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Unidirectional step-up isolated DC-DC converter for MVDC electrical networks**Piotr DWORAKOWSKI^{*1}, Pierre LE METAYER^{1,3}, Drazen DUJIC², Cyril BUTTAY^{1,3}**¹ SuperGrid Institute
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France**piotr.dworakowski@supergrid-institute.com****pierre.lemetayer@supergrid-institute.com****drazen.dujic@epfl.ch****cyril.buttay@insa-lyon.fr****SUMMARY**

The medium voltage direct current (MVDC) technology is emerging in power distribution and collection after the high voltage direct current (HVDC) has been demonstrated and exploited as the economically viable solution for long-distance transmission of bulk power. This article focuses on the DC-DC converter for MVDC electrical networks. A classification of DC-DC converters is proposed according to three criteria: power flow directionality, galvanic isolation and modularity. A 20 MW ± 10 kV radial MVDC network is defined. Three unidirectional step-up, isolated and monolithic DC-DC converter topologies (phase-shifted full bridge - PSFB, single active bridge - SAB and SAB with output inductor - SAB-L) are discussed focusing on the output filter design (LC , C or CL). They all offer full power controllability and fault blocking capability in case of faults in low voltage direct current (LVDC) and MVDC systems. A simulation model of the case study MVDC network and the DC-DC converters is presented. Simulation results are presented in steady state showing the typical voltage and current waveforms of the selected DC-DC converters. Six fault scenarios are defined including pole-to-pole and pole-to-ground faults. Simulation results are presented focusing on the fault current in the diode rectifier bridge. The most severe fault case is the pole-to-pole fault at the DC-DC converter terminals. The MVDC voltage polarity reversal occurs, forward biasing the rectifier bridge diodes. The pole-to-ground fault results in low fault current due the high value grounding resistance. The PSFB is observed to offer the best performance in steady state and fault conditions. The PSFB output filter inductor fulfils the role of current ripple filtering and fault current limitation.

KEYWORDS

Direct current system, medium voltage, power electronics, indirect DC converter, boost converter.

INTRODUCTION

The medium voltage direct current (MVDC) technology is emerging in power distribution and collection after the high voltage direct current (HVDC) has been demonstrated and exploited as the economically viable solution for long-distance transmission of bulk power [1]. The MVDC technology is an attractive solution for applications involving DC loads and sources where high energy efficiency and high power flow controllability are required. It has been implemented in some pilot projects in China [2], [3] and Europe [4], [5]. The researchers evaluate the interest of MVDC in solar [6] and wind [7] applications. The benefits of MVDC technology can be analysed in terms of energy efficiency [8], power dispatch, power capacity, power supply range, raw material consumption, CO₂ emissions, resilience of distribution network or ancillary services to the AC grid. However, the actual benefits of MVDC technology must be evaluated case by case according to application requirements.

CIGRE has provided some foundations for the MVDC network development in the technical brochure (TB) 793 [9] and the efforts continue in the ongoing working group (WG) C6/B4.37 “Medium Voltage DC distribution systems”. CIRED has analysed DC networks in the TB with an intriguing title “DC Networks on the distribution level – New trend or Vision?” [10]. CIGRE WG A3.40 is currently working on the MVDC switching equipment. CIGRE WG B1.82 has started, addressing the MVDC cable system requirements. This article focuses on the DC-DC converter - solid state transformer (SST) for MVDC electrical networks.

In the future medium voltage electrical networks, the DC-DC converters may exist as standalone, interfacing MVDC systems with low voltage direct current (LVDC) systems, with HVDC systems or with another MVDC system (Fig. 1). The DC-DC converters may also exist as a part of power electronics-based transformers, as currently studied by CIGRE WG B4.91. The main role of a standalone DC-DC converter is to adapt the voltage between two DC systems. However, the DC-DC converter can also provide power flow controllability and fault current blocking/limiting, and can be classified according to power flow directionality, galvanic isolation and modularity. In this article a LVDC-MVDC, unidirectional step-up, isolated and monolithic DC-DC converter is analysed. The converter structure and operating principles are devised for an interface between a LVDC photovoltaic energy source and the MVDC network.

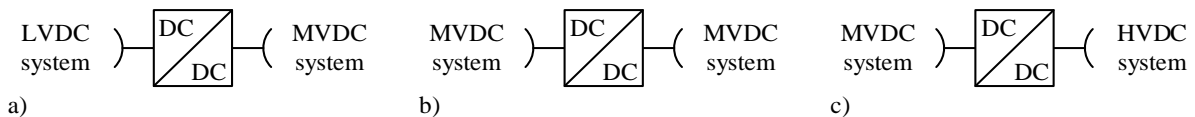


Fig. 1. DC-DC converter interfacing: LVDC with MVDC (a), two MVDC systems (b) and MVDC with HVDC (c). In majority cases where voltage difference between two DC systems is high, galvanic isolation by means of medium frequency transformer is needed.

This article is organised as follows. Section 1 proposes a classification of DC-DC converters for MVDC networks. Section 2 presents a case study MVDC network. Section 3 discusses three DC-DC converter topologies. Section 4 presents a simulation model of the case study network and DC-DC converters. Section 5 illustrates the performance of the DC-DC converter thanks to simulations in steady state and transient regimes.

SECTION 1: CLASSIFICATION OF DC-DC CONVERTERS FOR MVDC NETWORKS

A classification of DC-DC converters suitable in MVDC networks is proposed according to three criteria: power flow directionality, galvanic isolation and modularity. The power flow directionality is the one of the major functional differences between a DC-DC converter in DC systems and a transformer in AC systems. The transformer is inherently bidirectional but the DC-DC converter can be designed to be either unidirectional or bidirectional. The DC-DC converters can provide:

- bidirectional power flow (for example between two MVDC systems),
- unidirectional power flow stepping down (for example from HVDC to MVDC),
- unidirectional power flow stepping up (for example from LVDC to MVDC).

The general diagrams of isolated DC-DC converter topologies are presented in Fig. 2. The isolated DC-DC converters are composed of DC-AC bridge, transformer and AC-DC bridge. In case of unidirectional converter, the rectifier bridge can involve diodes only. Obviously, a bidirectional DC-DC converter can be also used in an applications which require unidirectional power flow only. However, the performance to cost ratio of the unidirectional converter is expected to be higher than its bidirectional counterpart.

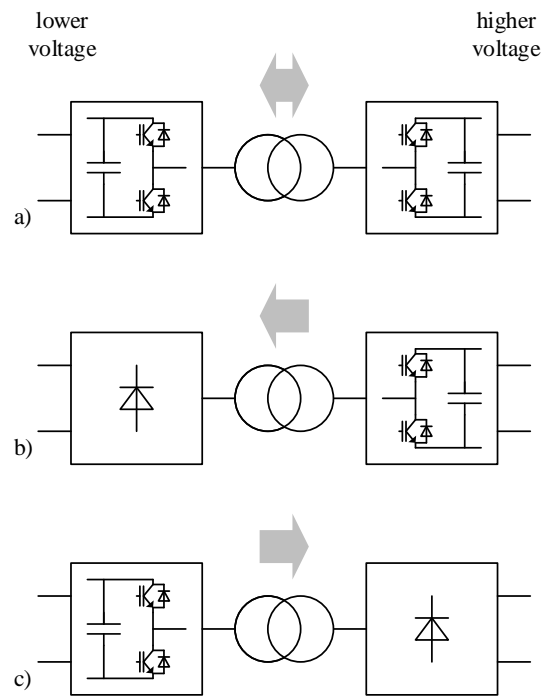


Fig. 2. General diagrams of isolated DC-DC converter topologies: bidirectional (a), unidirectional step down (b) and unidirectional step up (c).

The choice between isolated and non-isolated DC-DC converters for DC systems is likely to be similar to the choice between transformers and autotransformers in AC systems. The galvanic isolation between two DC systems allows the independent isolation coordination design and grounding choice between lower and higher voltage circuits. If there was no galvanic isolation, then the DC system with lower voltage would have to respect the overvoltage constraints of the DC system with higher voltage, resulting in more bulky and costly equipment. The same approach applies to AC networks where the autotransformer is used in low ratio applications only.

The choice of isolated DC-DC converters may be also driven by the power electronics design constraints. The isolated DC-DC converters based on the conversion chain {DC-AC bridge / transformer / AC-DC bridge} allow to decouple the constraints in the similar way as it is done in transformers. The transformer has a low number of turns of thick wire in the low voltage winding and a high number of turns of thin wire in the high voltage winding. Finally, a comparable quantity of copper in both low voltage and high voltage windings is used. In isolated DC-DC converters the low voltage bridge can be optimised for high current and the high voltage bridge can be optimised for low current. In non-isolated DC-DC converters the power electronic switches have to withstand both the voltage of the DC system with higher voltage and the current of the DC system with lower voltage. This results in a design which is far from the optimum and it is clearly visible when analysing a basic non-isolated converter like buck/boost [11] presented in Fig. 3. Finally, it can be concluded that the DC-DC converter with high stepping ratio is likely to be isolated. According to [12], high stepping ratio is equal or higher than 5.

The DC-DC converters for MVDC networks can be designed as monolithic or modular. In the monolithic isolated DC-DC converter there is one DC-AC bridge, one transformer and one AC-DC

bridge which process the entire power. In the modular isolated DC-DC converter there are multiple bridges and transformers, each processing a fraction of power. The input and output bridges can be connected either in parallel or in series. For example, the input parallel and output series (IPOS) connection allows to reach high step-up ratio. The modularity of DC-DC converters can be also achieved thanks to the modularity of the bridges. The typical modular bridge structures are neutral point clamped (NPC) [13] and modular multilevel converter (MMC) [14]. The DC-DC converters based on MMC are suitable for HVDC applications [15] and may be also suitable for MVDC applications where the 2-level and NPC are not cost effective (likely above 10/20 kV).

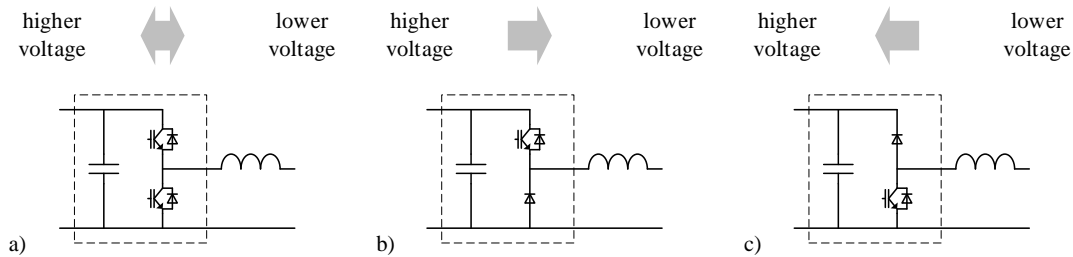


Fig. 3. Basic non-isolated DC-DC converters: bidirectional (a), unidirectional step down - buck (b) and unidirectional step up boost (c).

The classification of DC-DC converters suitable for MVDC networks is summarised in Fig. 4. It is noted that the combinations between the classification according to power flow directionality, the classification according to galvanic isolation and the classification according to modularity are possible. For example, a bidirectional monolithic DC-DC converter can be either isolated or non-isolated.

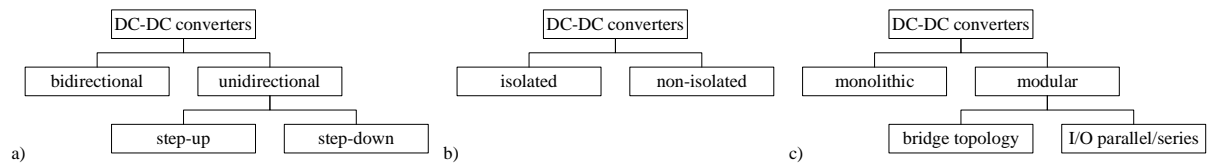


Fig. 4. Classification of DC-DC converters for MVDC networks according to power flow directionality (a), galvanic isolation (b) and modularity (c).

SECTION 2: CASE STUDY MVDC NETWORK

An MVDC collection network suitable for wind [7], [16] and photovoltaic (PV) [6], [17] power plants is analysed. A radial MVDC network is proposed for the case study as presented in Fig. 5. A symmetrical monopole topology is selected. The grounding on the DC side with high value resistance allows to minimise the DC fault current. The MVDC network is realized with underground cables. The interface with the AC network is ensured by an AC-DC station with a voltage source converter (VSC) and a transformer. DC-DC converters are considered to interface with the LVDC photovoltaic sources. The ratings of the analysed MVDC network, representative of a large-scale PV power plant, are presented in Table 1.

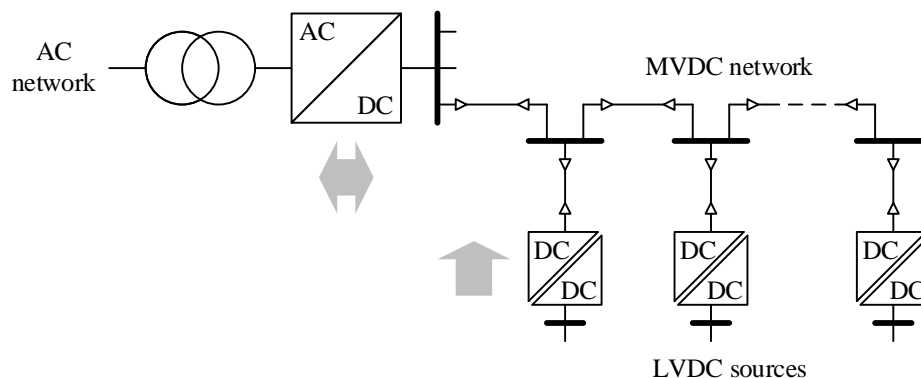


Fig. 5. Single line diagram of the case study MVDC network. Switchgear is not represented.

Table 1. Ratings of the case study MVDC network.

AC-DC power	MVDC voltage	MVDC line current	DC-DC power	LVDC voltage
20 MW	± 10 kV (20 kV)	1 kA	250 kW	1.2 kV

SECTION 3: MVDC DC-DC CONVERTER

The isolated DC-DC converter topologies suitable in high power applications include series resonant converter (SRC) [18], *LLC* DC-DC resonant converter [19], phase-shifted full bridge (PSFB) [20], single active bridge (SAB) [21] and dual active bridge (DAB) [22]. The isolated DC-DC converters often involve a transformer operating at frequency higher than 50/60 Hz (for example 10 kHz), offering size and weight reduction compared to a transformer operating at 50/60 Hz [23].

In this article three unidirectional isolated DC-DC converter topologies suitable for MVDC networks are analysed: PSFB, SAB and a variant of SAB. The PSFB is composed of LV inverter bridge, medium frequency transformer (MFT), MV rectifier bridge and output L_oC_o filter as presented in Fig. 6. The SAB topology is very similar, but the output filter involves the capacitor C_o filter only. A variant of the SAB with output filter C_oL_{ext} is considered as well (SAB-L). The output filter influences the DC-DC converter response under MVDC network fault conditions. The resonant topologies (SRC and *LLC*) and the DAB are not analysed in this article, but they are expected to have similar responses under MVDC faults to the SAB. All analysed topologies are expected to offer similar cost, size and efficiency but their response to MVDC faults is different as presented in the following sections.

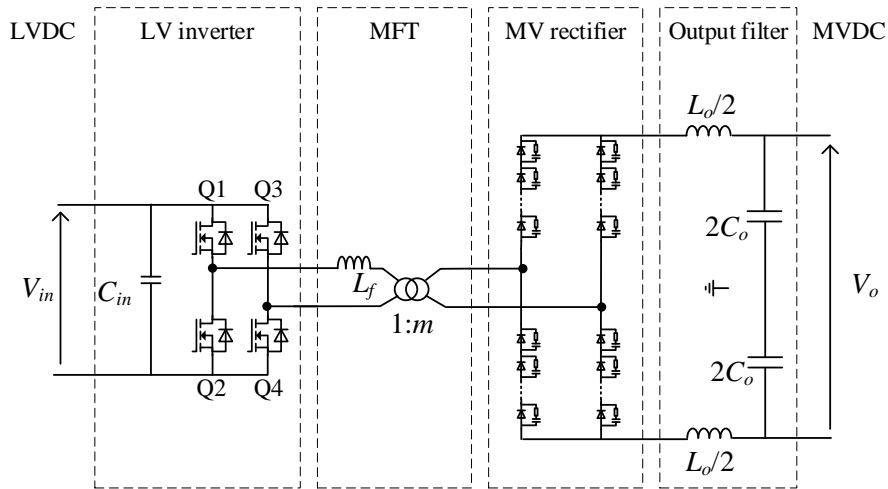


Fig. 6. Circuit diagram of the unidirectional isolated monolithic DC-DC converter based on phase-shifted full bridge topology. 1.7 kV SiC MOSFETs are used in LV inverter and 1.7 kV SiC Schottky diodes with RC snubbers are used in MV rectifier.

The PSFB converter design was presented by the authors in [24] and the SAB design was presented in [25]. The main design parameters are presented in Table 2. In the PSFB the LV inverter bridge generates a square waveform voltage while controlling the phase shift ϕ between two legs: the leading leg (switches Q1, Q2) and the lagging leg (switches Q3, Q4). The resulting duty cycle D is defined by

$$D = 1 - \frac{\phi}{180^\circ} \quad (1)$$

In this paper, the SAB LV inverter bridge is controlled with phase shift as in the PSFB.

Table 2. Design parameters of the selected DC-DC converters.

	Input capacitor	MFT frequency	MFT turns ratio	MFT leakage inductance	Filter inductor	Filter capacitor
PSFB	$C_{in} = 250 \mu\text{F}$	$f = 20 \text{ kHz}$	$m = 20.125$	$L_f = 5 \mu\text{H}$	$L_o = 8 \text{ mH}$	$C_o = 100 \text{ pF}$
SAB					NA	
SAB-L					$L_{ext} = 8 \text{ mH}$	

The control of the MVDC network is based on the master-slave principle where the DC-AC converter controls the MVDC voltage and the DC-DC converters inject the maximum power generated by the LVDC sources. In practice, the DC-DC converter regulates the input LVDC voltage. In case of fault in the MVDC network, the DC-DC converter blocks the LV bridge. This effectively prevents any steady state fault current contribution from the LVDC source to the MVDC network. A fault in the LVDC source does not impact the MVDC network in steady state, thanks to the diode rectifier and galvanic isolation.

SECTION 4: SIMULATION MODEL

The electromagnetic transient simulation models were developed to support the analysis of the DC-DC converter in the case study MVDC network as presented in Fig. 7. The model is suitable for the analysis of DC-DC converter under faults in the MVDC network.

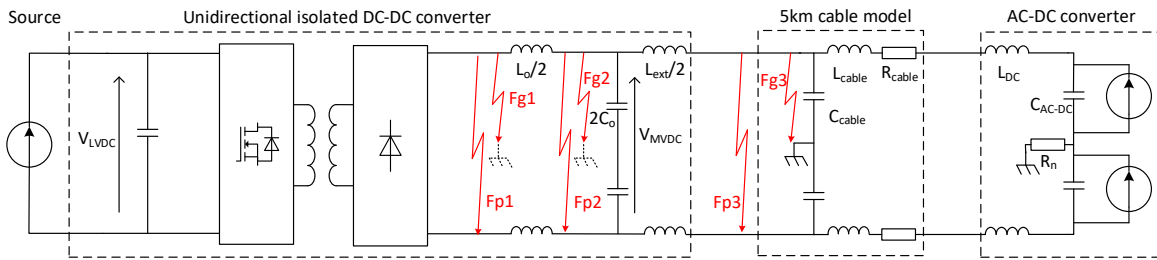


Fig. 7. Simulation model of the MVDC network with: DC-DC converter (detailed switched model), cable (π model) and AC-DC converter (average model). Fault cases defined in Table 4 are visualized.

The detailed switched model [26] of the DC-DC converter was used. The MV diode bridge is modelled with an equivalent diode with a forward voltage drop of 16.8 V and an on-state resistance of 2.57 m Ω . These values correspond to the series connection of silicon carbide (SiC) Schottky diodes [27]. The LVDC source is modelled with a current source controlled to deliver the nominal power. The 5 km cable section is represented by a π model (Table 3). The AC-DC converter is represented by the average model [26] which was detailed in [28] (Table 3).

Table 3. Design parameters of the MVDC cable and AC-DC converter.

Cable		AC-DC converter	
R_{cable}	8.8 m Ω /km x 5 km	R_n	1 k Ω
L_{cable}	134 μ H/km x 5 km	L_{DC}	500 μ H
C_{cable}	1.81 μ F/km x 5 km	C_{AC-DC}	1.8 mF

The fault cases are summarized in Table 4. The short circuit is modelled by a simple switch with internal resistance of 10 m Ω .

Table 4. Definition of fault cases.

Name	Description
Fp1	Pole-to-pole fault in the diode rectifier
Fg1	Pole-to-ground fault in the diode rectifier
Fp2	Pole-to-pole fault in the output filter
Fg2	Pole-to-ground fault in the output filter
Fp3	Pole-to-pole fault at the DC-DC converter terminals
Fg3	Pole-to-ground fault at the DC-DC converter terminals

SECTION 5: SIMULATION RESULTS

The steady state waveforms of three selected DC-DC topologies are presented in Fig. 8, for the maximum power and nominal output voltage. The input is regulated to the nominal LVDC system voltage. It is seen that, with the analysed design, the SAB and SAB-L present higher current ripple and, since the same output capacitor is kept for all cases, higher output voltage ripple. This higher current ripple results in higher repeated peak current of semiconductor switches.

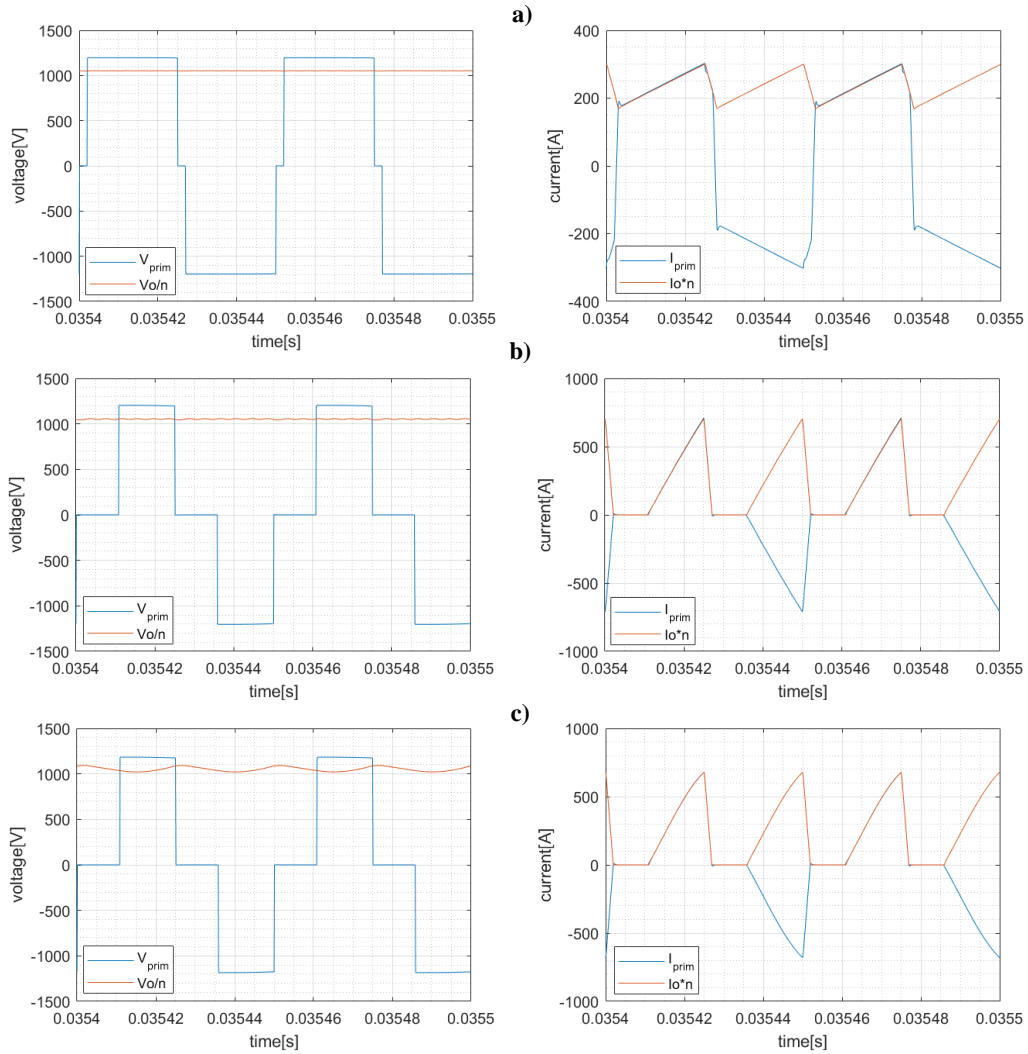


Fig. 8 : Steady state waveforms of the DC-DC converters: PSFB (a), SAB (b) and SAB-L (c).

Simulation results for the fault cases defined in Table 4 are presented in Fig. 9. The fault occurs at 0.04 s. The LV inverter bridge is blocked 5 μ s after the fault instant considering that the protection triggers due to overcurrent or overvoltage. In order to discard the influence of the AC-DC converter control on the analysis of DC-DC converter, its current reference is brought down to 0 A after 5 μ s. The focus of this section is to study the influence of the output filter configuration on the diode rectifier bridge current during faults.

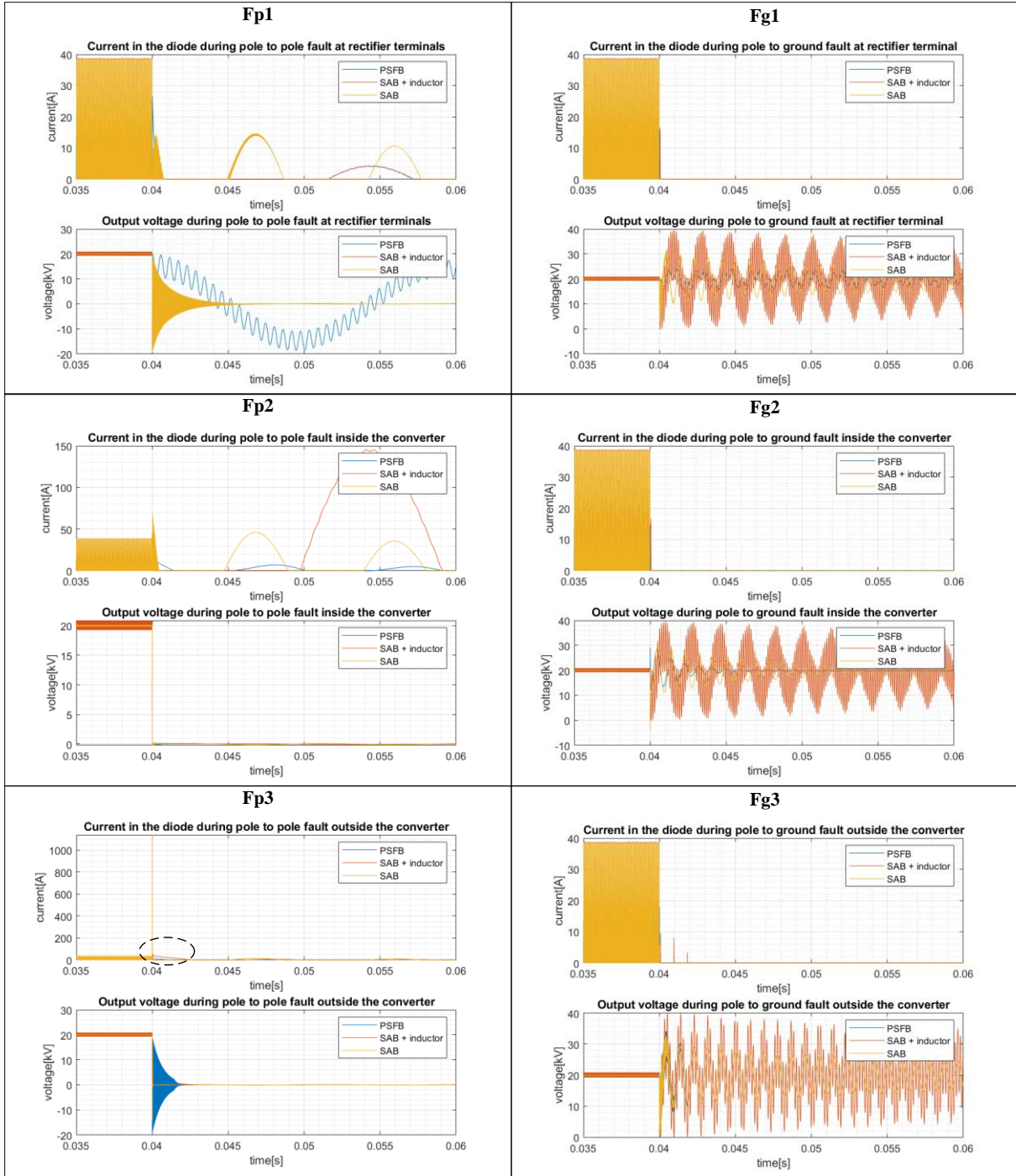


Fig. 9. Current in diode and output voltage V_{MVDC} of the DC-DC converter for fault cases defined in Table 4. The rated current of the diode is 25 A.

One can observe that the most severe fault case for the diode bridge is the pole-to-pole fault at the DC-DC converter terminals (Fp3). In the SAB the diode current peaks above 1000 A (compared to the rated current 25 A) because there is no inductor to limit the current. Such high current, even for a short time, would require a significant oversizing of the diode bridge to prevent destruction. Fig. 10 shows a zoom at the time right after the fault instant. One can observe that the high current in the SAB is the result of voltage oscillations due to the discharge of cable capacitance. The voltage polarity is reversed, forward biasing the diodes. In the SAB-L the current does not reach high values as the inductor L_{ext} limits the capacitor discharge and there is no voltage polarity reverse. In the PSFB the oscillations are still present but they do not result in important current in the diodes thanks to the filter inductor L_o .

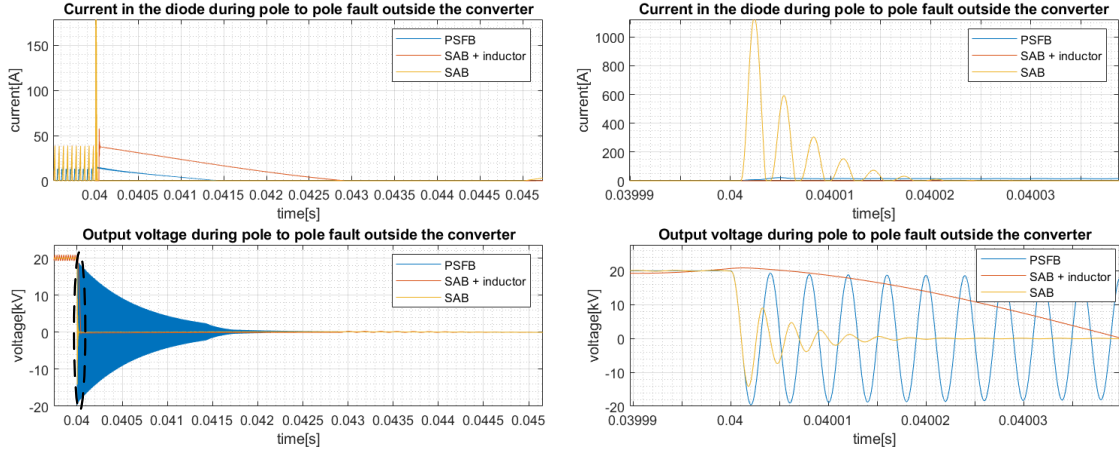


Fig. 10. Zooms at the fault instant for the fault case Fp3.

The same filter capacitor C_o was used for each DC-DC topology. For SAB and SAB-L this results in larger output voltage ripple than in the PSFB as there is no DC inductor inside the converter to reduce the current ripple. In order to have a similar voltage ripple in all topologies, the output capacitor would have to be increased for the SAB and SAB-L. In case of fault, this would result in even higher diode current due to capacitor discharge. The PSFB filter inductor fulfils the role of current ripple filtering and fault current limitation.

It can be observed that the pole-to-pole faults in the output filter, in the diode rectifier or at the DC-DC converter terminals, do not result in high current in diodes. In Fp1 case it is seen that the output voltage polarity is reversed. However, this does not result in high current in diodes because the fault is localised between the filter capacitor (energy source) and the rectifier. The fault current simply does not flow through the diodes.

The pole-to-ground faults have no impact on the diode bridge but it can be observed that output voltage oscillations are triggered. The SAB-L presents the most severe oscillations. However, the output capacitor voltage never generates the voltage polarity reversal, so the diodes are never forward biased.

CONCLUSION

The DC-DC converter for MVDC electrical networks was introduced. The classification of DC-DC converters was proposed according to three criteria: power flow directionality, galvanic isolation and modularity. The case study MVDC network was defined. Three unidirectional step-up, isolated and monolithic DC-DC converter topologies were discussed focusing on the output filter design (LC , C or CL). They all offer full power controllability and fault blocking capability in case of faults in LVDC and MVDC systems. The simulation model of the case study MVDC network and the DC-DC converters was presented. The simulation results were presented in steady state showing the typical voltage and current waveforms of the selected DC-DC converters. Six fault scenarios were defined including pole-to-pole and pole-to-ground faults within the DC-DC converter. The simulation results were presented focusing on the fault current in the diode rectifier bridge. The most severe fault case was found to be the pole-to-pole fault at the DC-DC converter terminals. The MVDC voltage polarity reversal occurs, forward biasing the rectifier bridge diodes. The pole-to-ground faults result in low fault current due to the high value grounding resistance. The PSFB was observed to offer the best performance in steady state and fault conditions. The PSFB output filter inductor fulfils the role of current ripple filtering and fault current limitation. The assessment of DC-DC converters should be completed including the response under the lightning and switching impulse minding the output filter (LC , C or CL). The main challenges related to the development of MVDC DC-DC converter include: medium voltage and medium frequency transformer and rectifier, dielectric design and integration for compact size, and SiC inverter design for high efficiency.

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