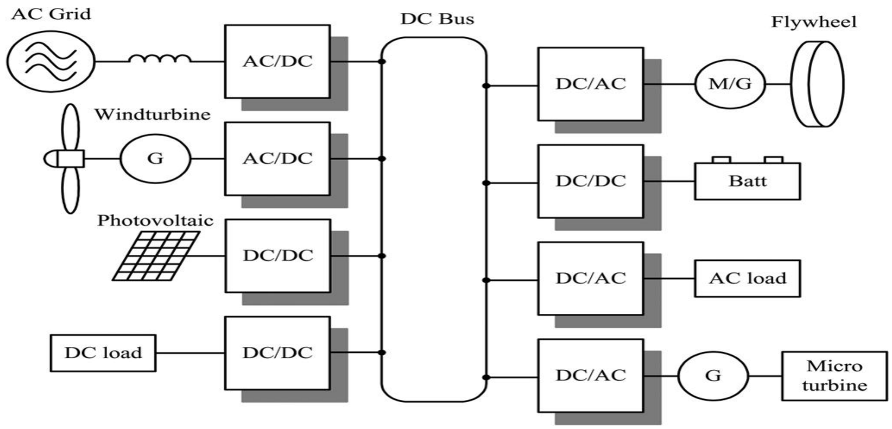

Fig. 1.Conceptual diagram of a dc-bus micro grid system.

Micro grid 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 micro grids is that the existing ac power grid technologies are readily applicable. However, problems with the ac grid issues, including synchronization, reactive power control, and bus stability, still persist. DC-bus-based systems can become a feasible solution because micro grids are small, localized systems where the transmission loss is negligible. Moreover, they do not have the problems that ac systems do, and system cost and size can be reduced com-pared to the typical ac -dc-ac conversion configuration because dc power is generally used in the power-electronics devices as a medium. A conceptual diagram of the dc-bus micro grid is shown in Fig. 1.

While the advantages of dc micro grids are considerable, the protection of dc distribution systems has posed many challenges, such as autonomously locating a fault within a micro grid, breaking a dc arc, dc protective equipment, and certainly the lack of standards, guidelines, and experience. This paper presents a fault detection and isolation scheme for a low -voltage dc- bus micro grid system. The goals of the proposed scheme are to detect the fault in a bus segment between devices and then to isolate the faulted section so that the system continues to operate without disabling the entire system. To accomplish these goals, this paper proposes a loop-type dc-bus-based micro grid system which has a segment controller between connected components.

II. LOW-VOLTAGE DC-BUS MICROGRID

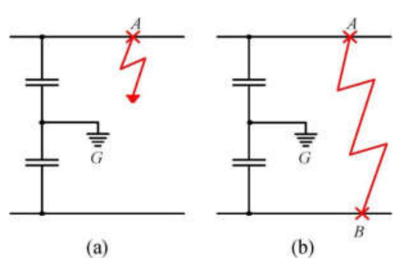

Fig. 2. Fault types in dc systems: (a) line-to-ground fault and (b) line-to-line fault.

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 micro grids have many advantages over traditional ac distribution systems. For both ac and dc micro grids, 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 $\sqrt{2}$ times 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 micro grids when a system needs re-liable 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 in order 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 cur-rents. More important, the fault persists because the operating time of the CB increases. Allowing a fault current to persist on a micro grid bus could be catastrophic.

Because the micro grid systems need to be multi terminal, 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. FAULTS IN DC DISTRIBUTION SYSTEMS

A. Possible Faults

Two types of faults exist in dc systems: 1) line to line and 2) line to ground, which can be seen in Fig. 2. A line-to-line fault occurs when a path between the positive and negative line is created, short circuiting them together. A line-to -ground fault occurs when either the positive or negative pole is short-circuited to ground. The line-to -ground faults are the most common types of faults in industrial distribution systems .VSCs may experience internal switch faults that can cause a line-to-line short -circuit fault. This is a terminal fault for the device that cannot be cleared and in most cases; the device needs to be replaced. Hence, dc fuses would be a proper protection measure for this kind of fault. In ac systems, the ac-side CB will trip.

B. DC Fault Currents

When a fault occurs in a segment, the line current will split between load current and fault current

I (line) = I (in) – I (out) …..(1)

The magnitude 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:

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

where V_s is the line voltage, R_c and L_c are the equivalent resistance and inductance including source, line and ground com-ponent, and R_c and C_e are the equivalent series resistance (ESR) 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 drop or even collapse, depending on the capacity of the power supply and energy-storage device in the bus, and the grounding impedance.

C. Current Techniques

The common practice in dc power systems is not to install any protection on the dc side, and upon fault detection the ac CBs that link the ac and dc systems are opened. A handshake method was suggested in 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 conduit between the ac systems and loads. However, this method can create unnecessary outages in LVDC micro grids where multiple sources and loads are connected to a common bus. Protection techniques such as over current time derivatives, under voltage and directional protection 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), IGBTs, and insulated-gate commutated thyristors. GTOs offer a high-voltage blocking capability and a low on-state voltage, but suffer from slow switching speeds. 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. However, high conduction loss is their disadvantage. 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. In order for the micro grid bus to allow power flow in either direction, the solid-state CB needs to be bidirectional.

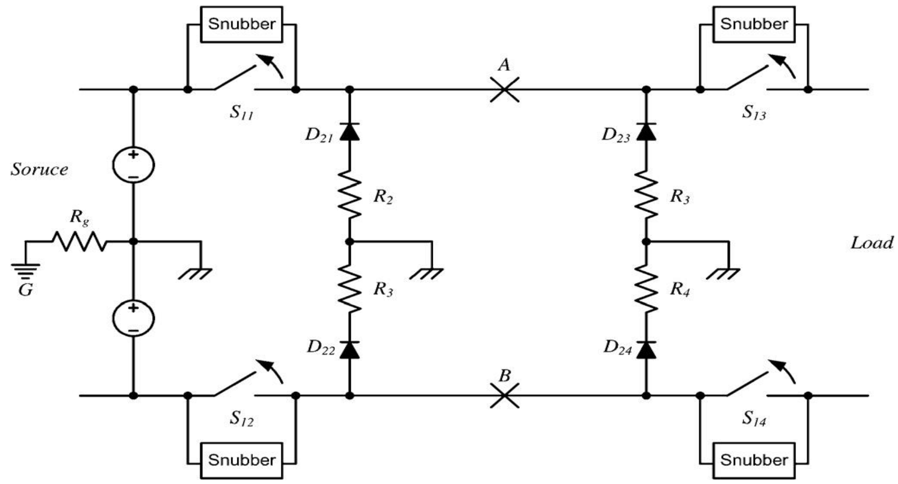

Fig. 3. Implementation of the proposed protection scheme. Arrows denote the switching action when a fault is detected.

Fuses or molded case CBs (MCCBs) can be utilized on dc systems [8]. Fuses can be problematic as they will only trip the faulted line, leaving the unfaulted pole energized. Although this problem can be solved with MCCBs, the drawback of fuses and MCCBs 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 cur-rent is to limit the bus current under fault conditions. The fault current limiters can be used in conjunction with CBs. The ad-vantages of fault current limiting include ride through 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, saturated inductors, and power-electronics devices.

IV. PROPOSED PROTECTION SCHEME

A. Proposed Controller

This paper proposes a novel protection scheme for the dc-bus micro grid 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. It has also been reported that the loop-type bus has good system efficiency especially when the distribution line is not long. 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. 3.

The protection system is shown only in segment A, and controllers on other segments 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 cur-rent 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 free-wheeling branch according to the commands from the master controller. In the course 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.

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) ……..(3)

Where i_{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. Be-cause the proposed system 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. 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 protection scheme is shown in Fig. 4, which shows the configuration of segment A in Fig. 3.

Semiconductor -based bidirectional switches S_1 and diodes D_{2x} are used for segment separation and fault current freewheeling, respectively. In normal operations, switches S_1 are closed and diodes D_{2x} are open. When a fault occurs, the master controller detects it using the current information from the slave controllers and opens S_1 switches. Diodes D_2 are conducting at the same time to form a freewheeling path for fault currents so that the S_1 switches can open and the fault current can be extinguished through resistors. The segment controllers can detect the fault current of the line-to-ground fault (from point A or B to G) and line-to-line fault (from point A to B). A turnoff snubber circuit is included for S_1 switches to limit the voltage overshoot due to the line inductance.

The line-to-ground fault and the line -to-line fault are shown in Fig. 5. It can be seen that the fault current is isolated and extinguished in the freewheeling loop. The freewheeling path impedance determines the extinction rate of the fault current, which can be given as follows:

$$i_{fault}(t) = \frac{V_s}{R_{eq}} e^{-\frac{R_{fw}}{L_{fw}} t} \quad \ldots\ (4)$$

Where R_{fw} and L_{fw} represent the resistance and inductance in the freewheeling path, respectively.

When a line-to-ground or a line-to-line fault occurs in the distribution line, the bus voltage collapse would not allow the load to ride through if the current is limited from the source because of insufficient capacity. This is especially true for the VSC-interfaced micro grid systems. Furthermore, the fault current needs to be extinguished as quickly as possible even if the system has sufficient current feeding capacity. Therefore, one of the best solutions would be to isolate the faulted line as soon as possible and continue operation with intact bus segments and subsystems. To achieve this, the segment controller needs to be capable of fast differential current detection and bus switch control. An automatic reclosing algorithm would be necessary for fault recovery and more robust operation.

C.Power Supply Circuit

Power supply circuits are indispensable to protect the solid-state CBs from the voltage transient due to the inductance of the bus cable. It is more so especially in a loop- type bus where the line inductance exists on both sides of the CB unlike the point-to -point-type system. Although the fault current needs to be interrupted as quickly as possible, the high di/dt could make the transient voltage catastrophically 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 [25]. 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.

Since the solid-state CBs do not switch in high frequency, charge-discharge-type RCD snubber has been chosen for better voltage suppression performance. Although the discharge -suppressing- type RCD snubber could eliminate the separate freewheeling path as can be seen in Fig. 6(a), it would be difficult to handle bidirectional currents. The charge-discharge-type RCD snubber is shown in Fig. 6(b).

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_l .

Block diagram:-

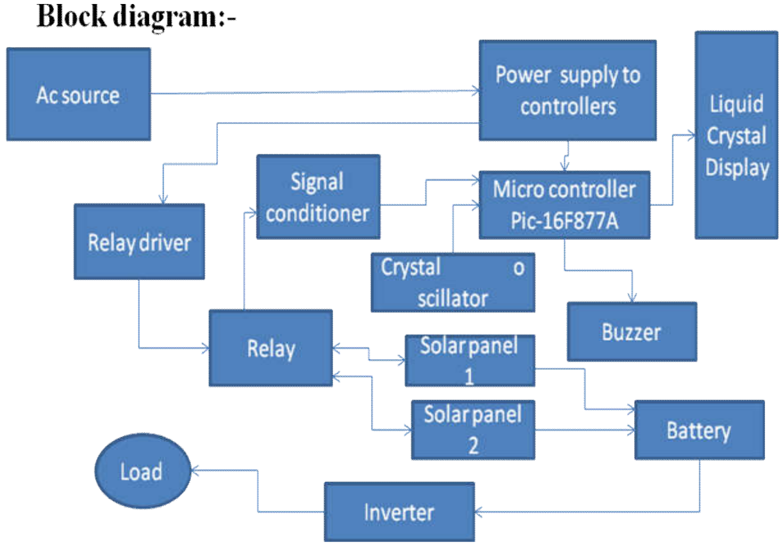

Fig.4.Block diagram for a proposed system.

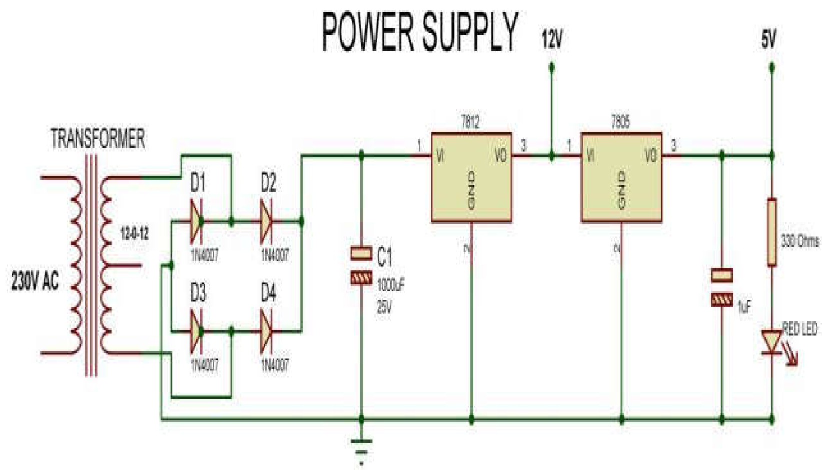

Fig.5.Circuit diagram for a power supply

The energy stored in the line inductance can be given as

$$W_l = \frac{1}{2} L_l I_{\bullet}^2 \qquad \text{....(5)}$$

where $I_{\bullet}$ is the line current.

D.Display With Micro Controller

The fault current to an appropriate level for detection and extinction. However, some protective devices are still needed even with the resistance grounding schemes, because the fault current cannot be sustained. The dc system grounding options are: 1) solid grounding; 2) low-resistance grounding; 3) high-resistance grounding; and 4) no grounding. Although ungrounded systems are used in some applications to avoid the effect of low-resistance pole-to-ground fault and stray current, ungrounded systems are sensitive to changes in the grounding plane and can be dangerous especially under abnormal fault conditions.

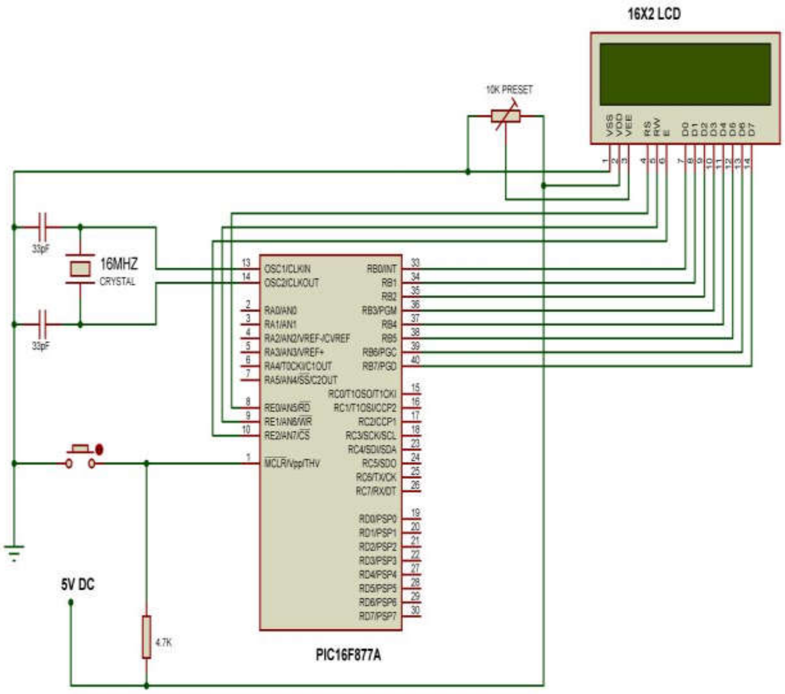

Fig.6.Display with micro controller.

International standard IEC 60364 defines three grounding systems. Low-voltage power systems

(< 1 kVac or 1.5 kVdc) uses the two- letter codes TN, TT, and IT depending on how the source and conductive body of electric devices are connected to earth [29]. The TN system ensures that distributed grounding and fault detection is straightforward but faults at a higher voltage level can increase the touch voltage. The TT system is easy to install and faults do not migrate to others but high-voltage stress is possible. The IT system has very low or even zero fault current and can operate with a single fault, but insulation monitoring is required and high fault current is possible with another ground fault.

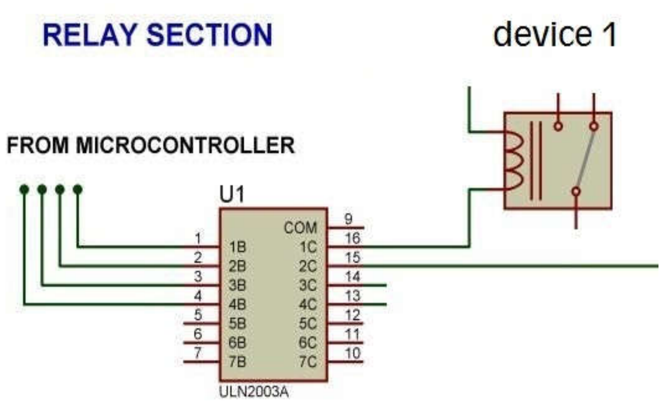

Fig.7.Relay section circuit diagram.

It is a common practice to ground power subsystems at a single point and as close to the source as possible, like in a TN system. Multiple ground points in a TT system could form unnecessary circulating current paths. Possible grounding point for a dc system can be either one of the poles or the midpoint of the bus, and it has been reported that the balanced dc-side mid-point grounding significantly reduces circulating current compared to the ac-side neutral system.

E.Circuit Diagram:

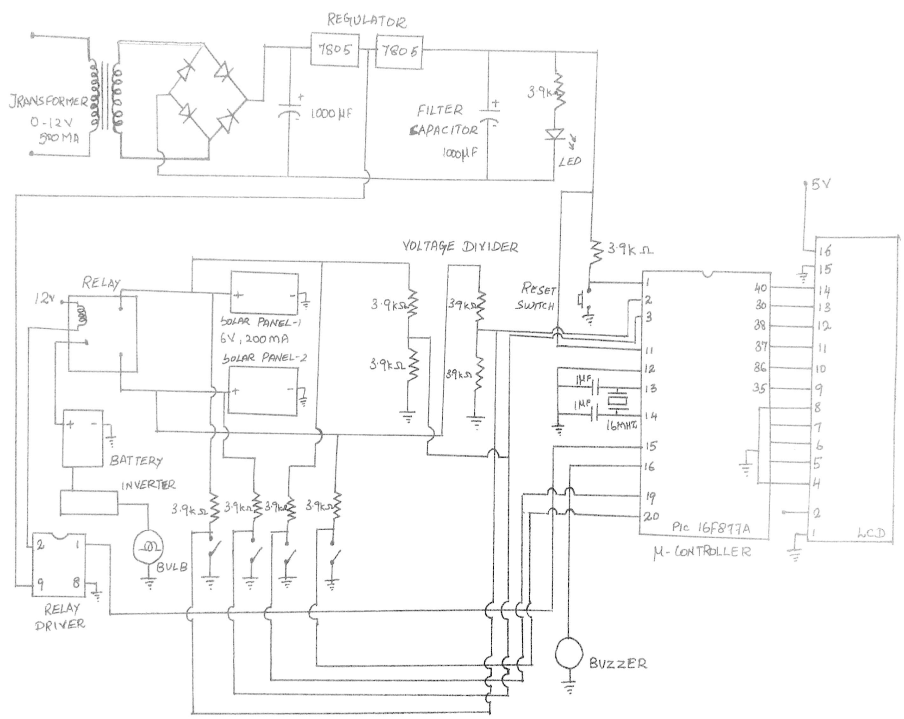

Fig.8.Complete circuit diagram.

Furthermore, it is safer because of lower ground potential compared to the direct pole grounding, and the ground impedance at the midpoint can limit the fault current under a safe level. The ground resistor can be used to detect the ground fault as well, although it is not able to identify the location of the fault because of the single ground point practices.

F.HARDWARE

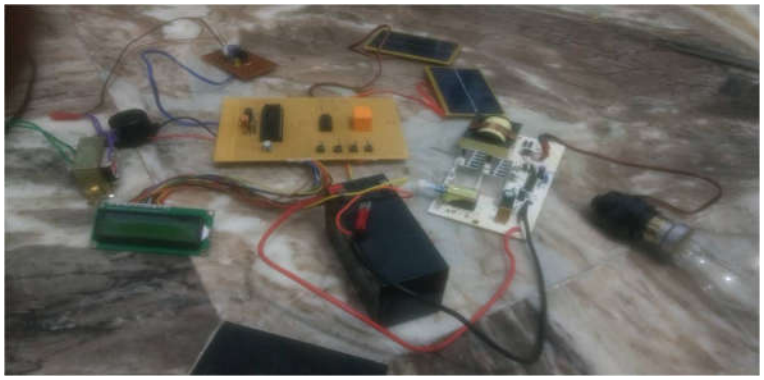

Fig.9.Hardware

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 Unit	
Resistance R_s	10Ω
Capacitor C_s	10μF

A computer simulation has been performed for a micro grid system that consists of three typical energy devices: a source, a load, and energy storage. They are connected as shown in Fig. 7. Stiff dc power sources are assumed so that a constant fault current is fed by the sources without a voltage drop. A 240 V bipolar dc bus with 200 m bus cable segments [31] and a fault at the middle (100 m) of the bus is simulated.

A positive line-to-ground fault in the middle of the bus segment A is simulated at 1 ms. Fig. 8 shows the source- and load-side current of a line-to-ground fault with and without protection. It can be seen that the current from source increased to 180 A after 0.5 msec. 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.

G.Output:

A lab-scale experiment setup in about 6:1 scale from the simulation circuit has been built to validate the feasibility of the pro-posed protection scheme with actual hardware. The setup has a source-load-storage structure of Fig. 3, but only with positive pole and ground to simulate a line-to-ground fault.

Fig.10.Output.

Two channels of 30-V 3-A power supply Instek GPC- 3030D have been utilized for 20-V source and energy storage, and 12.5-Ω resistive load is used load is used. Each source supplies about 1 A of load current in normal operation. Three 15-μH inductors and six 220-pF capacitors are installed in the positive line to simulate the line. The freewheeling path has an IR diode T40HF60 and a 2-Ω freewheeling resistor.

V. CONCLUSION

This paper has presented a fault detection and isolation scheme for the low -voltage dc-bus micro grid 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 micro grid 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 proposed scheme can be applied to dc power systems, such as Green Buildings, with sustainable energy resources and data centers with a server array. Challenges, such as a reduction of conduction loss in the solid-state CBs and fault ride through capability, and fault-location techniques need to be investigated.

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