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Protection Strategies for Medium Voltage Direct Current Microgrid at a Remote Area Mine Site

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***Abstract* -- This paper presents the protection strategies for a medium voltage direct current (MVDC) microgrid at a remote area mine site. The microgrid is operated to provide high power quality and reliability to sensitive loads, and also improve the energy efficiency of the mining equipment. In the MVDC microgrid, various local distributed energy resources (DERs) have been used including photovoltaic (PV) arrays, wind turbines, fuel cell stack, energy storage system and mobile diesel generators. For the protection of transmission lines, a communication-based differential protection scheme with solid state electronic relays is employed to isolate the faulted part of the MVDC microgrid. This is further reinforced by a dc overcurrent protection as backup. Earlier research work had neglected the backup protection for dc systems. Besides, communication-based dc directional overcurrent protective relays are used for both source and load protection to support bidirectional power flow. MATLAB®/Simulink™ modeling and simulation results are presented and discussed to illustrate the proposed system's dependability and security.**

***Index Terms* -- Circuit faults, delays, distributed power generation, energy storage, microgrids, mining, overcurrent protection, voltage control, wind turbines.**

I. Introduction

Mine sites are often in remote places where the mineral resources are abundant, but seldom is there a large and well established grid infrastructure. However, it is important to have a secure and reliable power supply for running the mining operations efficiently and reliably. Recent technological trends show an increased interest in the medium voltage direct current (MVDC) systems with several publications available [1-5]. This has led to various power equipment manufacturers introducing new products into the market, for instance, the references [6, 7]. Many other MVDC systems are expected to become available in the near future. Hence, it is imperative that the protection problems in MVDC systems are investigated for industrial power systems in a comprehensive manner.

This paper proposes protection strategies for an MVDC microgrid to offer reliable and secure power supply in a remote area mine site. Installing a long transmission line from the distantly located main power grid is acknowledged to be expensive. Hence, this paper explores the feasibility of an islanded MVDC microgrid system that makes use of locally available energy resources.

For reliable operation of the industrial power system, a carefully designed dc protection scheme is vital in guaranteeing the microgrid's dependability and security. As compared to the ac microgrids, dc systems are not yet matured enough with full-fledged standards, especially on the protection aspects [8-11]. Protection problems in dc systems involve detection and determination of fault locations, and extinction of dc arc [10]. The fault isolation in dc systems is a serious problem since the levels of fault current are relatively higher. Traditional ac breakers, which depend on the zero crossings of the fault current to open the circuit, are not suitable for operation in dc systems. In hybrid ac/dc systems, the common practice in dc protection was to not install protection devices on the dc bus, but to instead have them on the ac side. This is because the faults on dc bus will be reflected on ac side too, which has well established and efficient techniques to clear the fault. But in a larger dc network, especially for an islanded dc microgrid, it has the major drawback of disconnecting the entire dc system. This will have a significant impact on the dependability and security of the entire system. The major challenge in such networks is to detect the fault and then isolate only the faulted section with the critical loads being kept energized. In this paper, a communication-based differential protection scheme with dc circuit breakers is proposed for the remote area mine site. A high resistance fault in MVDC systems is investigated as it has not been in any earlier work to the best knowledge of the authors.

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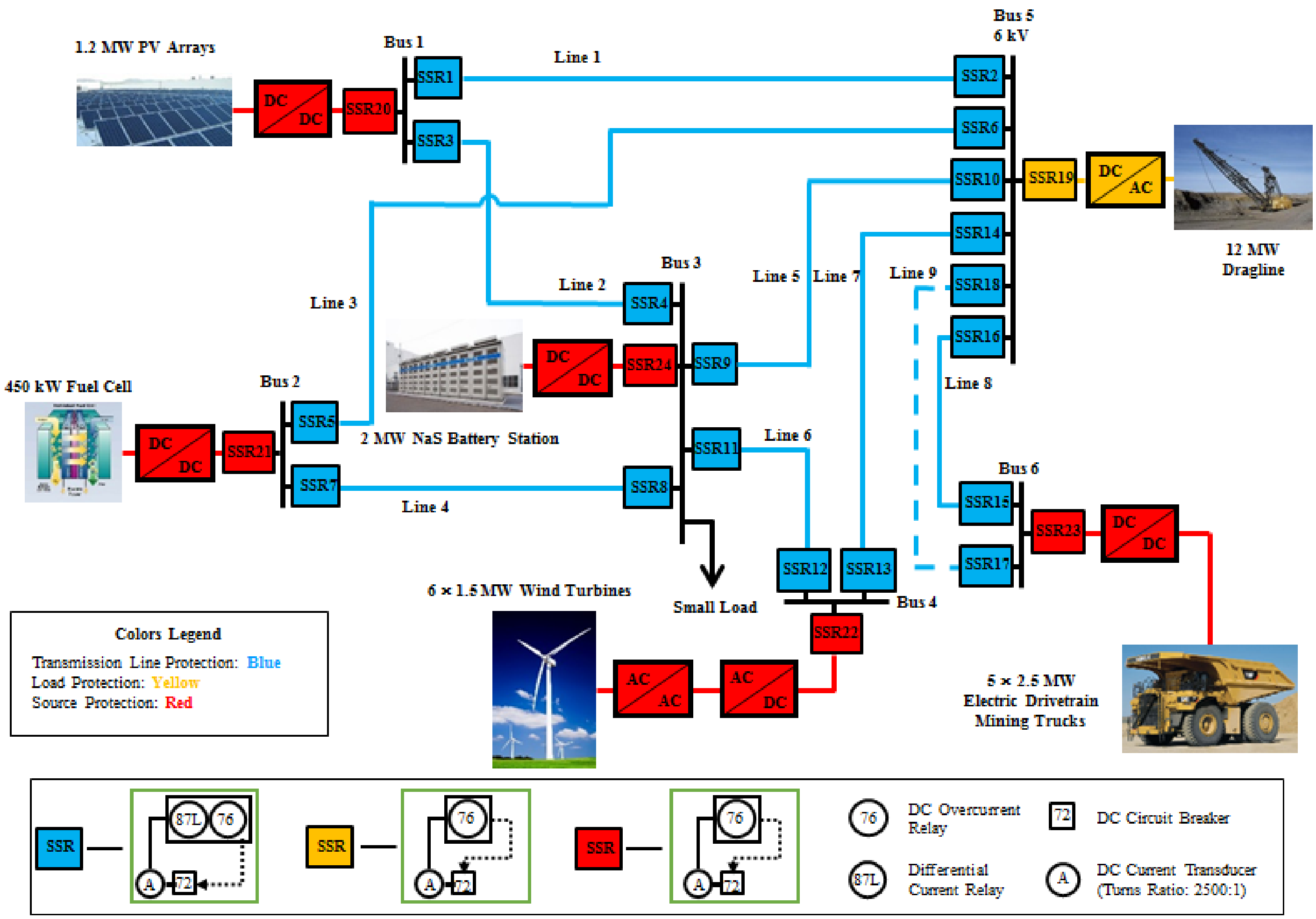

Figure 1. Simplified schematic of an islanded MVDC microgrid at a remote area mine site

II. Mine Site Microgrid — Basic Operation and Control

The islanded MVDC microgrid at the mine site is assumed to use a diverse array of distributed energy resources (DERs) such as solar/photovoltaic (PV) arrays, wind turbines, a fuel cell stack, and a battery energy storage system as shown in Figure 1. Among these DERs, the wind turbines and PV arrays work at their maximum power points (MPP) [12-14], the fuel cells are controlled to regulate the dc bus voltage at ~6 kV, and a battery energy storage system aims at balancing the supply and demand. There also exist diesel generators, which have quick start characteristics, for backup generation and dc bus voltage regulation. A visual depiction of the overall control strategy for the microgrid is illustrated in Figure 2.

Instead of installing stationary diesel generators, other forms of mobile generators have been used including those that are connected to the electric drivetrains of haul trucks, locomotives and mining vehicles. For example, the diesel engine of an electric drivetrain mining truck can be connected to the microgrid from its 2400 V dc link via the pantograph to offer backup power when needed; and also for re-injecting the regenerative electrical power during retarding period [15-17]. In this manner, large savings can be achieved in the capital costs. With the interconnection of all DERs through the trolley lines at the mine site, the power system reliability can be significantly improved through increased mean time between failures (MTBF).

Another key part of the islanded mine site microgrid is the energy storage. In this paper, a practical and widely deployed

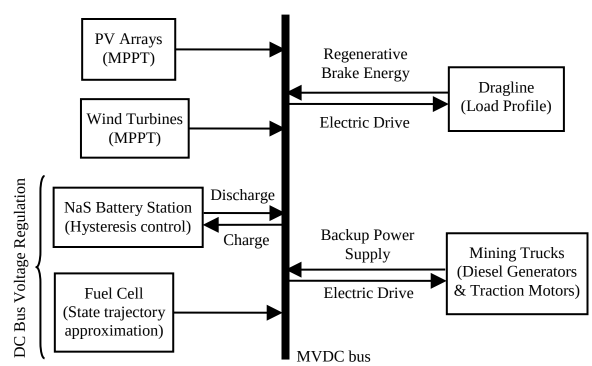

Figure 2. Block diagram of the control strategy and power flow

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utility scale 2-MW Sodium Sulfur (NaS) battery station has been used as the energy storage system. With this addition, the regenerative brake energy of a majority of equipment like hoists, draglines and shovels can improve the system efficiency and bring energy savings [18-23].

The microgrid makes use of dc bus signaling (DBS) to control the power drawn from the fuel cell stack, energy storage system and diesel generators for maintaining a constant dc bus voltage (*cf.* Figure 2). The NaS battery energy storage exploits voltage hysteresis control scheme, whereas the fuel stack uses a state trajectory approximation strategy known as hybrid control algorithm [24]. The backup power sources of mobile diesel generators in the mining machinery, not in service, are also used.

A simulation model of the system in Figure 1 has been created in MATLAB®/Simulink™ using SimPowerSystems toolbox. Power quality and reliability at the remote area mine site depends, to a large extent, on whether the microgrid can handle the typical large varying loads without resulting in significant voltage fluctuations on the load bus. The load demands of mining machines were varied to simulate real-life operating conditions for verifying the performance of the control strategy. The NaS battery was controlled to charge when the dc bus voltage increases above 6060 V and discharge if the dc bus voltage decreases below 5940 V, thus regulating the load bus voltage at ~6 kV with 1% fluctuation. For brevity, the simulation results illustrating the operation and control of MVDC microgrid have been omitted.

III. Specialized Protection Schemes for the Islanded MVDC Microgrid

As seen in Figure 1, the MVDC microgrid has a meshed architecture for boosting the system robustness and reliability. Even if one or more transmission lines are disconnected, the system can continue its operation without interruption. The protection of such a microgrid is categorized into three parts: transmission line, load and source. Transmission line protection detects and isolates a fault which happens on main transmission lines; load protection isolates a fault on the load side from the rest of the microgrid; and source protection cuts off the fault from the source and the network, disconnecting the source from the system. It has been assumed that every piece of equipment installed in the microgrid was originally factory tested by its manufacturer. As such, the individual component protection is out of scope in the following analysis. In this paper, the loads are mining machines, whose regenerative brake energy will be captured in the NaS battery. The load protection needs to take into consideration whether the power flow is into or from the load side. Before delving into the details of the protection strategies, the microprocessor-based solid state relay (SSR) and its associated communication delays are discussed in the following two sections:

A. Microprocessor-Based Solid State Relay (SSR)

This paper proposes current differential protection and overcurrent protection as the main protection scheme and backup protection scheme, respectively. To realize the mentioned protection strategy, microprocessor-based solid state relays take the responsibility and play the key role. Inside SSRs, digital microprocessors are utilized to process the monitored data and send out the command signals to control individual circuit breakers. Thus, the current differential protective relay is used to offer high speed and accurate transmission line protection. In addition, the dc overcurrent relay is installed for the backup protection of transmission lines.

Besides the microprocessor, the SSR also includes a dc current transducer for sending real-time data to the microprocessor, a sensor that responds to the microprocessor's relay control signal, a solid state electronic switching device as a dc circuit breaker, and specific coupling mechanism to enable the control signal to activate this switch without moving parts (*cf.* Figure 1). Reference [25] presented an overview of MVDC protection via SSR technology and a practical method to create medium voltage SSRs by combining several power semiconductor devices in series/parallel. An SSR has the same function as the electromechanical relay (EMR), but it has no moving parts. Table 1 gives a comparison between SSR and EMR features.

B. Communication Delay Analysis

In this paper, all measurements are processed locally, within the microgrid, thus eliminating any risk of significant communication delay. But current differential protection is the primary protection scheme for transmission lines. Hence, a backup protection is also included to enhance the dependability and security of the islanded MVDC microgrid.

Table 1. Comparison Between SSR and EMR

Relay Type / Characteristics	SSR versus EMR
Switching Speed	The SSR has a response time in the order of tens of microseconds while the EMR needs several hundred milliseconds.
Reliability	SSR will gain the edge due to longer service life and bounce free operation.
Fault Current Level and Arc-Flash Energy	Due to the fast switching speed, SSR can limit both of fault current and arc-flash energy to a lower level.
ON Resistance	EMR's ON resistance is around 100 milliohms, whereas that of SSR is about a few ohms.
Package Dimension	EMR has lots of mechanical parts inside, so the package size is limited to the physical dimensions of functional internal components. While the SSR is limited to the size of the semiconductor components, and could be manufactured in a much smaller package.
Lifetime	SSR exhibits a longer operational life as it has no moving parts and its life span is virtually infinite under ideal conditions.
Cost	In the past, the EMR's price was much lower than the price of an SSR. With advancements in manufacturing technology the gap has been reduced, but SSR is still on the higher side.

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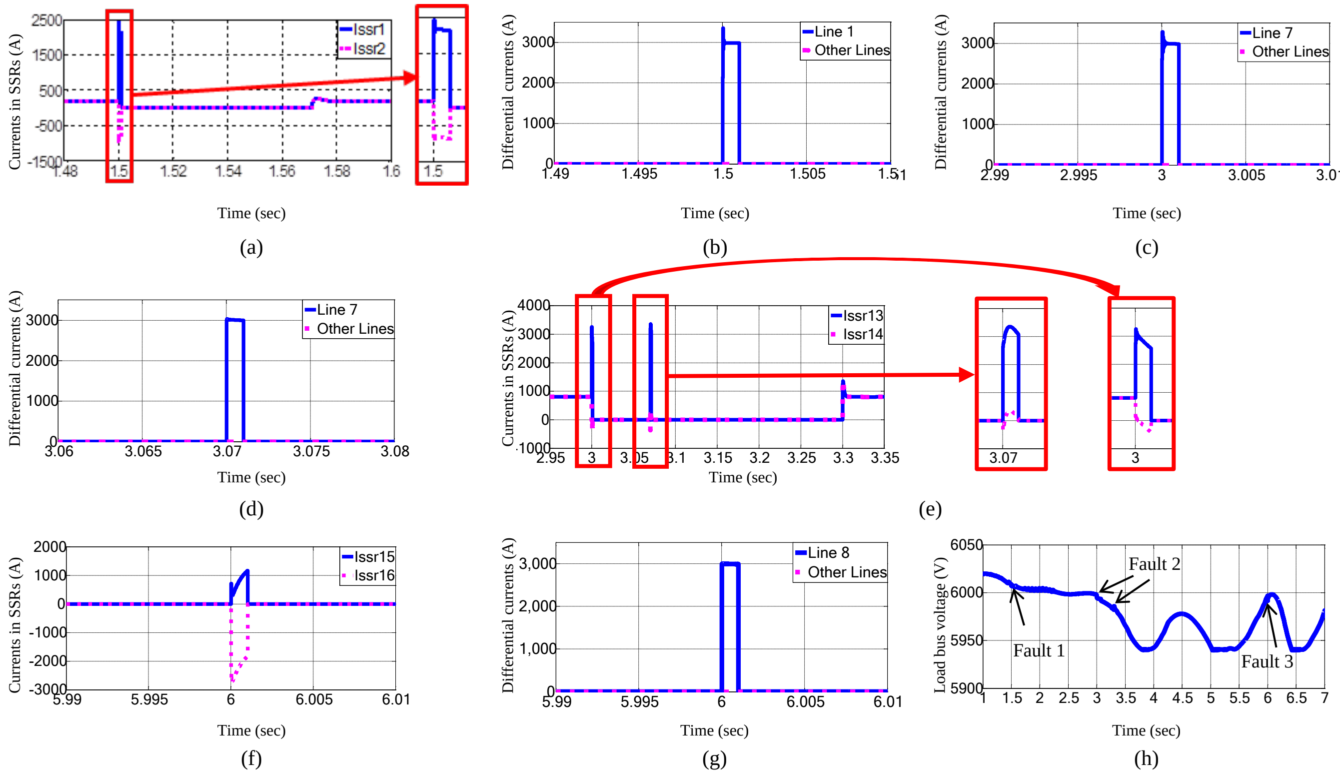

Figure 3. Selected simulation results of: (a) currents through SSR1 and SSR2 during Fault 1; (b) differential currents in line 1 and other lines when Fault 1 occurred; (c) differential currents in line 7 and other lines when Fault 2 occurred; (d) differential currents in line 7 and other lines around 3.07 s when SSR13 and SSR14 reclosed; (e) currents through SSR13 and SSR14 during Fault 2; (f) currents through SSR15 and SSR16 during Fault 3; (g) differential currents in line 8 and other lines when Fault 3 occurred; (h) load bus voltage during the entire testing period.

Hence, even small communication delays need to be considered for correct design. Normally, the communication delay includes propagation delay and transmission delay. Given the short distances of the mine site microgrid, the propagation delay is between several tens of microseconds [26], so this delay could be ignored. Transmission delay is the time spent to send out and receive a signal. This is the delay caused by the data rate of the link. Apart from that, transmission delay is also a function of the package length and has nothing to do with the distance between two nodes. Here, a common point-to-point system is chosen and a 1 Mbps is adopted. An average transmission delay of 1 ms can be obtained via OPNET simulation.

C. *Transmission Line Protection*

For transmission lines, this paper proposes a communication-based current differential protection associated with solid state electronic devices. Besides that, dc overcurrent protection will be also used as a backup protection strategy. Investigation is carried out for different fault resistance values in the MVDC system, with particular emphasis on a high resistance fault.

1) *Primary Protection: Current Differential Protection*

This protection scheme is based on the basic theory of Kirchhoff's Current Law (KCL), which states that the sum of the currents entering (or exiting) a node is equal to zero. Under normal conditions, a transmission line could be seen as a node, so the current flowing in the line should be equal to the current flowing out of the line. However, this is not the case when a fault occurs — as the summation of currents will be equal to the fault current (*i.e.*, ≠ 0). This understanding can help in accurately detecting a fault and instantaneously sending the tripping signal. The key approach to guarantee the precision of differential protection is synchronous measurement and comparison. Given that transmission lines in microgrids are of 5~10 km (*i.e.*, not very long), the problem of asynchronous currents can be neglected. Also, the GPS synchronized clock could be used to receive synchronous measurements if the transmission line is extending over a long distance.

A computer simulation was carried out in MATLAB®/Simulink™. Three ground faults occurred in the microgrid of Figure 1 on Line 1 (Fault 1), Line 7 (Fault 2) and Line 8 (Fault 3), respectively, at different times. During each fault event, the responses of SSRs are presented in Table 2. As seen in this table, SSR15-SSR18 have responded to the Fault 3. It is to be noted that Line 8 has a bypass Line 9 in Figure 1 — to ensure that the diesel generators are always connected to the load as backup sources. Thus, when Line 8 is disconnected because of a fault, Line 9 will be connected to the load bus at once. Under a condition of 2 ohm ground fault, selected simulation results of the current through SSRs, dc bus voltages on Bus 5, and differential currents of the faulted lines and other lines, are displayed in Figure 3.

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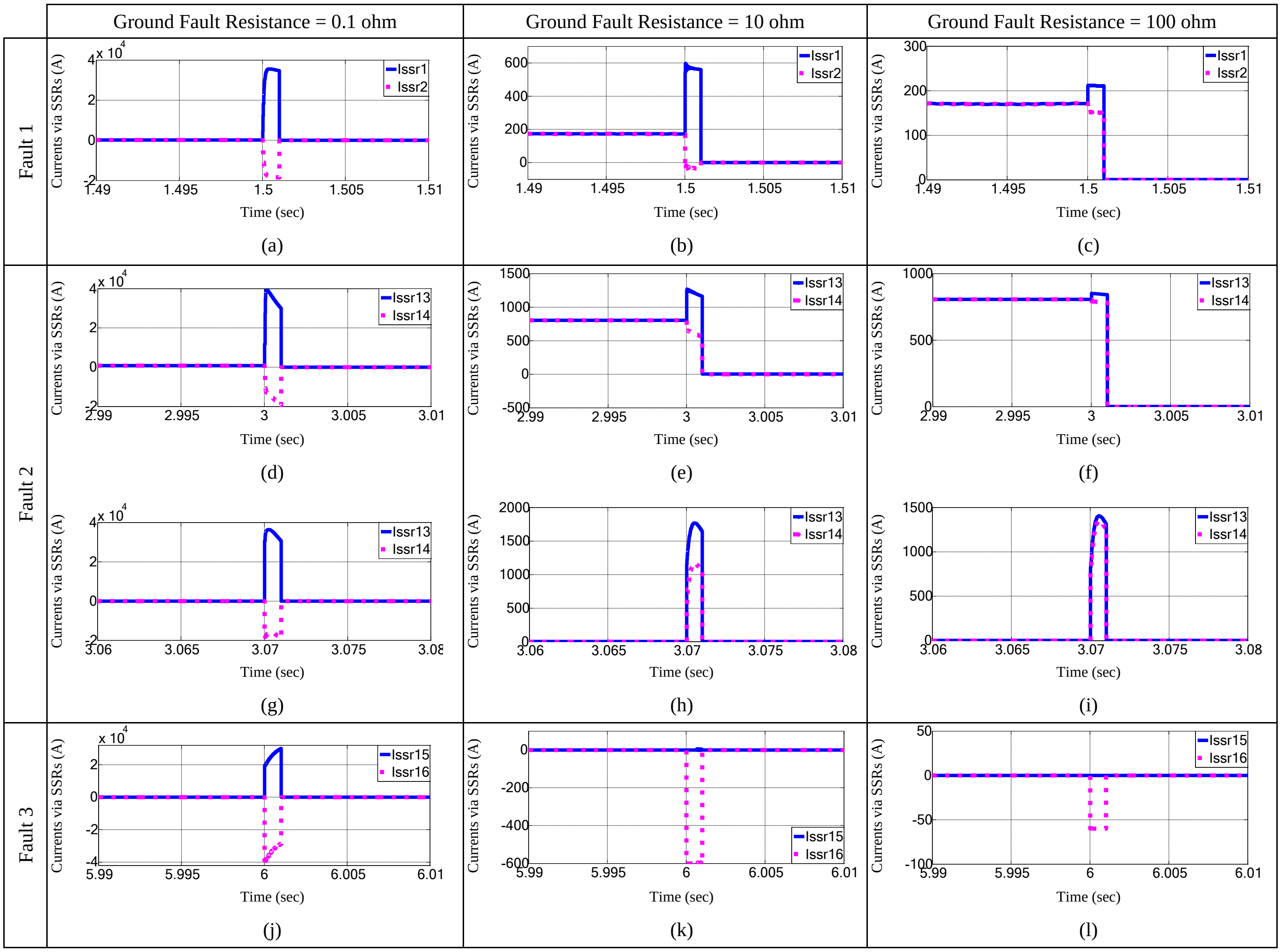

Figure 4. Currents through SSRs under different fault conditions: (a) – (l)

TABLE 2. SSR RESPONSES DURING FAULT EVENTS
(DEPENDABILITY AND SECURITY)

	Fault 1	Fault 2	Fault 3
SSR1	✔	✘	✘
SSR2	✔	✘	✘
SSR13	✘	✔	✘
SSR14	✘	✔	✘
SSR15	✘	✘	✔
SSR16	✘	✘	✔
SSR17	✘	✘	Δ
SSR18	✘	✘	Δ
SSR3/SSR6/SSR10/SSR12	✘	✘	✘

Note: ✔ denotes that the corresponding SSR tripped during a fault event, Δ indicates that the corresponding SSR closed during fault event, and ✘ means no response from the corresponding SSR.

As seen in Figure 3, case (a) shows that when Fault 1 has occurred, SSR1 and SSR2 isolated the fault at once and reclosed 70 ms later after Fault 1 was cleared. The cases (b) – (d), and (g) in Figure 3 illustrate the differential current waveforms during Fault 1, Fault 2, and Fault 3 in respective. Figure 3(e) shows that right after Fault 2 struck on Line 7 at time of 3 seconds, SSR13 tripped to isolate the fault, and then after 70 ms, SSR13 reclosed. Since the Fault 2 was not cleared by that time, SSR13 opened again until 230 ms later after the fault was cleared. At 3.3 seconds, SSR13 reclosed and remained in closed position — this means that the fault was cleared before the reclose of SSR13. Figure 3(f) displays the speed and precision in the response of SSR15 and SSR16 when Fault 3 occurred. Finally, Figure 3(h) shows that the load bus voltage has been maintained constant, within ~1% fluctuation, during the testing period by the control strategy explained in Section II.

For investigating the main protection scheme's dependability and security, another set of tests were carried out under the same three fault conditions, but for three different ground fault resistance values [27]. The

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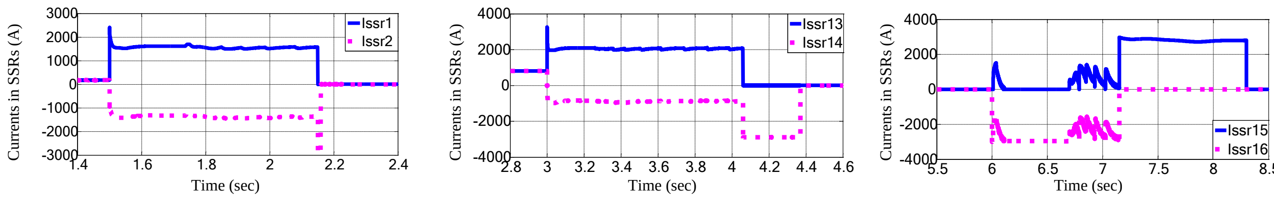

(a) (b) (c)

Figure 5. Action of backup protection when the main protection failed — fault currents through SSRs under the 2 ohm ground fault conditions: (a) Fault 1; (b) Fault 2; (c) Fault 3

corresponding simulation results are presented in Figure 4. From Figure 4, it can be observed that the faults got isolated by the line current differential protection, even when the ground fault resistance is high and the fault current is much lower than the full load current. So, when the current differential protection is used as the main protection scheme, there is no need to be concerned about the ground fault resistances. This system's robustness is clear from the observation that the product of differential current and the fault resistance is always ~6 kV.

2) Backup Protection

If a primary protection device failure and/or communication failure occurred in any line, detecting and isolating a fault will become more challenging. The situation can have dire consequences as this is a meshed microgrid. In case the fault can't be isolated promptly, the rest of network will be affected, and may even result in a system collapse. For a line connected to a current source integrated bus, the under-voltage protection device needs to be installed as a backup protection. However, in the case of a line linked to a voltage source connected bus, the overcurrent protection is preferred. This is because for a current source, the current will be maintained within an acceptable range during a ground fault, but the voltage could drop to near zero value with a small ground fault resistance. In contrast, a voltage source's output voltage will not be affected by a ground fault, but its output current will increase to a high value under a low ground fault resistance condition.

For bus 5 in Figure 1, the load bus voltage is controlled by the energy storage system, the fuel cell and diesel generators. The load bus can be viewed as a bus associated with voltage sources. Similarly, the bus 3 voltage is controlled by the energy storage system, and it can also be protected by overcurrent protection. Thus, the overcurrent protection devices are recommended for backup protection for lines connected to bus 5 and bus 3.

Likewise, the PV arrays can also be considered as a voltage source — as they are being controlled by maximum power point tracking (MPPT) and their voltage is kept around the voltage of maximum power point. Therefore, all the transmission line SSRs' backup protection schemes could be equipped with overcurrent protection. As such, this paper proposes to add dc overcurrent protection devices to all transmission lines as the backup protection. The inherent time delay between main and backup protection is set to 0.5 s. In addition, the overcurrent protection also has its time-current curve [28]. Specifically, two settings are included in a time-overcurrent curve, *viz.*, (i) pickup current, and (ii) time delay. In the proposed scheme, the backup protection uses inverse current-time characteristics; for example, the relay studied in Figure 5 used a moderate inverse current-time characteristics (U1) [29]. Figure 5 displays the fault currents through SSRs under the 2 ohm ground fault condition — action of backup protection when the main protection has failed.

As seen in Figure 5, the backup protection response can be both quick and precise. Since the backup protection response depends on the overcurrent relay's time-current curve and fault currents through different SSRs, each circuit breaker's tripping time can be different. It can be seen that the difference between the currents through any two associated SSRs approximately equals the value of nominal dc bus voltage divided by 2 ohm, which is the fault resistance. Thus, the system's dependability and security against fault conditions can be significantly improved.

D. Load (e.g., Dragline) Protection

As indicated in Figure 1, the mine site includes a dragline that is supplied by the microgrid. The dragline is a regenerative load, and the protection for it must take the bidirectional power flow into account. This paper proposes to apply the communication-based dc directional overcurrent protection element for the fault on the line between the dragline load and bus 5 (*cf.* Figure 1). The reason a directional protection is chosen is to avoid malfunction when a fault occurs in other transmission lines. For a low resistance fault, the bus side relay, *i.e.*, SSR19 (*cf.* Figure 1), will trip the corresponding circuit breaker at once. Generally, the trip setting for current based relay could be 2-3 times higher than the peak load current. But the dragline has a time varying load, so the fault current will also vary. Therefore, the trip settings should be changed accordingly. However, for a high impedance fault (such as >100 ohm ground fault) in the microgrid, it is preferred to feed the fault for a while, rather than open the circuit breaker and disconnect the load at once — which is otherwise often required in the main grid for the protection of critical loads.

E. Source Protection

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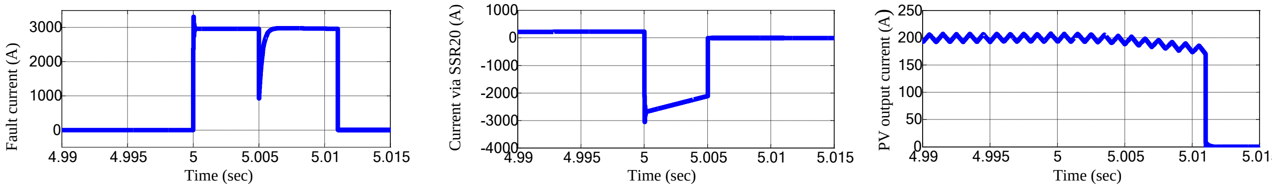

Figure 6. Action of source protection when a 2 ohm ground fault occurs on the source side: (a) fault current; (b) current through SSR20; (c) PV output current.

The protection scheme suitable for a voltage source for fault conditions between the bus and source uses the communication-based dc directional overcurrent protection device — like the protection applied to load. In Figure 6, a test of PV loss is illustrated caused by a source-side ground fault at 5 s. The directional overcurrent protection is used in SSR20, shown in Figure 1, to protect PV arrays. Figure 6(a) shows the fault current has sag at 5.005 s and will be cut to zero at 5.011 s. This is because SSR20 detected the fault current, based on directional overcurrent protection, tripped the circuit breaker in 5 ms, and signaled PV arrays to stop feeding the fault, as presented in Figure 6(b) and Figure 6(c), respectively.

It is essential to safeguard the energy resources. If the energy storage system is disconnected from the network, it is necessary to send out signals to control the electric drives of mining machines to prevent them from operating in regenerative braking mode. This is because no other device can store that energy, and it may cause a rapid increase of the microgrid's bus voltage and affect network's stable operation. Moreover, a bypass transmission line is needed between the load and diesel generators to keep the microgrid's bus voltage within an acceptable range, avoiding disconnection between backup generation and the system, labeled as Line 9 in Figure 1. In the proposed microgrid, PV arrays and wind turbines are renewable energy resources with intermittent characteristics. They are always controlled to maximize output power to save energy and earn greatest benefits. The load comprises several large varying machines in a dragline. Hence, besides the energy storage system and the fuel cell stack, diesel generators are needed as backup sources to support the power balance, and prevent the dc bus voltages to fluctuate widely. As otherwise, it may cause a system outage, especially when the energy storage system is disconnected.

It is to be noted that the PV arrays in the microgrid (*cf.* Figure 1) had been earlier considered as equivalent to a voltage source. However, if the current drawn from the arrays exceeds the value corresponding to its maximum power point, it can cause a collapse of the PV voltage. This is when the PV arrays are more or less equivalent to a current source, and an under-voltage protection device is appropriate to resolve this fault condition.

To further illustrate the advantages of the proposed protection strategies, Table 3 illustrates the performance comparison between different protection schemes for the islanded MVDC microgrid. From this table, it is evident that the proposed protection scheme gives superior dependability and security.

IV. Conclusions

The MVDC microgrid comprises a diverse set of distributed energy and storage resources like PV arrays, wind turbines, a fuel cell stack, battery energy storage system and mobile diesel generators. This paper has presented a comprehensive analysis of the protection strategies for an islanded MVDC microgrid solution at a remote area mine site. A solid state relay (SSR) based protection scheme was proposed for safeguarding the microgrid against the fault conditions, and it was compared with that of conventional electromechanical relays. Line current differential protection was the primary protection for transmission lines, and it was further reinforced by a backup dc overcurrent protection. This is a salient feature of the specialized protection scheme as the

TABLE 3. Comparison Between Different Protection Schemes for the Islanded MVDC Microgrid

Fault Condition \ Protection Scheme	Proposed Protection Scheme (w/o Backup Protection for Transmission Lines)	Proposed Protection Scheme (w/o Bypass Transmission Line)	Proposed Protection Scheme
Ground Fault on Transmission Line	✔ (main protection works) ✘ (main protection fails)	✔	✔
Ground Fault Close to Generation Source	✔	✔	✔
Ground Fault Close to the Load (Dragline)	✔	✔	✔
Ground Fault Close to Backup Diesel Generation	✔	✘	✔

Note: ✔ denotes that the system is well protected under corresponding protection scheme, and ✘ indicates no satisfactory protective action takes place and may result in a system crash.

backup protection had been neglected in the earlier research on dc systems. On the other hand, the load protection and source protection use communication-based dc directional overcurrent protection devices.

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