Analysis and Design of the Protection Scheme for a LVDC Microgrid

R. Lazzari*, L. Piegari**

* RSE, Ricerca sul Sistema Energetico, via R. Rubattino 54, I-20134 Milano, Italy

** Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, p.zza Leonardo da Vinci, 32, I-20133 Milano, Italy

***Abstract*— The growing diffusion of renewable energy sources is leading to a considerable revision of the distribution network. In this context, the adoption of direct current distribution grid can bring benefits to the hosting capacity and energy efficiency. However, the protection of such network involves many challenges, especially in case of LVDC microgrids with more than one feeder. The traditional protection schemes used for AC grid are not able to isolate faults and to protect the components of the DC grid. This paper deals with the analysis and design of the protection scheme for a low voltage DC microgrid, in presence of different renewable generators, energy storage systems, loads and front-end converter with the AC grid. The proposed centralized protection scheme overcomes issues of fast fault clearing time, cost effectiveness and selectivity in the case of pole-to-pole fault.**

***Index Terms*—DC Microgrids, DC fault, Electrical fault detection, Power system protection**

I. Introduction

Nowadays, the development of power electronics technology, the wider diffusion of renewable energy sources (RESs) and the integration of energy storage systems (ESSs), are supporting the realization of low voltage direct current (LVDC) microgrids [1], [2]. The advantages of DC distribution respect to the AC distribution are well known [3] and include higher energy efficiency [4] and the natural interface with RESs, electronic loads and ESSs [5]. In addition, DC microgrids do not exhibit the typical issues of AC microgrids, such as synchronization, frequency regulation, reactive power flow and three-phase unbalances.

However, the implementation of a LVDC grid presents significant technical challenges in order to protect and operate the system. This type of grid introduces, indeed, a complex mix of power converters of different typology, that require capacitance filters to mitigate the voltage ripples. In case of a DC bus short-circuit, these capacitors rapidly discharge into the fault, causing a current surge with an amplitude that depends on the filter design and the location of the fault [6]. It is worth noting that not all the converters are capable of blocking the fault current. Indeed, when the capacitor voltage drops, the antiparallel diodes of voltage source converters (VSCs) and boost converters, will be forward biased and the source will continue to supply the fault [7] also if the converter components are turned off. The diodes only have the ability to withstand a certain level of fault current, so the fault current must be detected and distinguished very quickly to protect the converters.

To solve this issue, the use of DC solid state circuit breaker (SSCB) are proposed in literature. In particular, in [8] the use of a semiconductor switch in series with the capacitor of the dc link is proposed. This solution limits the fast rising of the discharge current of the capacitors, but affects the voltage of the dc grid and cannot avoid the conduction of the antiparallel diodes of the converters. The authors in [9] suggest the use of a ring-type LVDC distribution system protected with SSCB installed at the terminal point of each line. Despite this solution limits the faulty current in a fast way, the use of IGBT in the circuit breaker increases energy losses.

For this reason, the authors in [10] proposed a novel structure of hybrid circuit breaker (HCB) able to trip the circuit during normal operation and during fault condition to avoid overcurrent and overvoltage on the breaker and DC grid's components. The proposed structure can also open during a short-circuit using its internal inductances to partially limit the increase of the current. Nevertheless, the use of HCBs can increase the final cost of the installation, and for this reason, in some cases, it's preferable to resort to mechanical circuit breaker (MCB). However, these breakers have a slow transition time due to the need to blow the arc in extinguishing chamber and the lifetime is reduced in case of high-current interruptions. This puts in evidence that the HCBs and MCBs in a DC microgrid must be coordinated in order to protect the system and to reduce the maintenance for the mechanical breaker. In this situation, it is essential to develop a well-designed protection scheme.

This paper deals with the analysis of the protection scheme for a low voltage DC microgrid, in presence of several renewable generators, energy storage systems, loads and VSCs that interface the AC grid. The paper proposes an effective centralized protection coordination which can overcome issues of fast fault clearing time, cost effectiveness and selectivity. The proposed method coordinates among MCB and HCB protection devices. Moreover, the analysis is performed resorting to a DC microgrid benchmark and considering the pole-to-pole fault.

This paper is organized as follows: Section II introduces the defined LVDC microgrid benchmark. Section III addresses the effect of a short-circuit incident in the LVDC microgrid to individuate the location of the HCB protection devices. In Section IV the effectiveness of the proposed HCBs' installation is verified through

978-1-7281-1356-2/19/$31.00 ©2019 IEEE

simulation. In Section V a centralized protection coordination is defined and finally verified resorting to a simulation's model. Finally, conclusions are given in Section VI.

II. LVDC Microgrid Benchmark

The paper aims to propose a centralized protection coordination which can overcome issues of fast fault clearing time, cost effectiveness and selectivity in the case of pole-to-pole fault. To analyze the possible protection scheme for a LVDC grid, a DC microgrid benchmark is built starting from an AC microgrid benchmark [11] opportunely modified to consider a voltage level of 380 V and a unipolar distribution. The DC microgrid operates ungrounded while the neutral point of the ac grid is grounded on the MV/LV transformer. The schematic of the LVDC microgrid benchmark is shown in Fig. 1.

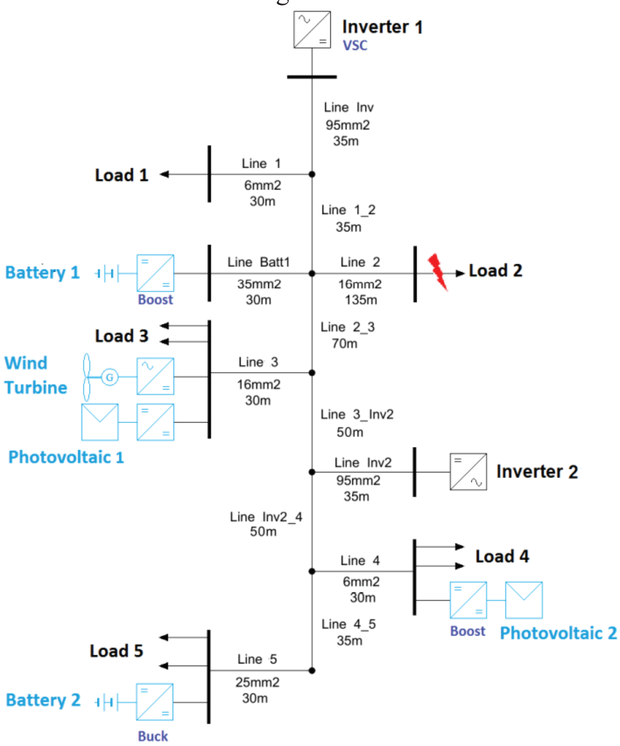

Fig. 1. Schematic of the LVDC microgrid benchmark

For the analysis proposed in this paper, the pole-to-ground fault is not taken into account. The behavior of the system during this type of fault is strongly influenced by the grounding configuration of the LVDC and the connected AC grid. In general, the DC grounding options can be classified in four types, which are the ungrounded system, the low-resistance grounded system, the high-resistance grounded system and the solidly grounded system. Compared with other grounding methods, the ungrounded dc system has a better continuity of power supply, lower ground leakage current, simpler implementation and lower installation cost. However, in case of hybrid AC-DC network in which the neutral point of the AC grid is grounded (on the MV/LV transformer), the occurrence of a pole-to-ground fault on the DC side caused a zero-sequence current provided by the AC grid and protection coordination must be obtained resorting a decentralized protection scheme [12].

The sections of the lines are calculated on the basis of the lines' power flows to maintain the voltage drop lower the ± 5%. The lines' parameters are indicated in TABLE I.

TABLE I
LVDC Benchmark Lines' Parameters

Line	*r* [Ω/km]	*x* [Ω/km]	*Length* [m]	*Section* [mm^2]
Line Inv	0.1874	0.0975	35	95
Line 1	2.8735	0.135	30	6
Line 1_2	0.1874	0.0975	35	95
Line 2	1.0776	0.112	135	16
Line Batt1	0.4926	0.101	30	35
Line 2_3	0.1874	0.0975	70	95
Line 3	1.0776	0.112	30	16
Line 3_Inv2	0.1874	0.0975	50	95
Line Inv2	0.1874	0.0975	35	95
Line Inv2_4	0.1874	0.0975	50	95
Line 4	2.8735	0.135	30	6
Line 4_5	0.1874	0.0975	35	95
Line 5	0.6896	0.106	30	25

III. Short-circuit occurrence in LDVC microgrid

To verify the behavior of the system in case of a short-circuit occurrence, simulations were carried out on the Matlab/Simulink model of the dc microgrid presented above. The simulation in this section are performed without protection devices integrated in the model. Furthermore, different typology of converters and sources are taken into account in order to verify the necessary protection devices.

In particular, the inverter1 is a VSC with a maximum current of 250 A, the load1 is a resistance of about 10 Ω, the battery1 is connected to the grid with a DC/DC boost converter with a input voltage of 300 V and with a maximum current of 250 A, the load2 is a resistance of 10 Ω, the photovoltaic2 has a maximum power of 3.3 kW and is connected to the grid with a DC/DC boost converter and, the battery2 is connected to the grid with a DC/DC buck converter with a input voltage of 450 V and with a maximum current of 250 A. The other components of the grid are not used during the simulations.

Simulations were carried out on the model of the dc microgrid presented above, resorting to simple battery and photovoltaic models, because it has no impact on the simulation results. The system is in a steady-state and at time t = 0.2 s a short-circuit with a resistance of 10 mΩ happens at the feeder of the load2.

During the fault, the voltage in each node of the microgrid falls down, as shown in Fig. 2. The voltage drop is different in each node due to the location of the fault and the typology of the source. Indeed, despite the battery1 is closer to the fault than the Inverter1, the voltage is higher for the battery1's node. As shown, in Fig. 3, the current provided by the battery1 is greater than the current of the Inverter1.

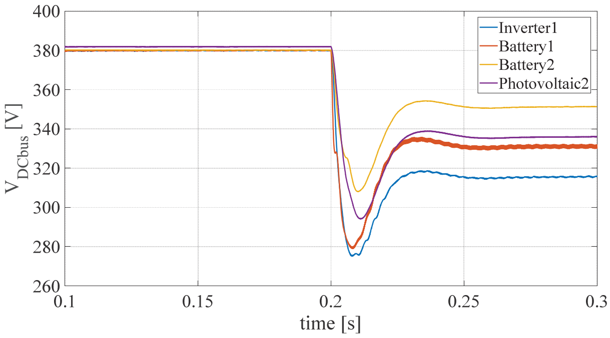

Fig. 2. Trend of the voltage during a short-circuit without protection device

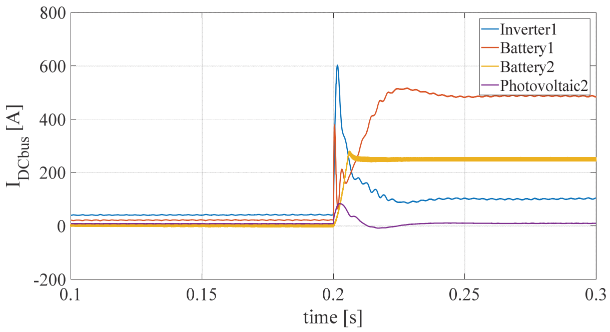

Fig. 3. Trend of the current during a short-circuit without protection device

Considering this scenario, during a fault in the DC microgrid, it occurs that the converter of the battery1 tries to reduce its duty cycle but it reaches the minimum value without any possibility to limit the current. In this condition, if the converter is turned off, the antiparallel diode of the output transistor is forward-biased and the battery1 is directly connected to the DC grid. The inverter1 presents an overcurrent due to the conduction of the antiparallel diodes. When the DC grid's voltage goes down, these components are forwarded bias and the control of the converter is not able to limit the current. The photovoltaic's converter shows an initial overcurrent due to the output capacitor discharge, but after that the current is limited because this source has a finite power. At the same time, the converter of the battery2 is able to limit the current because there aren't forward-biased diodes and so the control is able to modulate the current acting on the switching characteristic of the transistors.

From this analysis, it is clear that the sources with limited power, such as the PV plant, or connected through self-limited converters, such as the one used for the battery 2, do not need fast circuit breakers able to open a current that could be unlimited, while it is necessary to protect the other types of sources.

IV. Protection Device Location

Considering the analysis in the previous section, it is worth noting that the intrinsically non-limited sources must be equipped with HCB able to interrupt the circuit before components' damages, like the one shown in Fig. 4.

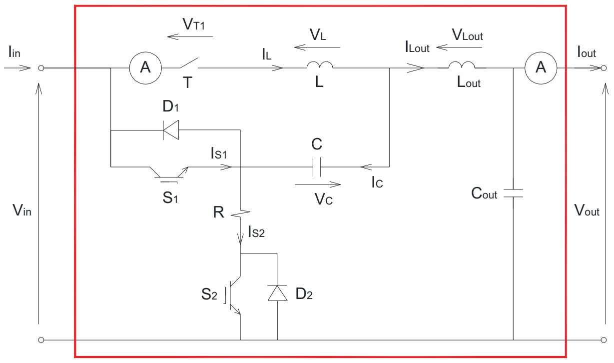

Fig. 4. Hybrid circuit breaker [10] used in the simulation

In this way, the current circulating during a fault is limited and all other feeders can be protected with a breaker able to open only the maximum current of the converters and the lines. These protection devices can be realized either with traditional breakers or with the hybrid circuit breaker sized to open only a limited current. Furthermore, the protection devices for the sources must be bidirectional or unidirectional depending on the type of the source. In any case, the ability to open in short-circuit must be guaranteed only in one direction. Instead, the breaker of the feeders must be able to open a short-circuit current in both directions. This is true for all the feeders on which at least one source or storage system is connected. These protection devices can be sized to open only the maximum current, and can be realized through two unidirectional HCBs connected in antiseries. The trip time of the feeder protections must be appropriately slower than the source protection systems to ensure that the opening occurs when the DC grid is no longer able to sustain a current higher than the nominal one. After the isolation of the faulty feeder, the sources can be reclosed on the DC grid.

To verify all these sentences, a simulation is done considering the use of hybrid circuit breaker, able to open in short-circuit, for the inverter1 and for the battery1 and the use of mechanical breakers, with a trip delay of 50 ms, installed on the faulty feeder. During the simulation, after a delay of 200 ms the sources connected through the HCBs are reclosed. It is worth noting that to achieve a reconnection without transients it is necessary that the converter regulators are reset after the trip of the breaker. Thus, the controller of the converters must be integrated with the protection. At the time instant t = 0.2 s a fault occurs, after 50 ms the faulty feeder opens and at the time t = 0.4 s the HCBs of the sources are reclosed.

Looking at the voltage graph, shown in Fig. 5, it is possible to observe an immediate voltage drop when the fault occurs. In the first milliseconds, this voltage drop is limited by the current provided by all the converters and remains quite contained. After a few milliseconds, the HCBs of the inverter1 and battery1 open causing a further rapid decrease of the voltage that remains sustained, over 100 V, by the battery2 and the photovoltaic panels.

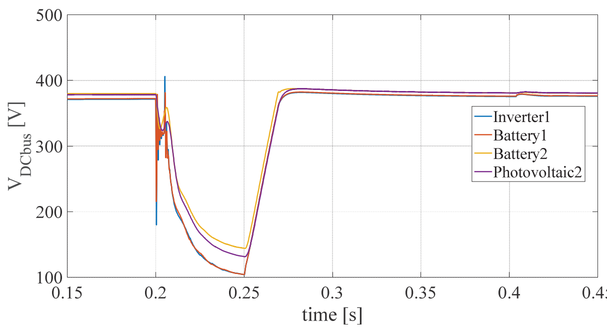

Fig. 5. Trend of the voltage during a short-circuit with protection device

The battery2 supplies its maximum current of 250 A, as shown in Fig. 6, while the photovoltaic plant supplies a current higher than the one delivered before the fault. Indeed, the PV plant works at its maximum power point and so when the voltage goes down the current increases until reaching the short-circuit current of the panel.

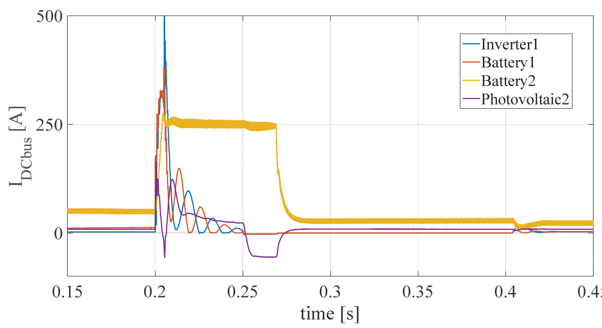

Fig. 6. Trend of the current during a short-circuit with protection device

After the HCBs trip off it is possible to observe an oscillation in the current, provided by the inverter1 and the battery1, due to the output capacitors. At the time instant t = 0.25 s the fault is cleared by the opening of the breaker on the feeder where the load2 is connected. The DC voltage starts to increase due to the battery2 which continues to supply a constant current. The photovoltaic system absorbs current for a short time to recharge the output capacitor of its converter. Finally, a new steady-state condition, in which the battery2 supply the whole DC grid (in island operation), has been reached. When at the time t = 0.4 s the HCBs of the two disconnected sources are reclosed, a new voltage transient, due to their reconnection, takes place.

It should be noted that, when the fault occurs, there is a peak of current that reaches about 800 A, as shown in Fig. 7. This high value is due to the sum of all the sources connected to the system that temporarily support the fault. However, after the HCBs trip off, the current naturally drops to about 250 A, value that is the current supplied by the limited sources. The feeder protection must be able to open this current.

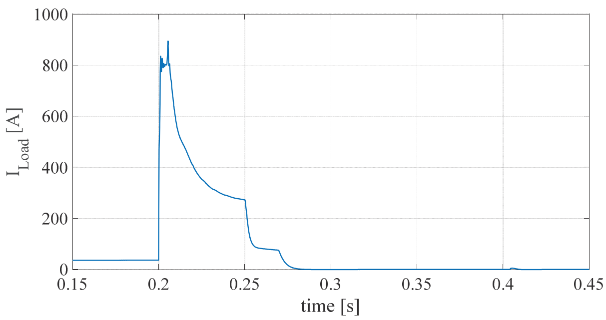

Fig. 7. Trend of the current in the load's feeder during a short-circuit

It is worth to note that if there are many limited sources in the grid, which are therefore not disconnected by the protections, the current that the faulty feeder breaker has to interrupt can reach very high values. For this reason, it is necessary to take into account this aspect when the network is sized, or defined a protection scheme able to reduce this current before the trip of the faulty feeder. In the following section, this problems will be analyzed.

V. Centralized Protection Scheme

In this section, a centralized protection scheme is proposed and verified resorting to simulation environment. As explained above, the breaker of the faulty feeder must be designed in order to interrupt high current in case of a high number of limited sources. This can cause the necessity of using a HCB, able to open a short-circuit current, also for the feeders, increasing the installation cost of the DC microgrid. To solve this problem, it is however possible to define a protection scheme able to reduce the current in the faulty feeder to a lower value before the breakers' trip.

The centralized controller is the easiest way to guarantee the coordination of the protections. However, communication delays must be taken into account. For this reason and to avoid issues related to communication system errors, basic functionalities must be implemented locally. For sake of simplicity, in this paragraph it is assumed that there are no communication problems. In any case, it is appropriate that the HCB protections of the non-limited components trip immediately, disconnecting the source without waiting the centralized controller. Obviously, the breaker must communicate to the controller both the identification of the short-circuit current and the tripping condition. Indeed, the controller uses a series of input parameters which are the short-circuit identification, the circuit breaker trip both for the line and for the non-limited sources and the values of the currents measured in the DC microgrid. The controller is realized using a state-flow approach. Based on its status, the centralized controller performs different operations as described below:

- *State 0:* during this state the DC microgrid works correctly and the controller is waiting the recognition of a short-circuit condition. This happens if a short-circuit identification is communicated by the breakers or if the controller identifies a faulty current. If the short-circuit condition is communicated by non-limited sources the controller sends a current limiting signal to the limited sources and goes to state 1. If the fault is identified by the same controller, in addition to sending the limitation signal to the limited sources, the controller sends the opening command to the non-limited sources before the transition to the state 1. It is clear that, if the fault occurs far from the non-limited sources, the controller must command the opening of HCBs before the current of those sources reaches the automatic trip threshold.

- *State 1:* the controller, starting from the short-circuit signals, identifies the faulty feeder. Based on the current that the faulty line breaker is able to open, it may decide to keep one or more intrinsically limited sources active, completely or partially. This functionality is to be considered useful only in the case where a residual voltage for the direct current microgrid may be necessary for emergency operations. In this paper, it can be assumed that during the opening operation the network can be completely disconnected so that, after identifying the place of the fault, the controller communicates to all the sources to disconnect (or in any case to bring its references to a minimum), and then waits. The controller exits this state and enters the state 2 when it has received from the non-limited sources the trip condition and from the limited ones the achievement of the reference current.
- *State 2*: as soon as the controller enters this state, it sends the trip signal to the breaker of the faulty feeder and keeps wait until this breaker confirm the opening of the faulty feeder. When this signal is received, before returning to state 0, the controller sends a reset signal to reconnect all the sources. If automatic reclosure are integrated in the scheme, the controller resets the fault indication and sends a closing command to the breaker of the faulty feeder. After a defined number of reclosures the controller definitively disconnects the faulty feeder and reports the need of maintenance.

To verify the effectiveness of the proposed centralized controller scheme, some simulations in Matlab/Simulink are performed. During the simulations it is imposed a cycle time for the controller of about 100 µs and a latency in communication equal to 10 ms in both the directions. Finally, the controller tries three consecutive reclosures that take place after a delay of 50 ms from the sources reconnection.

In the simulation included in this paper, at the time instance t = 0.2 s a fault occurs and it is extinguished at the time t = 0.3 s. Looking at the voltage graph, shown in Fig. 8, it is possible to observe an immediate voltage drop when the fault occurs. In the first milliseconds, this voltage drop is limited by the current provided by all the converters, as shown in Fig. 9, and remains quite contained.

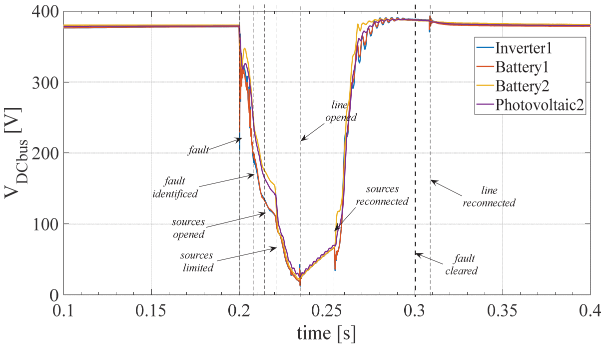

Fig. 8. Trend of the voltage during a short-circuit with centralized protection scheme

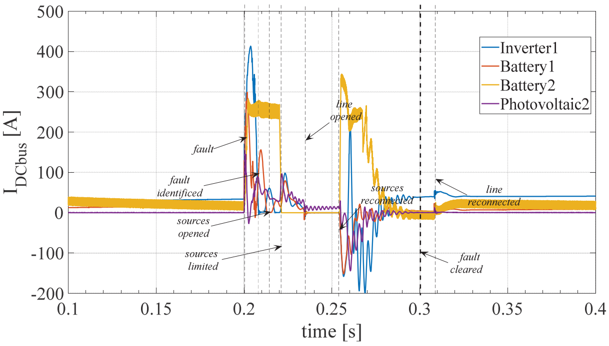

Fig. 9. Trend of the current during a short-circuit with centralized protection scheme

When the current of the converter of the battery1 and the inverter1 reaches the current's threshold, the HCBs of both the components open. This happens after the fault recognition by the centralized controller, but before it is able to signal it to the breakers. This is due to the communication latency that requires 10 ms. After the fault identification, the trip of the HCBs of the inverter1 and battery1 causes a further rapid decrease in the voltage, that remains sustained only by the battery2 and the photovoltaic panels.

The controller reaches the state 1 and, after the identification of the faulty feeder, sends a limitation command to the battery2 and photovoltaic2 converters. When both these converters have limited their currents, the voltage goes down because the grid is no more supplied. After receiving the communication of shut-down by the limited sources, the controller exits this state and enters the state 2. As soon as the controller enters this state, it sends the trip signal to the breaker of the faulty feeder and waits the answer from it. After the recognition of this new state for the breaker, the controller sends a reset signal to the converters of the sources, that will be reconnected after a delay of 10 ms. The DC microgrid is thus re-energized reaching the initial voltage condition. After a delay of 50 ms, the faulty feeder will be reconnected. In this situation if the fault is not cleared, the process described previously is replicated until is reached the maximum number of tolerated reclosures. However, the controller returns to the state 0 and waits the possible recognition of a new short-circuit condition.

VI. Conclusion

This paper presents a centralized protection scheme for a DC microgrid in case of pole-to-pole fault. Starting from a DC microgrid benchmark in which different typologies of converters and sources are taken into account, some simulations are performed resorting to a Matlab/Simulink model. It has been verified that protection devices able to interrupt a short-circuit occurrence must be used to protect sources, non-limited in power, and connected to the grid by means of VSCs and boost converters. For these converters, indeed, the DC voltage drop, can cause that the antiparallel diodes are forward biased and the source continues to supply the fault also after turning off the converter. Once these converters are protected, the current during a pole-to-pole fault is limited to a value that depends upon the sources connected to the grid. In this situation, it is possible to use mechanical breaker to protect the feeders and the other sources. However, these breakers have a slow transition time due to the need to blow the arc in extinguishing chamber and the lifetime is reduced in case of high-current interruptions. The proposed centralized protection coordination overcomes issues of fast fault clearing time, cost effectiveness and selectivity in the case of pole-to-pole fault. Resorting to a centralized controller, it is possible to identify the faulty feeder and to reduce the current flowing through the protection device before its trip. This solution, as demonstrated by the simulation results, permits the selectivity in case of short-circuit occurrence, coordinating the MCBs and HCBs protection devices.

References

[1] A. Agustoni. E. Borioli. M. Brenna. G. Simioli. E. Tironi and G. Ubezio. "LV DC distribution network with distributed energy resources: Analysis of possible structures." *Electricity Distribution. 2005. CIRED 2005. 18th International Conference and Exhibition on*. Turin. Italy. 2005. pp. 1-5.

[2] D. Ronchegalli and R. Lazzari, "Development of the control strategy for a direct current microgrid: A case study," *2016 AEIT International Annual Conference (AEIT)*, Capri, 2016, pp. 1-6.

[3] J.J. Justo. F. Mwasilu. J. Lee. J.Jung. "AC-microgrids versus DC-microgrids with distributed energy resources: A review. Renewable and Sustainable Energy Reviews". Volume 24. August 2013. Pages 387-405

[4] L. Pellegrino. R. Lazzari and F. Almasio. "Energetic and economical analysis for a LVDC residential district." *2018 AEIT International Annual Conference*. Bari. Italy. 2018. pp. 1-6.

[5] T. Dragicevic. J. C. Vasquez. J. M. Guerrero and D. Skrlec. "Advanced LVDC Electrical Power Architectures and Microgrids: A step toward a new generation of power distribution networks.." in *IEEE Electrification Magazine*. vol. 2. no. 1. pp. 54-65. March 2014.

[6] R. M. Cuzner and G. Venkataramanan. "The status of DC micro-grid protection." in Industry Applications Society Annual Meeting. 2008. IAS'08. IEEE. pp. 1–8. IEEE. 2008.

[7] A. A. S. Emhemed and G. M. Burt. "An Advanced Protection Scheme for Enabling an LVDC Last Mile Distribution Network." in IEEE Transactions on Smart Grid. vol. 5. no. 5. pp. 2602-2609. Sept. 2014. S. Papathanassiou. N. Hatziargyriou e K. Strunz. «A benchmark for low voltage microgrid network.» in *CIGRE Symposium on Power Systems with Dispersed Generation*. Athens. 2005.

[8] C. Peng, A. Q. Huang, A protection scheme against DC faults VSC based DC systems with bus capacitors, in: 29th Annual Applied Power Electronics Conference and Exposition, 2014, pp. 3423–3428.

[9] G. Patil, M. F. A. R. Satarkar, Autonomous Protection of Low Voltage DC Microgrid, in: International Conference on Power, Automation and Communication, 2014, pp. 23–26.

[10] L. Piegari. R. Lazzari. "Design and Implementation of LVDC Hybrid Circuit Breaker". in IEEE Transactions on Power Electronics

[11] S. Papathanassiou, N. Hatziargyriou e K. Strunz, «A benchmark for low voltage microgrid network,» in CIGRE Symposium on Power Systems with Dispersed Generation, Athens, 2005.

[12] R. Lazzari, L. Piegari, S. Grillo, M. Carminati, E. Ragaini, C. Bossi, E. Tironi, "Selectivity and security of DC microgrid under line-to-ground fault," Electric Power Systems Research, Volume 165, 2018, Pages 238-249.