Zonal DC Distribution System based on Multiport Converters: Fault Analysis and Protection Design

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***Abstract*—In this paper a high-quality zonal DC distribution system is proposed. The system layout and the relative power converters are presented in detail and fault analysis is performed in the different sections of the system. Reliability considerations are presented to support the effectiveness of the proposed layout and criteria for protection design are provided. The proposed distribution system allows obtaining high levels of reliability and selectivity with no need for particular switching devices by mean of suitable converters selection and control, overcoming traditional issues of DC distribution systems.**

***Index Terms*—Fault Analysis, Multiport Converters, Power System Reliability, Zonal DC Distribution System.**

I. INTRODUCTION

Power supply continuity is becoming a strong need for many electric power systems, in that short interruptions or uneven voltage quality can cause production processes to stop and eventually create significant safety risks; this issue is usually addressed by mean of UPS systems feeding the most sensitive loads. On the other hand, power-electronics based loads intrinsically work with DC and many studies have highlighted the advantages of DC distribution systems with respect to conventional AC ones in terms of sizing and energy efficiency [1]-[5]. Moving from these considerations, in this paper a high-quality DC zonal distribution system [5],[6] is proposed. The considered system is based on two partially redundant DC feeders connecting the different zones the system is divided into. The two DC feeders power supply is granted by two independent AC sources by mean of IGBT-based VSC, while each zone is feed by a multiport converter [7]-[11]. Feeder converter are constituted by an active rectifier cascaded with a DC/DC stepdown converter. This solution can avoid the typical issues related to VSC DC faults vulnerability: in fact, it is well known that DC short circuits are the worst operating conditions for VSC. Even if the IGBT can be opened in very small time, the free-wheeling diodes are exposed to uncontrollable overcurrent, which requires large oversizing to avoid semiconductors damage [12],[18]. The proposed solution also allows coordination among feeders fault protection and DC capacitors sizing, obtaining effective protection and selectivity with traditional circuit breakers and no need for static ones.

Multiport converters are connected to both DC feeders and are equipped with a certain number of outputs, each feeding a small group of loads. Note that, due to the modular constitution of the multiport converter, each output port can provide different voltage levels and be configured for DC or, if necessary, AC loads with no issue [10],[12]. Furthermore, the multiport converter configuration can control the system both in steady state and fault conditions [11],[12]. In addition, multiport converters can effectively avoid fault propagation, such that healthy ports are not affected by faulted ones and exhibits higher quality performances [7],[9]-[11]. In comparison, the achievement of similar results through traditional UPSs would require to install one UPS for each group of loads, hence increasing system complexity and reducing efficiency. Of course, the proposed solution is also suitable for applications where the continuity requirements vary form one load to another.

The paper is organized as follows: section II presents the proposed system topology, while section III reports the analysis of fault currents and their relationships particular system components. Section IV reports considerations on reliability indexes to support the effectiveness of the proposed system, while criteria for protection design and selectivity are presented in section V. Final conclusions are reported in section VI.

II. ZONAL DC DISTRIBUTION SYSTEM LAYOUT

The proposed zonal distribution system layout is depicted in Fig.1. It consists of two feeder converters (active rectifier and DC/DC stepdown) connected to two independent AC sources, two DC feeders and N multiport converters (Fig.2), one feeding each zone the system is divided into, which provide the different voltage levels required by the loads. This configuration is particularly suited for applications where it is necessary to feed several loads with different voltage and reliability requirements, since the usage of multiport converters as interface among the two DC feeders and the loads allows providing quality power supply to DC and AC

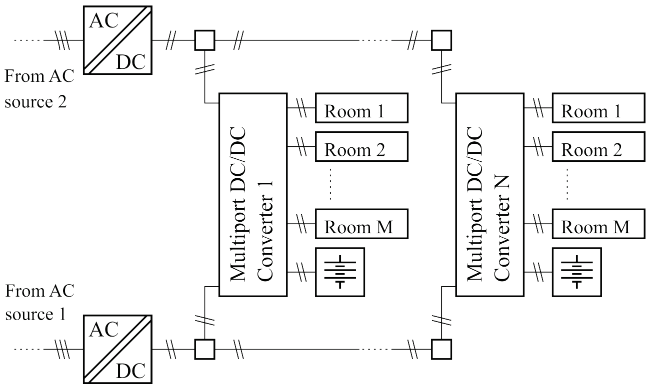

Figure 1 - Proposed zonal DC distribution system

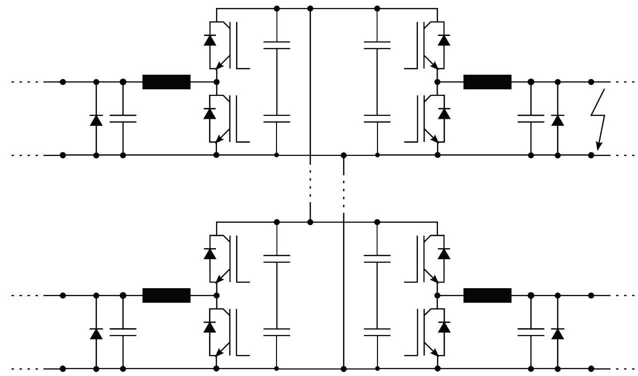
Figure 2 - DC multiport converter layout

loads (both three-phase or single-phase) independently. Furthermore, it is easy to include storage devices in multiport converters to integrate UPS functionality if necessary. Each feeder converter should have a rated power equal to

$$P_{feeder} = \alpha \sum_{i=1}^{N} P_i \quad (1)$$

where P_i is the *i-th* multiport converter rated power and α is a parameter related to the number of uninterruptible loads, such that $0.5 \leq \alpha \leq 1$. Assuming that the non-uninterruptable loads can be included in load shedding policies when one of the two feeders is out of service, the parameters α will be directly proportional to the percentage of uninterruptible loads over the total loads. This implies α=0.5 when uninterruptable loads are up to 50% of the total load and, eventually, α=1 when all loads are uninterruptable. The extensive use multiport converters to feed and manage DC zones grants several advantages over other topologies, including:

- seamless interface with the two available power sources, even in case of faults
- control of external voltages or exchanges power
- integrated UPS function where necessary
- integrated load shedding strategies: predetermined loads are disconnected in case of fault on one feeder
- short-circuit current control: the multiport converter control can easily recognize external faults and current controllability is maintained during faults

Considering the cost and efficiency issues related with static DC circuit breakers, the converter capability to control steady state short-circuit currents is particularly interesting. In fact, it is easy to introduce control algorithms such that multiport converters provide a predetermined short-circuit current $I_{sh\text{-}n}=k_{sh}I_n$ (with $2 \leq k_{sh} \leq 5$) towards loads and zero short circuit current toward the feeder. Analogously, the feeder converter can be controlled to provide a similar short-circuit current contribution in case of faults on the feeder. Obviously, short circuit-current should not be maintained over few seconds to avoid safety issues. Circuit breakers are still necessary for safety and selectivity reasons, but their operation is less critical and traditional circuit breakers can be used; further consideration on circuit breakers will be presented in Section IV.

III. Fault Analysis

The short circuit current can be calculated considering, at least as first instance, the contribution of one converter only. This is clearly the case of a fault on the load side, which is fed by one port of the multiport converter only, but the results can also be extended to a feeder fault as long as the fault current contribution from multiport converters is sufficiently small. Since the fault affects an RLC circuit, it is possible to experience oscillations, which can be critical for two reasons: firstly, the capacitors used for this applications are often electrolytic capacitor, which cannot withstand significant negative voltages. Furthermore, a negative capacitor voltage would cause the converter to loose current controllability, which can lead to converter damage. In order to avoid these issues, a diode has been included in each multiport converter module to avoid negative voltages across the capacitor. This leads to three different transient phases, depending on the diode conduction state, but assures that eventual voltage oscillations cannot reach negative values. Assuming the current controllability condition to be maintained up to current limit of the control, the short circuit current expression is given by

$$i_{sh}(t) = \begin{cases} \dfrac{V_n - R' \cdot I_{sh-n}}{L' \cdot (s_1 + s_2)} (e^{s_1 t} - e^{s_2 t}) + I_{sh-n} & for\, t \in [0, t_{on}] \\ i_{sh}(t_{on}) e^{-\frac{R'(t-t_{on})}{L'}} + I_{sh-n} & for\, t > t_{on} \end{cases} \quad (2)$$

where V_n is the converter nominal voltage, $I_{sh\text{-}n}$ is the steady-state short-circuit current injected by the converter and t_{on} is the instant in which the voltage across the capacitor reach the diode turn-on threshold. R' is defined as $R'=(R_f+d\cdot r_l)$ and L' is defined as $L'=d\cdot l_l$, where r_l and l_l are the resistance and inductance per meter of the line between the converter and the fault, d is the distance between the converter and the fault, R_f is the fault resistance. The roots of the characteristic equation are given by

$$s_{1,2} = -\frac{R'}{2L'} \pm \sqrt{\left(\frac{R'}{2L'}\right)^2 - \frac{1}{L'C}} \quad (3)$$

and they are real as long as $R'>2\sqrt{(L'/C)}$, which permit to determine the portions of the line in which the transient fault current would have a natural oscillatory behaviour, if any. The approximation on controllability lead to an overestimation of the current initial value, which can be considered precautionary. Furthermore, simulation results show that this difference has a small impact on the overall current transient. Analogously, the voltage across the capacitor during the transient is given by

$$v_C(t) = \begin{cases} \dfrac{[V_n - R'\cdot I_{sh-n}]}{(s_1+s_2)}(e^{s_1 t} - e^{s_2 t}) + R'\cdot I_{sh-n} & for\, t \in [0, t_{on}] \\ -V_{diode} & for\, t \in [t_{on}, t_{off}] \\ -\dfrac{R'\cdot I_{sh-n}}{(s_1+s_2)}[e^{s_1(t-t_{off})} - e^{s_2(t-t_{off})}] + R'\cdot I_{sh-n} & for\, t > t_{off} \end{cases} \tag{4}$$

where t_{off} is the instant in which the current flowing through the diode reach its turn-off threshold.

Let us consider the main parameters affecting the fault current. While the line resistance and inductance can be easily calculated given the line rated power, voltage and length, the converter filter capacitance is not univocally defined. It is possible to define a minimum value for C necessary to obtain acceptable voltage ripple, namely

$$C = \frac{\Delta I_L}{8 f_s \Delta V_C} \tag{5}$$

where ΔI_L is the maximum current ripple in the switching inductance, ΔV_C is the maximum acceptable voltage ripple and f_s is the switching frequency. However, one should also consider that, in order to further stabilize voltage, this capacitor is usually oversized in DC converters. This consideration suggests that, in order to both increase voltage stability and to increase the peak value of fault currents, it may be of interest to determine alternative sizing criteria for the feeder converter capacitor. One possible solution is to size the capacitor such that it is granted that, at the end of the line, the short circuit current I_{sh} satisfies $I_{sh} \geq kI_n$, where usually $5 \leq k \leq 10$. It is possible to determine the capacitance value which will provide the desired fault current peak value from (2) and (3), neglecting fault resistance, which is very difficult to estimate. This capacitance value is given by

$$C = \frac{d_{\max}\cdot l_l}{\left(\dfrac{V_n - d_{\max}\cdot r_l \cdot I_{sh-n}}{kI_n - I_{sh-n}}\right)^2 + \dfrac{(d_{\max}\cdot r_l)^2}{4}} \tag{6}$$

Anyway, this value will not provide the desired fault current because of the natural dampening of the transient, which again depends on fault resistance. Iterative solutions of the problem are possible, but still the dependence on fault resistance can cause issues. Another possible solution is the definition of sizing criteria based on energetic considerations, which means choosing a capacitor such that it can provide the converter rated power for a predetermined time period t_C within a limited relative voltage discharge dV_r, which leads to

$$C = \frac{2\cdot P_n \cdot t_C}{V_n^2(1 - dV_r^2)} \tag{7}$$

Note that (7) leads inevitably to a significant oversizing over the minimum acceptable value of C needed for the converter correct functioning, but this allows obtaining significant short circuit currents even in case of non-negligible fault impedances, which otherwise could create selectivity issues.

When considering a fault on one feeder, the fault current is constituted by transient contribution from all converter, while the steady-state short circuit current is limited to the feeder converter predetermined contribution. The exact determination of the short circuit current is uneasy in that it requires the solution of system of differential equations of dimension 2(N+1). If necessary, the problem can be stated considering that a short circuit on a feeder splits the system into two independent subnetworks which can be studied separately, where the only significant difference is the steady-state short circuit current, which is present only in the subnetwork comprising the feeder converter. Assuming a short circuit happening on *m-th* feeder section, the independent variables can be expressed as

$$\begin{aligned} \mathbf{v} &= [v_0, v_1, \ldots, v_m]^T \\ \mathbf{i} &= [i_0, i_1, \ldots, i_m]^T \end{aligned} \tag{8}$$

where **v** is the vector of capacitors voltages; the vector **i** is constituted by the currents in the lines connected to each converter, which means that i_0 is the current in the first section of the feeder, while $i_{1 \ldots m}$ are the currents in the derivations connecting, respectively, each multiport converter to the feeder. The system inputs are defined as

$$\mathbf{i}_{sh} = [i_{sh-n0}, i_{sh-n1}, \ldots, i_{sh-nm}]^T \tag{9}$$

where $\mathbf{i}_{sh}$ is the vector of short-circuit currents injected from the converters, which usually implies all terms are null except from the first one, due to the feeder converter. The considered dynamic system can then be written in quasi-normal form as

$$\begin{bmatrix} \mathbf{L} & \mathbf{0} \\ \mathbf{0} & \mathbf{C} \end{bmatrix} \frac{d}{dt}\begin{bmatrix} \mathbf{i} \\ \mathbf{v} \end{bmatrix} = -\begin{bmatrix} \mathbf{R} & \mathbf{-I_3} \\ \mathbf{I_3} & \mathbf{0} \end{bmatrix}\begin{bmatrix} \mathbf{i} \\ \mathbf{v} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{I_3} \end{bmatrix}\mathbf{i}_{CC} \tag{10}$$

where **R**, **L** are defined in Appendix, $\mathbf{I}_h$ is the *hxh* identity matrix. **C** is defined as $\mathbf{C}=[C_0, C_1, C_2, \ldots, C_m]\cdot\mathbf{I}_m$, with C_0 being the feeder converter output capacitor and $C_{1 \ldots m}$ being the input capacitor of the different multiport converters. The system can then be solved assigning suitable initial conditions, and the other subnetwork can be studied with this same approach. An approximated evaluation of short-circuit currents for protection design purposes will be presented in Section V.

IV. Reliability Considerations

In this section reliability considerations supporting the effectiveness of the proposed distribution system are presented. For these purposes, the possibility of a line fault is considered negligible with respect to a converter or AC source fault, in that the reduced extension of the proposed distribution system and the fact that there are no loads directly connected to the feeders reduces the possibility of line faults merely to cable faults, which is usually remote. In fact, the cable Mean Time Between Failure MTBF usually reaches values so high that, in real applications, the probability of cable faults is negligible with respect to unpredictable accidents involving the cable itself. As a first instance, let us consider total redundancy (α=1) and no storage devices in the system. This implies that, in case one AC source is out of service, the relative feeder goes out of service. Let λ_1 and λ_2 be, respectively, the frequencies of AC source 1 and 2 black-outs. Being the two AC sources independent and α=1, a load can experience a loss of power supply only if, during the black-out period $T_{black-out}$ of one AC source, the other AC source experiences black-out. Consequently, the frequency of load power-supply loss is given by:

$$\lambda_{load\_mult} = 2 \cdot T_{black-out} \cdot \lambda_1 \cdot \lambda_2 \tag{11}$$

According to Italian norms, one MV user can experience no more than 6-10 interruptions during more than one second per year, depending on the location. This implies that, in the worst allowed case, one AC source experiences a blackout every 36 day (864 h) and, assuming λ_1=λ_2 and an average $T_{black-out}$ = 2 min, the frequency of load power supply loss is equal to λ_{load_mult} = $8.93 \cdot 10^{-8}$. This results in a MTBF of load power supply equal to $MTBF_{load\_mult}$ = $11{,}196 \cdot 10^{6}$ *h* = 1278 Y.

Strictly speaking, a load can experience a power-supply loss also if, during the out-of-service of one feeder, the other AC/DC feeder converter or the multiport converter module connected to that feeder is affected by a fault. The possibility of a converter fault during a black-out of one AC source, which usually is only a short interruption, is negligible with respect to probability of a converter fault. In order to consider the possibility of converter faults, the fault frequency λ_{load} is to be incremented of a quantity $\Delta\lambda_{load}$ equal to:

$$\Delta\lambda_{load\_mult} = 2 \cdot MRT \cdot \lambda_{conv}{}^{2} \tag{12}$$

Considering for power converters a reasonable MTBF equal to 250000 *h* and a Mean Repair Time MRT = 24 *h*, it follows $\Delta\lambda_{load\_mult}$ = $7{,}7 \cdot 10^{-10}$. Considering the frequency of load power-supply loss due to converters faults with reference to the frequency of load power-supply loss due to the black-out of one AC source, the former is clearly negligible.

These considerations cover the possibility of all loads connected to a multiport converter experiencing a power supply loss. Anyway, the frequency of power supply loss experienced by a single load is higher, in that it is necessary to consider the possibility of fault of the module feeding the load itself. Since the module, especially if the load is fed in DC, is a very simple converter, its fault is pretty rare. Typical values for this kind of converters, obtained from statistical surveys, are, conservatively, $MTBF_{gate}$ = $7 \cdot 10^{5}$ *h* = 80 Y, corresponding to λ_{gate} = $1{,}43 \cdot 10^{-6}$. Consequently, a single load can experience a power supply loss frequency given by

$$\lambda_{load} = \lambda_{load\_mult} + \lambda_{gate} \tag{13}$$

which, considering the aforementioned typical values, results in λ_{load} = $8.93 \cdot 10^{-8} + 1{,}43 \cdot 10^{-6}$ = $1{,}51 \cdot 10^{-6}$, corresponding to $MTBF_{load}$ = $6{,}622 \cdot 10^{5}$ *h* = 75,6 Y. If this value is considered unacceptable for a certain load, it is possible to significantly increase it using two redundant modules to feed that particular load. In this case, a load experiences a power supply loss if a fault of one module happens during the reparation time of the other. Considering MRT_{gate} = 2 *h*, which is reasonable considering the modular structure of the multiport converter,

$$\Delta\lambda_{load} = 2 \cdot MRT_{gate} \cdot \lambda_{gate}^{2} \tag{14}$$

resulting in $\Delta\lambda_{load}$ = $8{,}18 \cdot 10^{-12}$. This value should be added to λ_{load_mult} = $8.93 \cdot 10^{-8}$, but it is clearly negligible such that λ_{load}=λ_{load_mult}, corresponding to $MTBF_{load\_mult}$ ≈ $11{,}196 \cdot 10^{6}$ *h* = 1278 Y.

Considering now the case of α<1, in case of black-out of one AC source, the previous considerations are valid for uninterruptible loads, which are obviously not included in load shedding strategies. The other loads, on the contrary, are disconnected by their relative multiport converter in case of loss of one power source. The frequency of power-supply loss experienced by non-critical loads is equal to λ_{load_nc} = λ_1+λ_2 = $2{,}31 \cdot 10^{-3}$, corresponding to a worst-case $MTBF_{load\_nc}$ = 432 *h* = 18 *days*. Considering that most grid outages are transitory (< 1 s) or short interruptions (< 3 min), an interesting possibility is the oversizing of the AC/DC converter and the module feeding the multiport converter such that it is possible to grant total redundancy (α=1) for few minutes. This solution is cheap and easy in that it only implies the usage of oversized semiconductor modules, while the heat sinks should be still dimensioned on the desired redundancy level. As a consequence, the system grants total redundancy (α=1) for short interruptions, while load shedding strategies are needed in case of long interruptions. In this case, λ_{load_nc} should be computed considering only long interruptions, which, from statistical surveys, are usually no more than two per year. This implies λ_{long_int} = $2{,}314 \cdot 10^{-4}$, and consequently λ_{load_nc} = $2 \cdot \lambda_{long\_int}$ = $4{,}629 \cdot 10^{-4}$, corresponding to a worst-case $MTBF_{load\_nc}$ = 2160 *h* = 90 *days*. Still, if the $MTBF_{load}$ is considered insufficient, it is possible to introduce storage devices, usually batteries or supercapacitors, to realize UPS functionality and reduce the impact of long interruptions.

To summarize, it is possible to divide the loads fed by each multiport converter into three categories:

- Type 1: fed when at least one AC source is available
- Type 2: fed when at least one AC source is available, but disconnected if one AC source is unavailable for more than few minutes
- Type 3: disconnected when one AC source is unavailable

The consequences of the proposed management strategy are reported in Table 1.

TABLE 1 - FAULT CONSEQUENCES ESTIMATION

Fault	Type 1	Type 2	Type 3
AC source short interruption	No consequence	No consequence	Power supply loss
AC source long interruption	No consequence	Power supply loss	Power supply loss
AC/DC converter fault	No consequence	Power supply loss	Power supply loss
MC (Multiport Converter) input module fault	No consequence	Power supply loss	Power supply loss
MC output module fault (without redundancy)	Power supply loss	Power supply loss	Power supply loss
MC output module fault (with redundancy)	No consequence	No consequence	No consequence

V. PROTECTION DESIGN AND SELECTIVITY

Distribution system selectivity requirements usually include selectivity among different load groups and on the feeders. With respect to selectivity among loads, the issue is directly addressed by mean of the adoption of multiport converters, which can easily decouple the different outputs even in case of faults. For each port, the consideration presented in section III are valid and, as a consequence, the short circuit current can be calculated by means of (2). Line protection from short-circuits and overloads can be obtained by means of magnetic-thermic circuit breakers. The peak value of the short circuit current can then be obtained by means of

$$i_{sh}(t) = \frac{V_n - R' \cdot I_{sh-n}}{L' \cdot (s_1 + s_2)} \left(e^{s_1 t_{\max}} - e^{s_2 t_{\max}}\right) + I_{sh-n} \qquad (15)$$

where $t_{max}=ln(s_2/s_1)/(s_1-s_2)$ is the instant when the current reach its maximum value. This value should be considered when selecting the switching devices breaking capacity. Furthermore, it is useful to remember that the multiport converter act as a backup protection in that it limits short-circuit currents to a predetermined value and, in case the fault is not extinguished in few seconds, finally forces the current to zero.

With respect to selectivity on the feeder, it is usually required to recognize faults among the different derivations from the main feeder to the loads and among different sections of the feeder itself. The resulting protection scheme is reported in Fig.3. However, the specific system considered in this paper and considerations on system reliability reported in Section IV suggest that it is not necessary to divide the feeder in different sections, in that faults on the feeder itself are remote. Consequently, even if all the switching devices reported in the schematic must be present for maintenance reasons, just S_{feeder}, S_1, … S_N need to be automatic circuit breakers; other switching devices may be simple disconnectors or, potentially, may not be present. While the general solution for short circuit current calculation has been presented in Section III, (10) is not particularly useful for general considerations in that the solution of the system is complex and strongly dependant on fault resistance. For this reason, it may be of interest to consider approximated approaches to the definition of short circuit currents for protection design purposes. In particular, one interesting solution is obtained considering the multiport converters filter capacitors to be dimensioned by means of (5), while the feeder converter filter capacitor can be dimensioned considering (7), such that the multiport converters contribution to the fault current is negligible. Consequently, the short circuit current can be calculated again by means of (2) and its peak value can be obtained from (15). For the sake of clarity, the behaviour of fault currents along the feeder is reported in Fig.4. A line length equal to *500 m* has been considered, while other circuit parameters are: V_n = 800 V, P_n = 100 kW, $I_{sh-n} = 2 \cdot I_n$, $r_l = 0,384\ m\Omega/m$, $l_l = 0,318\ \mu H/m$, $R_f = 0$, $t_C = 10\ ms$ and $dV_r = 0,9$. Short-circuit currents are computed every *50 m*.

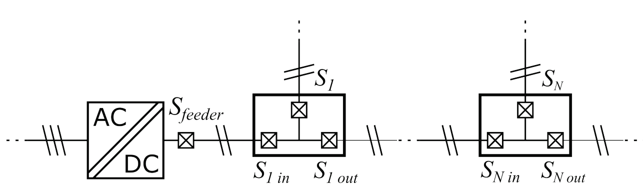

Figure 3 - Protection schematic

This approach allows obtaining amperometric selectivity by mean of magnetic-thermic circuit breakers among the feeder and the derivation towards multiport converters, in that, in a system comprising N multiport converter, each would have a rated power roughly similar to P_{feeder}/N. Consequently, the switching devices S_1, … S_N will have a rated current which is much smaller than S_{feeder} rated current. On the contrary, it is not possible to obtain selectivity among different feeder sections because of the decreasing values of the peak current. Anyway, this is little issue in that the system can reach high levels of reliability even if the whole feeder is disconnected in case of a fault. In particular cases where selectivity along the feeder is requested, this can be obtained introducing magnetic-thermic circuit breaker instead of disconnectors and implementing automatic reclosure. This would not guarantee direct selectivity on the feeder, but at least permits to isolate the faulted section and not to disconnect healthy ones. Consequently, only some multiport converters experience the loss of one feeder and less loads may be involved in load shedding. However, considering the reliability indexes reported in Section IV, this further protection strategy is usually unnecessary.

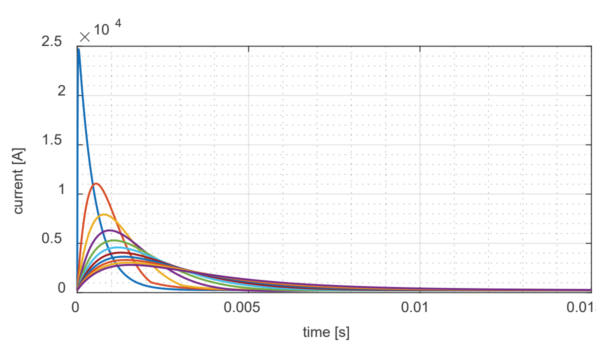

Figure 4 – Short circuit current behavior: fault current in case of fault at the feeder converter terminals (blue) and fault currents in successive feeder sections (calculated every 50 m)

VI. CONCLUSIONS

Power electronic converters can provide interesting solutions for the ever-growing power supply reliability requirements. In particular, a zonal DC distribution system has been considered in this paper, which allows obtaining high reliability performances with no need for traditional UPS. Power converters capabilities regarding fault currents control and limitation are exploited in order to obtain the required selectivity levels with no need for particular switching devices, overcoming the traditional issue of DC distribution systems.

VII. APPENDIX: R, L, C MATRIXES DEFINITON

The matrices used in (10) are defined in this section. Quantities with 0 subscript indicates the different section of the feeder, while other ones indicate the derivation towards multiport converters. The parameter β indicates the portion of the last line section before the fault.

$$\mathbf{R} = \begin{bmatrix} R_{01} + R_{02} + R_{03} + ... + \beta R_{0m} + R_g & R_{02} + R_{03} + ... + \beta R_{0m} + R_g & R_{02} + ... + \beta R_{0m} + R_g & ... & \beta R_{0m} + R_g \\ R_{02} + R_{03} + ... + \beta R_{0m} + R_g & R_1 + R_{02} + R_{03} + ... + \beta R_{0m} + R_g & R_{02} + R_{03} + ... + \beta R_{0m} + R_g & ... & \beta R_{0m} + R_g \\ R_{03} + ... + \beta R_{0m} + R_g & R_{02} + R_{03} + ... + \beta R_{0m} + R_g & R_2 + R_{02} + R_{03} + ... + \beta R_{0m} + R_g & ... & \beta R_{0m} + R_g \\ ... & ... & ... & ... & \beta R_{0m} + R_g \\ \beta R_{0m} + R_g & \beta R_{0m} + R_g & \beta R_{0m} + R_g & \beta R_{0m} + R_g & R_{m-1} + \beta R_{0m} + R_g \end{bmatrix}$$

$$\mathbf{L} = \begin{bmatrix} L_{01} + L_{02} + L_{03} + ... + \beta L_{0m} & L_{02} + L_{03} + ... + \beta L_{0m} & L_{03} + ... + \beta L_{0m} & ... & \beta L_{0m} \\ L_{02} + L_{03} + ... + \beta L_{0m} & L_1 + L_{02} + L_{03} + ... + \beta L_{0m} & L_{02} + L_{03} + ... + \beta L_{0m} & ... & \beta L_{0m} \\ L_{03} + ... + \beta L_{0m} & L_{02} + L_{03} + ... + \beta L_{0m} & L_2 + R_{02} + L_{03} + ... + \beta R_{0m} & ... & \beta L_{0m} \\ ... & ... & ... & ... & \beta L_{0m} \\ \beta L_{0m} & \beta L_{0m} & \beta L_{0m} & \beta L_{0m} & L_{m-1} + \beta L_{0m} \end{bmatrix}$$

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