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Short-circuit Calculations in Hybrid AC/DC Microgrids

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Abstract – **In this paper, the issues related to short-circuit calculations in hybrid AC/DC microgrids are discussed. The reference standard for short-current calculations in DC systems is the IEC 61660, which provides a mathematical formulation of the problem. The standard only includes radial DC grids and does not consider a more complex system, such as meshed DC systems or a hybrid AC/DC microgrid. This paper proposes a generalized approach that can be used independently of the characteristics of the hybrid system. The proposed approach is applied to two test microgrids and the results are compared with those obtained simulating the same grids with Neplan 360.**

Index Terms—**AC/DC Microgrids, Short-circuit, Fault calculation, hybrid systems.**

I. INTRODUCTION

Over the past decade, the concepts of DC and hybrid AC/DC microgrids have become a popular topic among engineers, fueling the debate on the advantages and disadvantages of transforming an AC distribution system into a DC. This matter has been examined from different perspectives and by considering structural, design, and operational concerns.

As an example, in [1] and [2], the authors present a comprehensive review of power architectures, applications, and standardization issues, control strategies and stabilization techniques for DC microgrids. The voltage control issue is discussed in [3], where the authors propose an energy management strategy of active distribution systems with a grid-connected DC microgrid, as well as for an isolated DC microgrid with hybrid energy resources. In [4], a power architecture for residential buildings consisting in a multilevel DC microgrid is presented, together with a method for maximizing the energy efficiency of parallel DC/DC converters. In [5], a microgrid based on solar PV-battery energy storage with a multifunctional voltage source converter is presented. In [6], a new and more flexible architecture for hybrid AC/DC microgrids with a multi-port interconnected converter is proposed. Finally, in [7] and [8] a simulation analysis for assessing the reliability of AC/DC hybrid microgrids is performed on four test grids and some system's indicators are assessed.

In this context, the topic of calculating short-circuit currents in DC networks is of interest. The standard IEC 61660 [9] proposes a short-circuit current calculation methodology but, given the age of this document, the most recent developments in technology and, among other things, the simultaneous presence of AC and DC sources, are not considered.

With the aid of a power grid simulation software, some authors have tried to overcome the limitations of the standard and have proposed improvements based on simulation results. In [10], the authors develop an original package of programs used for the analysis and rating of DC protective devices in power systems. In [11], two different modeling approaches to evaluate DC-side short-circuit currents in DC distribution systems fed by rectifiers, are presented and validated by a time-domain simulation. Reference [12] presents an algebraic model to approximate the DC short-circuit current contribution of converters without DC fault ride-through capability. In [13], the authors analyze the limits in the application of the IEC 61660 standard to HVDC systems and, finally, in [14], an approach to extend the IEC 61660 standard to meshed systems is proposed.

In this context, this paper proposes a generalized approach that can be used for calculating AC/DC short-circuit currents in hybrid AC/DC microgrids, independently of the characteristics of the hybrid system. The methodology is based on the main equations of the IEC 61660 standard, employed for the calculation of equivalent resistances for a matrix formulation of the problem. To demonstrate the robustness of the proposed method, two test microgrids are examined and the results are compared with those obtained with the modelling software Neplan 360®.

II. METHODOLOGY

Fig. 1 shows a generic topology of a DC microgrid with N buses, loads, and sources. Each DC source can be a rectifier, a battery energy storage system (BESS), a capacitor, or a DC motor (Fig. 2). Other types of DC sources, such as fuel cells or photovoltaic systems, are not considered because the IEC 61660 standard does not provide any guidance for calculating the short-circuit current in the presence of such elements.

Rectifiers are located at the connection points between DC microgrids and AC grids, and their presence will be used to include the contribution of the main AC system into the calculation.

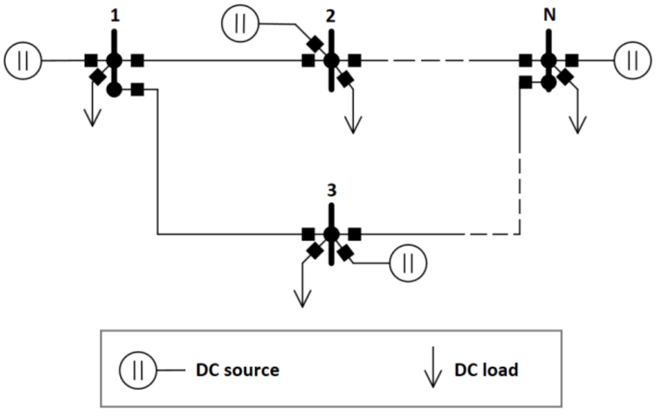

Fig. 1. Generic representation of a DC microgrid with N buses.

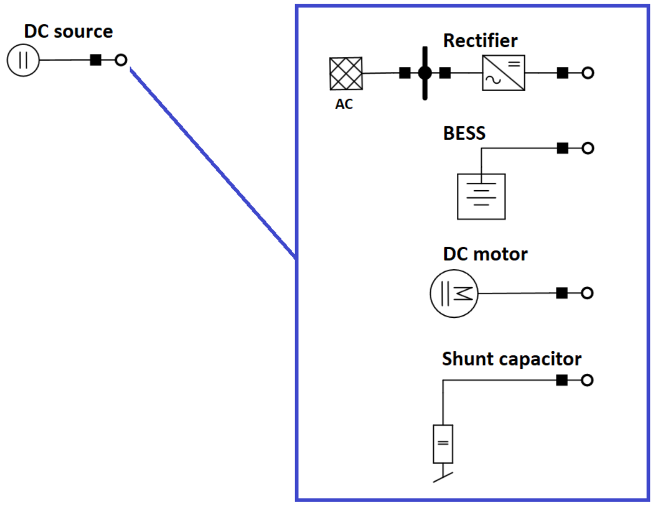

Fig. 2. DC sources considered in the study according to IEC 61660.

The steady-state short-circuit current calculation in a generic ith bus of the DC microgrid in Fig. 1 is performed by calculating the short-circuit conductance matrix $[G_{SC}]$ [14]-[15].

According to this method, the short-circuit current is found solving the matrix equation:

$$[I_F] = [G_{SC}][U_0] - [G_{SC}][U_F] \tag{1}$$

Where $[I_F]$ is a vector that has all null elements except the ith element, which is the fault current $I_{F,i}$ at the i-th node, $[U_0]$ is a vector whose elements are the voltages at the nodes of the DC microgrid, which are assumed to be equal to the rated voltage of the system, or to the pre-fault voltages obtained by means of the load flow analysis of the microgrid. Finally, $[U_F]$ is a vector whose elements are the voltages at the nodes of the DC microgrid during the fault. The ith element of $[U_F]$ is set to zero in the case of a bolted short-circuit fault (i.e., zero impedance), all other elements, including the fault current, are the unknowns of the system. Equation (1) represents, therefore, a system with N equations and N unknowns (1 current and N-1 bus voltages). The diagonal element G_{kk} of the conductance matrix $[G_{SC}]$ is obtained as the sum of all conductances of all elements connected to the kth bus. The extra-diagonal element G_{kh} of the matrix is the opposite of the sum of all conductances of all elements connecting buses k and h.

For calculating the contribution of a DC source to a generic G_{kk} element, the expressions reported in the standard IEC 61660 are used.

In the case of a BESS, the equivalent resistance of the source is given by:

$$R_{BB} = \frac{0.9 \cdot R_B + R_{BL}}{0.95 \cdot k_B} \tag{2}$$

where R_B is the short-circuit resistance of the battery provided by the manufacturer, R_{BL} is the resistance of the connection cable from the battery to the DC bus, k_B is a coefficient set to 1.05 for charged batteries and to 0.9 for low-charged batteries. The battery voltage before and during the fault is set to the rated voltage of the DC microgrid.

DC motor resistance is simply the resistance of the DC circuit from the output terminal of the motor and the DC bus.

In the case of a shunt capacitor with rated capacity C, the equivalent resistance of the source is given by:

$$R_{CB} = \frac{R_{CL}}{k_C} \tag{3}$$

where R_{CL} is the resistance of the connection cable from the capacitor to the DC bus and k_C is a coefficient given by IEC 61660 and dependent on the inductance L_{CL} of the same connection cable and on the frequency $\omega_o = 1/\sqrt{L_{CL}C}$. This resistance can be used for calculating the peak value of the short-circuit current but, for steady-state contribution, the resistance must be set to infinity.

Finally, in the case of rectifier, the equivalent resistance of the source must consider the contribution of the AC grid upstream of the converter. Using the expressions in IEC 61660, the following resistance can be obtained:

$$R_{CONV} = \frac{1}{c}\left(\sqrt{\frac{2}{3}} \cdot \pi \cdot \frac{Z_Q}{\lambda_d} + R_{loss} + R_{RL}\right) \tag{4}$$

where Z_Q is the module of the short-circuit impedance of the AC grid at the input terminals of the rectifier referred to the DC-side voltage, calculated, according to IEC 60909, by neglecting the presence of the rectifier as a possible element for creating a reclosing loop during the fault on the AC side; λ_d is a coefficient provided by IEC 61660, whose value depends on the rate between the real and imaginary part of Z_Q and the rate between the resistance of the DC circuit downstream of the converter and the resistance of the AC circuit upstream of the converter; R_{loss} is an additional resistance that takes into account the internal power losses of the converter; and R_{RL} is the resistance of the connecting cable from the rectifier to the DC bus. Finally, in (4) the coefficient *c* is the voltage factor defined by IEC 60909, which is herein introduced to simplify the calculations.

Based on the same principle, it is possible to propose a similar approach for taking into account the presence of PV generators in the calculations. In DC microgrids, PV plants are connected directly to the DC bus or by a DC/DC converter and in both cases their contribution to the short-circuit current is always known and provided by the PV module manufacturer.

Since a photovoltaic field is composed of strings of modules connected in parallel, the short-circuit contribution I_{SC} of a PV plant with N_S strings during a fault in the DC microgrid can be expressed as:

$$I_{SC} = N_S \cdot I_{SC,mod} \tag{5}$$

where $I_{SC,mod}$ is the short-circuit current of a single PV module provided by the manufacturer. With the aim of calculating the maximum short-circuit current in the DC network, it is possible to define an equivalent short-circuit resistance of the PV field in order to integrate also this source in the proposed methodology:

$$R_{FV} = \frac{U_{out}}{I_{SC}} + R_{FL} \tag{6}$$

where U_{out} is the voltage at the output voltage of the PV plant, assumed equal to the rated voltage of the DC system and R_{FL} is the resistance of the connection cable from the PV field to the DC bus.

Using the resistances above defined and the resistances of the DC cables connecting the buses of the DC microgrids, all elements of the matrix $[G_{SC}]$ are known for the specific microgrid and the short-circuit current and the voltages in all buses during the fault are obtained by solving equation (1) written in explicit form:

$$\begin{aligned} 0 &= \sum_{k=1}^{N} G_{hk}(U_{0k} - U_{Fk}) \qquad \forall h \neq i \\ I_{F,i} &= \sum_{\substack{k=1 \\ k\neq i}}^{N} G_{ik}(U_{0k} - U_{Fk}) + G_{ii}U_{0i} \end{aligned} \tag{7}$$

III. CASE STUDY

The proposed approach is applied to two test microgrids, which are parts of the hybrid MV/LV grid of Fig. 3 [7]-[8]: an underground station and a smart car parking microgrid. Two DC-side faults are considered at the main DC buses of the two microgrids N1 and N2.

The figure shows the state (open/close) of the AC lines since their state influences the value of the impedance Z_Q in equation (4). According to the proposed methodology, the initial symmetrical short-circuit powers defined by IEC 60909 at the rectifiers input terminals, necessary for the Z_Q evaluation, are reported in Fig. 3. The two short-circuit currents are calculated neglecting the contribution of the PV plants (since the IEC 61660 standard does not give any indication for considering such elements) and including, in the calculation of the fault current at node N2, the contribution of the batteries of electric vehicles connected to the grid. Capacitors and DC motors are not present in any bus of the hybrid grid.

The parameters for the calculation are reported in Tables I and II.

A. Underground station microgrid

From the data in Table I, the following quantities are calculated:

$$Z_Q = 0.0407\ \Omega;\ \ R_{CONV} = 0.101\ \Omega;\ \ R_{BB} = 0.206\ \Omega;\ \ R_{FV} = 41.32\ \Omega$$

The schematic representation of the DC microgrid of Fig. 4, which neglects the lines connecting loads, can be used. For the short-circuit current calculation in *N1*, the microgrid can be represented by a simple 4-bus network where *N1* is indicated as bus 2.

The matrix $[G_{SC}]$ in this case is:

$$[G_{SC}] = \begin{bmatrix} 9.88 & -9.88 & 0.00 & 0.00 \\ -9.88 & 14.75 & -4.85 & -0.02 \\ 0.00 & -4.85 & 4.85 & 0.00 \\ 0.00 & -0.02 & 0.00 & 0.02 \end{bmatrix}$$

Imposing that the voltage at buses 1, 3 and 4 during the fault are equal to the rated voltage of the microgrid (such hypothesis is realistic, since these voltages are those internal to the DC sources), the fault current obtained by (7) is 22.13 kA. The same current evaluated by Neplan is 21.77 kA. The difference is 1.6%.

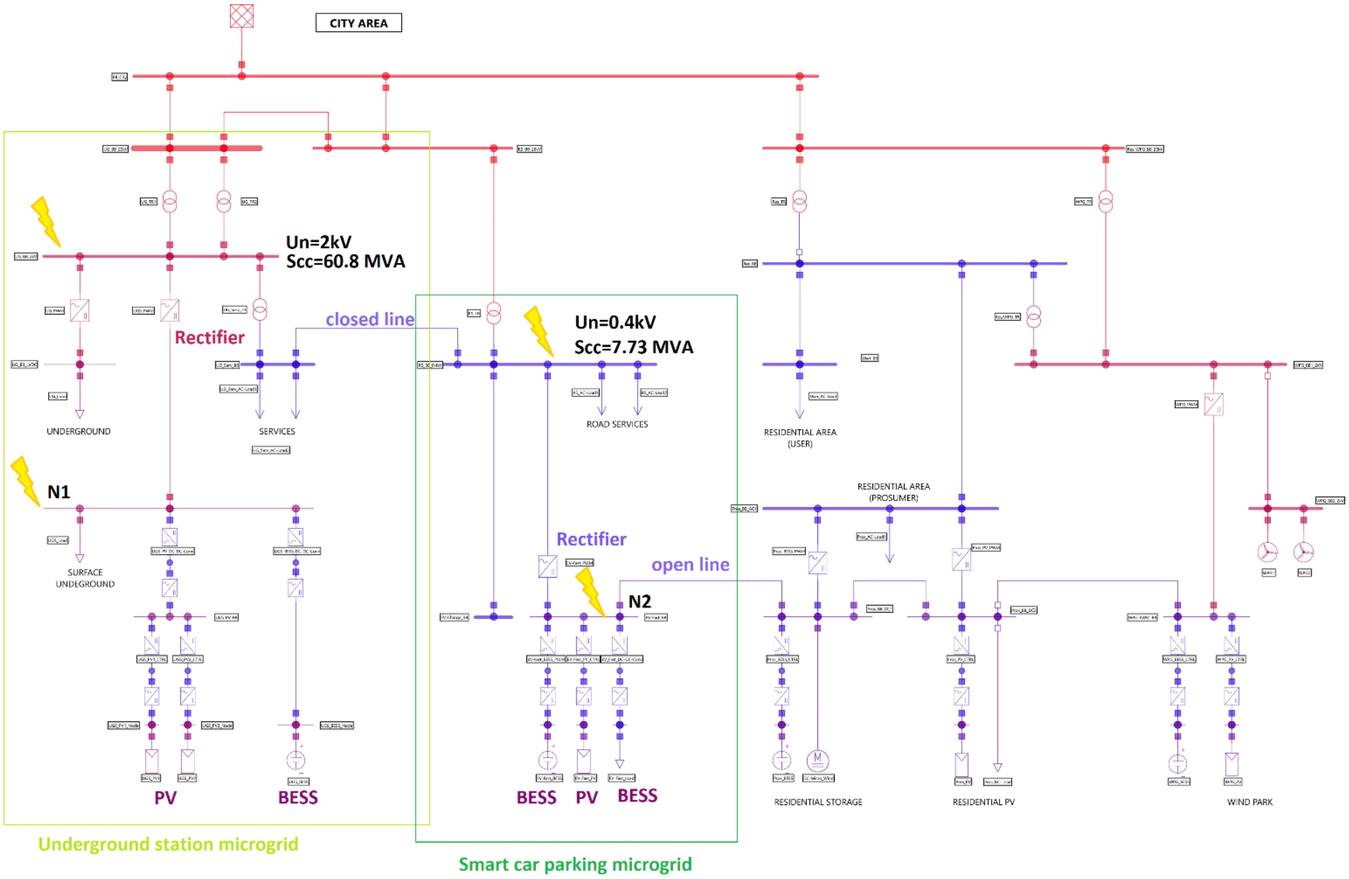

Fig. 3. City area MV/LV AC/DC microgrid.

TABLE I. UNDERGROUND STATION MICROGRID: PARAMETERS FOR THE CALCULATION OF THE SHORT-CIRCUIT CURRENT.

AC grid	Rated Voltage U_n=2 kV; Initial symmetrical short-circuit power at the input terminals of the rectifier S_{cc}=60.8 MVA
Rectifier	Output Voltage U_{out}=1.5 kV; Rated power S_r=800 kVA; Internal resistance R_{loss}=0.001 Ω DC connection cable lenght d=5 m; DC connection cable series resistance R_{RL}=0.0025 Ω
BESS	Output Voltage U_{out}=1.5 kV; Charged battery k_B=1.05; Rated power S_r=250 kVA; Short-circuit resistance of the battery R_B=0.2 Ω; DC connection cable length d=50 m; DC connection cable series resistance: R_{BL}=0.025 Ω
PV	Output Voltage U_{out}=1.5 kV; Number of modules N_m=44; Number of strings Ns=3; Rated power S_r=50 kW; DC connection cable length d=20 m; DC connection cable series resistance R_{BL}=0.011 Ω

TABLE II. SMART CAR PARKING MICROGRID: PARAMETERS FOR THE CALCULATION OF THE SHORT-CIRCUIT CURRENT.

AC grid	Rated Voltage U_n=0.4 kV; Initial symmetrical short-circuit power at the input terminals of the rectifier S_{cc}=7.73 MVA
Rectifier	Output Voltage U_{out}=0.6 kV; Rated power S_r=400 kVA; Internal resistance R_{loss}=0.01 Ω DC connection cable length d=5 m; DC connection cable series resistance R_{RL}=0.0025 Ω
BESS	Output Voltage U_{out}=0.6 kV; Charged battery k_B=1.05; Rated power S_r=40 kVA; Short-circuit resistance of the battery R_B=0.2 Ω; DC connection cable length d=20 m; DC connection cable series resistance R_{BL}=0.011 Ω
EV BESS	Output Voltage U_{out}=0.4 kV; Charged battery k_B=1.05; Rated power S_r=400 kVA; Short-circuit resistance of the battery $R_{B,ev}$=0.2 Ω; DC connection cable length d=20 m; DC connection cable series resistance $R_{BL,ev}$=0.0007 Ω
PV	Output Voltage U_{out}=1.5 kV; Number of modules N_m=44; Number of strings Ns=3; Rated power S_r=50 kW; DC connection cable length d=20 m; DC connection cable series resistance: R_{BL}=0.011 Ω

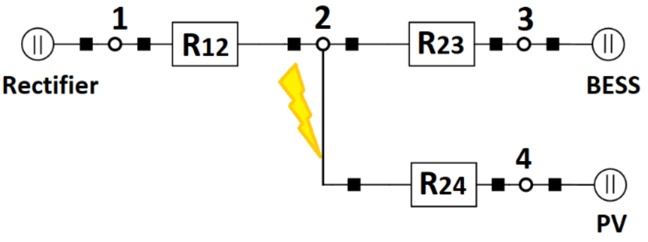

Fig. 4. Schematic representation of the Underground station microgrid.

B. *Smart car parking microgrid*

From the data in Table II, the following quantities are calculated:

$$Z_Q = 0.0489\ \Omega;\quad R_{CONV} = 0.135\ \Omega;\quad R_{BB} = 0.206\ \Omega;$$
$$R_{BB,ev} = 0.181\ \Omega;\ R_{FV} = 41.32\ \Omega$$

The schematic representation of the DC microgrid is reported in Fig. 5, where the lines connecting loads and PV systems have been neglected. For the short-circuit current calculation in *N2*, the microgrid can be represented as a 5-bus network where *N2* is indicated as bus 2.

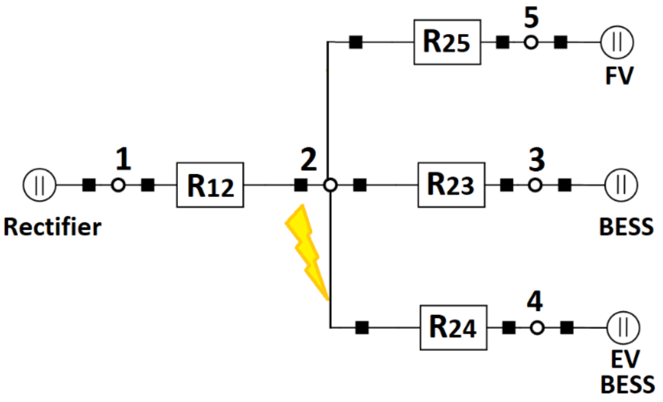

Fig. 5. Schematic representation of the Smart car parking microgrid.

The matrix $[G_{SC}]$ in this case is:

$$[G_{SC}] = \begin{bmatrix} 7.40 & -7.40 & 0 & 0 & 0 \\ -7.40 & 17.80 & -4.85 & -5.52 & -0.02 \\ 0 & -4.85 & 4.85 & 0 & 0 \\ 0 & -5.52 & 0 & 5.52 & 0 \\ 0 & -0.02 & 0 & 0 & 0.02 \end{bmatrix}$$

Imposing that the voltages at buses 1, 3, 4 and 5 during the fault are equal to the rated voltage of the microgrid, the fault current obtained by (5) is 10.68 kA. The same current evaluated by Neplan is 10.90 kA. The difference is 2%.

IV. CONCLUSION

The proposed methodological approach shows great accuracy and proves to be easy to apply in all cases where there is no specialized software for the calculation of short-circuit currents in hybrid DC microgrid. The matrix approach lends itself to an iterative implementation that is fairly simple to implement and easily automated. In addition, it allows to take into account in a simple way also the presence of PV generators connected to DC buses crossing the limits of IEC 61660 standard.

Finally, the method can be still improved and simplified considering the additional indications from IEEE Standard 946-2020 [16]. As an example, according to this standard, the contribution of DC motors and inductive loads to the short-circuit current can be conservatively estimated as ten times the motor's rated full-load current. This allows to eliminate from the microgrid graphs those nodes containing DC motors and inductive loads and to take into account their contribution as a second step by adding it to the fault current calculated in the network without these elements, as suggested similarly for AC networks by IEC 60909.

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