ESTIMATION OF SHORT CIRCUIT CURRENTS IN FUTURE LVDC MICROGRIDS

Ali Virdag
Hager Group
Blieskastel, Germany
ali.virdag@hager.de

Torsten Hager
Hager Group
Blieskastel, Germany
torsten.hager@hager.com

Prof. Rik. W. De Doncker
RWTH Aachen, Forschungscampus
Flexible Electrical Networks, Germany
dedoncker@fenaachen.de

ABSTRACT

In order to have a viable design of LVDC protection devices like circuit breakers and fuses, it is important to design them for the correct short circuit ratings keeping the network configuration in account. In this paper, fault characteristics for different future LVDC network configurations are simulated (PLECS[1]) to analyze the maximum short-circuit current rating of the network. DAB (Dual Active Bridge) topology for DC-DC converter is considered for the connection of renewable energy sources and MVDC link to the LVDC grid. Results show that due to the current limiting characteristics of DC-DC converter, there is a potential of decreasing the maximum SC rating of the protection devices in LVDC microgrids compared to LVAC grids (10kA)[2].

Keywords: *Short-circuit in LVDC microgrids, LVDC fault, maximum short-circuit current, design of protection devices*

INTRODUCTION

Ever since the advancements in the semiconductor technology have gained momentum, evolvement of LVDC grids is gaining significant importance. This helps in reducing the overall losses making LVDC a preferable choice over its AC counterpart. The LVDC microgrid which most often is developed through connection of DC sources including photovoltaic (PV) and energy-storage system (ESS), connection to MVAC grid and connecting DC and AC loads, has been the state- of-the-art concept for residential and commercial buildings due to its stability and flexibility [8]. One such LVDC system considering PV and ESS has been simulated in [1].

The maximum amplitude of short-circuit current in LVDC network is comparatively higher compared to LVAC networks due to DC bus capacitors at the output of power converters. The PV and ESS contribute to the SC current in case of fault on the DC bus. On the other hand, the converters in the DC networks have the capability to limit the short circuit current that can avoid large SC current in DC systems. It is therefore important to study and analyze the behavior of LVDC network under fault conditions. Different short-circuit fault analysis and protection schemes in LVDC networks have been discussed in the literature [2].

In order to design an effective protection scheme, a careful assessment of the short-circuit currents is needed. According to IEC 61660-1 [3], the most widely used standard for DC short-circuits characterization, the source of DC short-circuit current can be from rectifier, battery, bus-capacitor and DC motor with independent excitation. The characterization of DC short circuit currents from these sources using IEC 61660-1 has been discussed in the literature [4,7]. The effectiveness of this standard in determining the SC currents in practical scenarios is discussed in [5]. SC calculations for photovoltaic source, which has a significant share in the overall SC current in modern LVDC grids, are however not precisely considered in the research up till now and need to be done for the future standardization of DC SC currents.

LVDC NETWORK CONFIGURATIONS

Network configurations of LVDC networks that are considered in this study are shown in Fig. 1. Three different topologies are considered taking into account three different configurations of connecting MVAC/MVDC grids to LVDC grids. SC current capacity changes accordingly based on the network components involved. Converter control inside the DC-DC converter that maintains the voltage to the rated value is employed; however the semiconductor devices are not turned-off during the SC and inherent behavior of the DC-DC converter is used to find the maximum SC current.

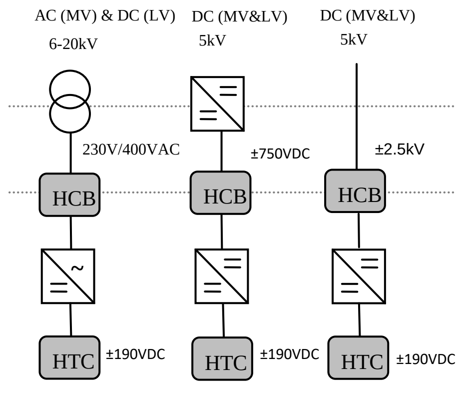

Fig. 1: Different network configurations of LVDC micro-grids (HCB: House Connection Box, HTC: Hager Technical Center used as electricity meter at house

1 PLECS is a simulation platform for power electronic systems. PLECS Blockset simulations use Matlab/Simulink solvers; whereas PLECS Standalone uses its own independent solvers

2 This publication evolved from work in the Forschungscampus Flexible Electrical Networks, Aachen, Germany

entrance)

Case: 1 Conventionally MV is stepped-down in AC and distributed among the end user customers in LVAC. The DC loads along with the renewable energy sources are connected to the common DC-bus fed using a rectifier. This approach requires minimum changes in the existing LVAC architecture. The short-circuit current flow from the MV network depends on the short-circuit capacity of the MV link and transformer.

Case: 2 For future DC grids, the concept of MVDC transmission (5kV) is the state-of-the-art of the concept. An intermediate LVDC level (±750VDC) is chosen for the transmission of power before the consumer premises. Using this intermediate voltage reduces the voltage level between MV network and HCB (consumer's step down point). The topology is considered keeping in view the connection of high power loads which are otherwise not suitable to be connected with 380VDC bus.

Case: 3 A more simplified case directly steps down the MVDC to LVDC 380V (±190VDC) at HCB. The topology reduces the losses by having an increased voltage level of 5kV compared to case 2 where 1.5kV was the voltage level just before the consumer premises.

LVDC MICROGRID WITH ENERGY SOURCES AND LOADS

The energy sources that are considered in this study are photovoltaic (PV), energy storage system (ESS) and connection with the MVAC/MVDC network.

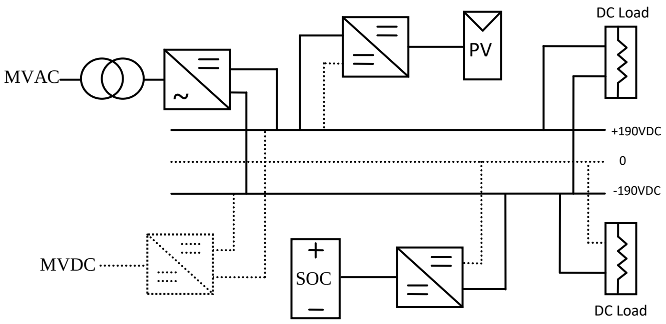

Fig. 2: LVDC network with energy sources and DC loads

Connection to MV Grid

Connection of LVDC microgrid to a MV network can be either AC or DC. With MVAC, during fault in LVDC grid, SC current from the MV grid will only be limited by the saturation of the transformer. Diodes inside the rectifier are uncontrolled and cannot limit the SC current. The used parameters of the transformer and rectifier are summarized in Table 1.

Setting up a MVDC grid (5kV) would require DC-DC converter instead of transformer for step-down of voltage. Dual Active Bridge (DAB) [6] is state-of-the-art topology for MV-LV and LV-LV [11-12] applications of DC-DC converters. SC current that flows from MV to LV grid during the fault in LVDC grid will no more depend on the saturation of the transformer but on the SC characteristics of DC-DC converter. The ability of DC-DC converters to limit the fault current using control operation gives a significant advantage of reducing the short-circuit current in MVDC-LVDC network configurations.

In this study DAB configuration is considered as the DC-DC converter topology. Case 2 utilizes two DC-DC converters that transform DC voltage first from 5kV to 1.5kV as the intermediate voltage level and then to 380V. Case 3 utilizes one converter in the downstream line from MV via HCB to the HTC (end-user). Table 1 summarizes the converter parameters used in both cases. Leakage inductance and DC-bus capacitance are important parameters that define the steady-state SC current and the duration of the peak current respectively3.

Case 1: AC (MV-20kV) and DC (LV-380V)	
Power conversion	Transformer and Rectifier
Rectifier	6-pulse 3φ diode rectifier
Windings ratio	$\sqrt{3}.V_{rms-pri}/V_{rms-sec}$
Case 2: DC MV and LV (5kV-1.5kV and 380V)	
Power conversion	2xDC-DC converters
Converter 1&2	Dual Active Bridge(3φ-1φ)
Rated power (P_1, P_2)	100kW/10kW
Switching freq. (f_s)	20kHz
Leakage inductances of converters (L_{s1}, L_{s2})	5.7µH
DC bus capacitances of converters (C_{dc1}, C_{dc2})	692µF
Case 3: DC MV and LV (5kV and 380V)	
Power conversion	DC-DC converter
Converter	Dual Active Bridge(3φ)
Rated power	100kW
Switching freq. (f_s)	20kHz
Leakage inductance of converter (L_s)	31µH
DC bus capacitance of converter (C_{dc})	34µF

Table 1: Connection of LVDC grid to MV grid in different cases

Photovoltaic (PV)

Conventional buck/boost converters have the drawback of high losses due to unfavorable duty cycle in high step-up applications and hard switching operation of the switches [11]. On the other hand, the bidirectional power flow of DAB converters, soft switching and high frequency galvanic isolation make DAB an efficient topology for DC-DC converters in PV applications. Using the phase-shift modulation technique, soft

3 Design of these parameters for DAB converter with respect to the SC current is planned to be discussed in future publication in the PEDG Conference 2017 (International Symposium on Power Electronics for Distributed Generation Systems)

switching of the switches can be realized reducing the losses and allows wide range input and output voltage operation [10].

A PV model from PLECS [9] is used in this study with 5kW rated power, 760V/380V input and output voltage and 20 kHz as the switching frequency is used. The SC rating of PV in case of fault on the LVDC bus depends on the power rating of PV panel and power transfer capability of the attached converter.

Energy Storage System (ESS)

Bi-directional power transfer is an inherent characteristic of DAB converters (using transformer leakage inductance) that allows flexible power transfer between DC grid and energy storage systems [12]. Using variable frequency and variable duty cycle during the operation, maximum and minimum battery voltages can be compensated to ensure constant power output [17]. A Li-ion battery model [13] is used for the study with 3kW rated power and 160V/380V as the input and output voltage of the converter.

DC Fault Resistance

Different grounding models have been used in the literature depending on the nature of the fault. In [14], high, medium and low impedance faults are considered with ground impedance ranging from 1mΩ-100Ω. Low fault resistance of 50mΩ for AC and DC fault in LVDC systems has been used in [16]. In order to design the protective equipment, low impedance fault of 10mΩ is considered in this study assuming the converter impedance and cable length of 100m (241.9mm^2) [15].

FAULT CHARACTERISTICS OF DC MICROGRID DURING BIPOLAR SHORT-CIRCUIT FAULT

DC microgrid is a fast transient system with large number of voltage source converters that connect energy sources to AC and DC loads. During normal operation, power balance is controlled and DC voltage remains largely constant. However, during the fault conditions DC voltage suddenly drops to a very low value governed by the fault resistance and high fault current flows in the system. Fig. 3 shows the direction of current flow before and during the fault condition.

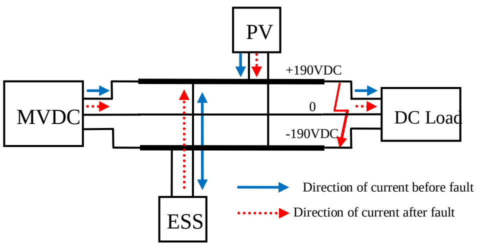

Fig. 3: Power flow in LVDC network before and after the fault

Case 1: In case of SC on the DC bus in mixed AC-DC system, the SC power of the system will depend upon the SC capability of all the power sources, fault resistance and load characteristics. In this case, steady state SC current will be provided by MVAC link, PV and ESS (eq. 2). MVAC link defines the peak short circuit current which depends on the fault resistance and DC link voltage of LVDC bus before the fault (eq. 1).

$$I_{sc-peak} = V_{out}/R_{fault} \qquad (1)$$

$$I_{sc-ss} = I_{sc-MVAC} + I_{sc-PV} + I_{sc-ESS} \qquad (2)$$

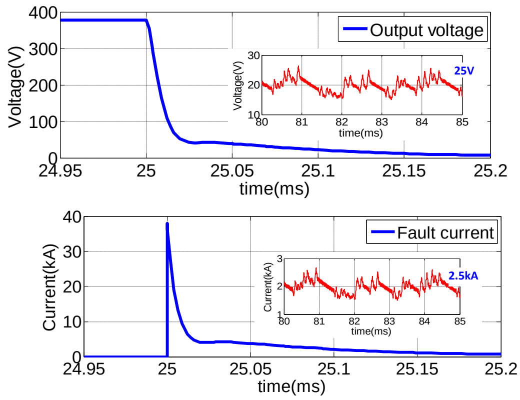

Fig. 4: Output voltage and fault current before and after the fault – Case 1 [MVAC (20kV) – LVDC (380V)] – Fault at 25ms

Fig. 5 shows the contributions of individual SC currents from different sources. The fact that many PV strings are connected in parallel, the overall SC rating is the combined rating of all the strings (SC current of one string is 120-130% the rated current). Filter capacitors in the AC-DC converter between MVAC and LVDC link produce high transient peak current during SC.

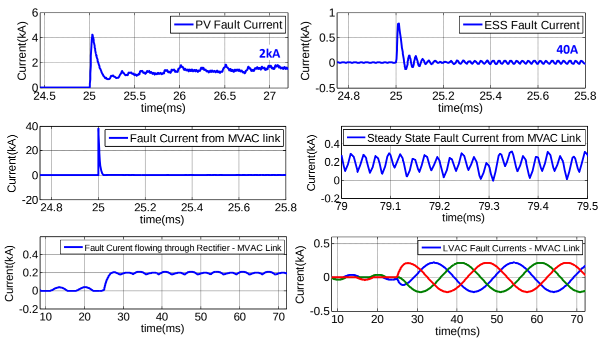

Fig. 5: SC behavior of different energy sources – Case 1

Case 2: Using an intermediate voltage level (±750VDC), introduces two DC-DC converters between MVDC and LVDC link. The MVDC side converter (5kV-1.5kV) used in the analysis has a power rating of 100kW that feeds a group of LVDC networks. The LVDC converter (1.5kV-380V) has a power rating of 10kW. Fig. 6 shows that the current peak is considerably reduced in this case compared to the previous case when fault is introduced at t=50ms. The two DAB DC-DC converters in series allow limiting the peak SC value (~10times).

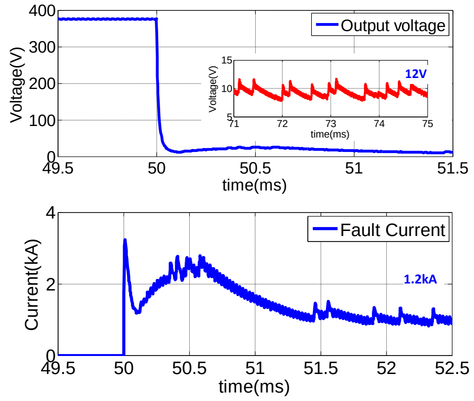

Fig. 6: Output voltage and fault current before and after the fault – Case 2 [MVDC (5kV) – LVDC (1.5kV)]

Fig. 7 shows the current contribution from different energy sources. It is important to observe the SC behaviour of MVDC link in this case where two DC-DC converters are connected in series. The series connection of high and low power converter not only allows reducing the current peak in the SC current but also the steady-state SC current contribution from MVDC link.

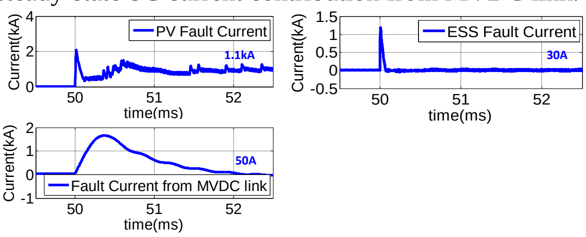

Fig. 7: SC behavior of different energy sources - Case 2

Case 3: The direct conversion of MVDC (5kV) to LVDC (380V) allows having one DC-DC converter that reduces the complexity of the system. The peak SC current is governed by the fault resistance and the value is same as in the first case.

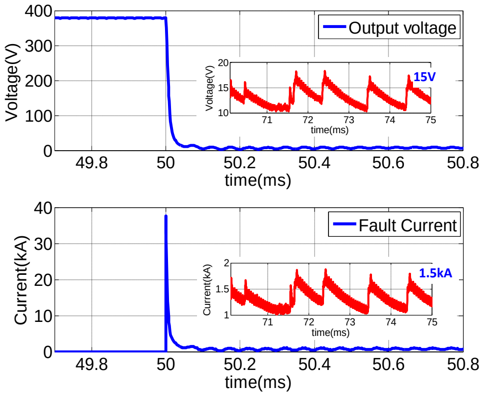

Fig. 8: Output voltage and fault current before and after the fault – Case 3 [MVDC (5kV) – LVDC (380V)]

In comparison to case 1, the individual contributions get more balanced PV and MVDC link with PV still the main contributing source in the steady-state SC current. The SC current from the battery remains same in all the three cases and in the range 30-40A.

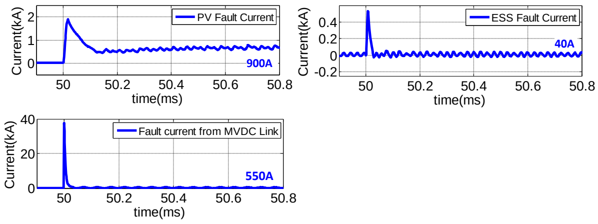

Fig. 9: SC behavior of different energy sources - Case 3

DISCUSSION ON RESULTS

The three considered network configurations have different SC characteristics and different individual SC current contributions from the energy sources. Fig. 10 shows the comparison in this regard which shows the photovoltaic as the major current contributor during the SC. As discussed before, the high number of strings in parallel in case of PV increases the overall SC capability of the PV unit. The high SC current from PV in the case-1 is due to comparatively high fault voltage which is otherwise low (in case-2 and 3) where DAB DC-DC converters are connected to the grid. Low fault voltage decreases the SC current of the network.

SC current from MV link is essentially constant (400-500A) in case 1 and 3 where rectifier and single DC-DC converter are utilized. However, in case 2, where back to back converter configuration is used, fault current from MV link is considerably reduced. This is because the voltage source of LVDC side converter is not a constant voltage source but based on the capacitive bus of the MVDC side converter DC output voltage. Also low power rating of the LVDC side converter limits the SC current flow to the LVDC grid from MVDC grid during fault.

The energy storage system which is considered of 3kW in this paper, contributes according to its capacity among 10kW PV and 100kW power transfer capability from MV link. The ESS SC current remains same as before the fault and in the range of 30-40A.

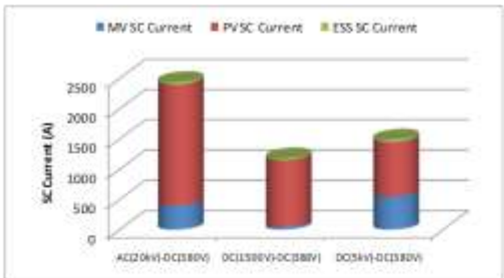

Fig. 10: Steady-state SC current contribution from energy sources in different scenarios

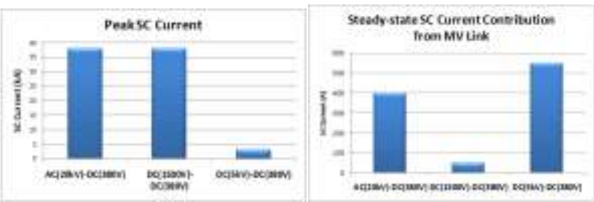

Fig. 11: Peak SC currents and steady-state SC current from MV link in different scenarios

CONCLUSION

SC current is simulated for different LVDC grid scenarios. Apart from the energy sources, the grid components play an important role in defining the maximum SC current of the grid topology. The use of DAB topology as DC-DC converter effectively limits the SC current due to its inherent SC protection feature. In all the three scenarios, SC current effectively remains less than 2.5kA which is quite less compared to standard SC current rating of 10kA in LVAC grids. In case 2 and 3, where connection to the MV grid is in the form of DC, SC current remains under 1.5kA which gives an advantage of lower SC rating of the protection devices in case of MVDC link to the LVDC microgrid.

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