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A Novel DC Fault Blocking Concept for Full-Bridge Based MMC Systems with Uninterrupted Reactive Power Supply to the AC Grid

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SUMMARY

Modern Modular Multilevel Converters (MMCs) equipped with full-bridge submodules are capable of controlling and interrupting DC fault currents by blocking all the converter's submodules. The first HVDC link using this technology will be the *Ultranet* project in Germany. Main advantage of full-bridge blocking is the almost instantaneous DC fault current interruption. Depending on the protection strategy DC fault blocking is used as primary or backup protection. Moreover, converter blocking is usually used for internal converter protection. However, a major drawback of the standard total converter blocking is the loss of the converter's reactive power generation capability. Especially during DC fault situations, where the active power infeed is interrupted, an additional loss of the reactive power supply can lead to further stress for the stability of the AC system. Consequently, a continuous support of reactive power to the AC system is a desirable functionality and might be a requirement set by grid operators.

Within this work a *partial blocking* concept for full-bridge based converters is proposed, which enables the interruption of DC fault currents without interruption of the reactive power support to the adjacent AC networks. For this purpose, only the submodules of the arms directly connected to the fault are blocked, while the other arms provide the requested reactive power to the adjacent AC grid. In electromagnetic transient simulations using PSCAD|EMTDC™ *partial blocking* shows a similar performance in comparison to *standard blocking* in regard to DC fault current interruption. With the proposed concept single conductor DC faults, as well as DC faults with multiple conductor involvement, can be interrupted, while reactive power is continuously supplied to the adjacent AC grid. Moreover, internal voltages and currents can be maintained within the converter's limits. The concept is tested for overhead line and cable based transmission systems within this publications.

KEYWORDS

HVDC, Full-Bridge Modular Multilevel Converter, Fault Blocking, Reactive Power Control, Continuous Operation

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1. MOTIVATION

The wind power generation capacity in the North and Baltic Sea in Europe has increased to more than 13 GW in 2016. Until 2030 it is planned to export 50 – 100 GW of wind power to the European grid [1]. To meet the future challenges caused by the integration the renewable energy into the existing power system, the European transmission grid needs significant reinforcements. Therefore, voltage source converter (VSC) based high voltage direct current (HVDC) systems, which enable a flexible and efficient bulk power transmission over long distances, are identified as key technology for future transmission systems [2]. Additionally, VSC HVDC systems can supply ancillary services, such as reactive power and frequency control as well as power oscillation damping, to the adjacent AC grids.

Hence, three VSC based HVDC transmission corridors are going to be built in Germany within the next ten years, with at least one of them based on overhead line (OHL) segments [3]. The fault probability is much higher in OHL compared to cable based transmission systems, due to atmospheric influences. Consequently, a major challenge in OHL based HVDC systems is a fast and secure interruption of DC fault currents with the option to perform auto-reclosing sequences to clear temporary faults [4]. Since full-bridge blocking interrupts DC fault currents almost instantaneously the energy input into an arc is smaller for blocking than for standard fault current control methods [4]. Moreover, new HVDC systems are planned as multi-terminal DC (MTDC) networks. A key component for a reliable operation of MTDC systems is a fast and selective isolation of DC lines in case of a fault [5]. Different concepts for fast and selective MTDC protection systems have been proposed in the past, most relying on DC circuit breakers. Since modern modular multilevel converters (MMCs) equipped with full-bridge submodules (SM) are capable of controlling and interrupting DC fault currents, MTDC protection systems based on converters with DC fault-blocking capability (e.g. full-bridge MMC) and DC High Speed Switches have been elaborated in the past as well [5]. The first HVDC system, using this technology will be the *Ultranet* project in Germany. Hence, it can be concluded that the fault blocking capability of full-bridge based converters will play an important role in future DC systems. Some key use cases for fault blocking are:

- *Primary DC line protection:*
  Full-bridge blocking can be used as primary DC fault handling option with the benefit of an ultra-fast current interruption and minimal energy input into the fault [4].
- *Backup DC line protection:*
  If a fault current control is used as primary protection, converter blocking is usually considered as backup protection [3].
- *Converter Protection*
  In case of converter internal overcurrents blocking is usually used as internal converter protection, since fault currents are interrupted immediately.

However, a major disadvantage of converter blocking is the loss of ancillary services to the connected AC grid, e.g. reactive power control. Especially during DC fault situations, where the active power infeed is interrupted, an additional loss of the reactive power supply can cause further stress the AC system's stability [3, 6]. Consequently, grid operators might require a continuous support of the AC system with reactive power (STATCOM mode). This paper presents a novel control concept for full-bridge based MMCs to block fault currents, without interruption of the reactive power supply to the connected AC system. Therefore, solely the arms directly connected to a faulty line are blocked, while the reactive power is continuously controlled with the unaffected arms. The concept is presented within a monopolar point-to point HVDC link. Nevertheless, the findings can be transferred to bipolar and multi terminal systems.

2. TECHNOLOGICAL CONSIDERATIONS

2.1. Modular Multilevel Converter

The *Modular Multilevel Converter* consists of six arms, which comprise a series connection of a discrete number n of identical submodules and a reactor represented as inductor L_S and resistor R_S, as presented in Figure 1. Each converter arm connects one of the three AC phases with one of the two DC poles. Each SM can insert or bypass a capacitor using bipolar switching devices. Thereby, a usually sinusoidal step voltage is created in each arm. Under a variety of different submodule configurations, half- and full-bridge submodules are the most established designs. In half-bridge submodules two bipolar power electronic switching devices, usually Insulated Gate Bipolar Transistors (IGBTs), and antiparallel diodes are used for bypassing or inserting a capacitor with positive polarity into the arms. Since a blocked half-bridge MMC behaves like a diode rectifier during DC faults, fault currents must be interrupted either by circuit breakers on the AC or DC side. In contrast, full-bridge SM can also be inserted with negative polarity and block DC fault currents, due to two additional IGBTs and diodes. Moreover, it is possible to control DC fault currents, since the DC pole voltage can be varied over the full range of $V_{DC} = [-V_{DC,max}; +V_{DC,max}]$ [6].

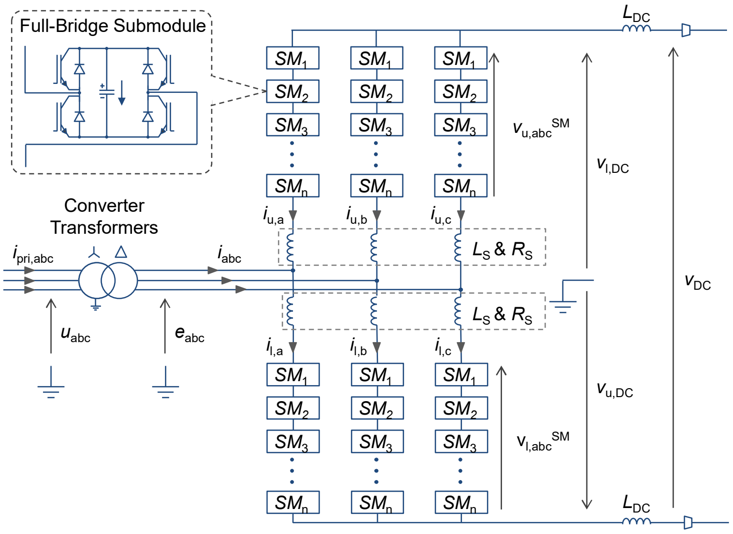

Figure 1: Modular Multilevel Converter scheme with full-bridge submodules

2.2. Converter Control

Within this paper a cascaded vector control proposed by CIGRÉ [7], is used. The control is divided into three functional levels: lower, upper and dispatch control level, as shown in Figure 2. The dispatch control provides set-point orders for the upper level control, like the required active power, DC voltage or the droop characteristics for MTDC systems. Based on these orders, the upper level control generates the AC reference voltage of the converter. The lower levels control the inner voltages and currents of the submodules. The conversion of the reference voltages to the IGBT switching pulses is also situated in the lower control level.

Upper Level Controls

Based on the dispatch control orders, the upper level control generates the reference AC voltage of the converter at the point of common coupling (PCC). Therefore, the current vector control regulates the direct (d) and quadrature (q) component of the AC current. The AC systems phase angle is tracked via a phase locked loop. The reference currents i_d^* and i_q^* are generated in the outer loop of the control. Standard reference current controls proposed by CIGRÉ are active power (P) and DC voltage (V_{DC}) controls for the d-component i_d^* and reactive power (Q) and AC voltage (V_{AC}) controls for the q-component i_q^*. Finally, a third harmonic injection is applied to reduce the amplitude of the AC and arm voltages [7].

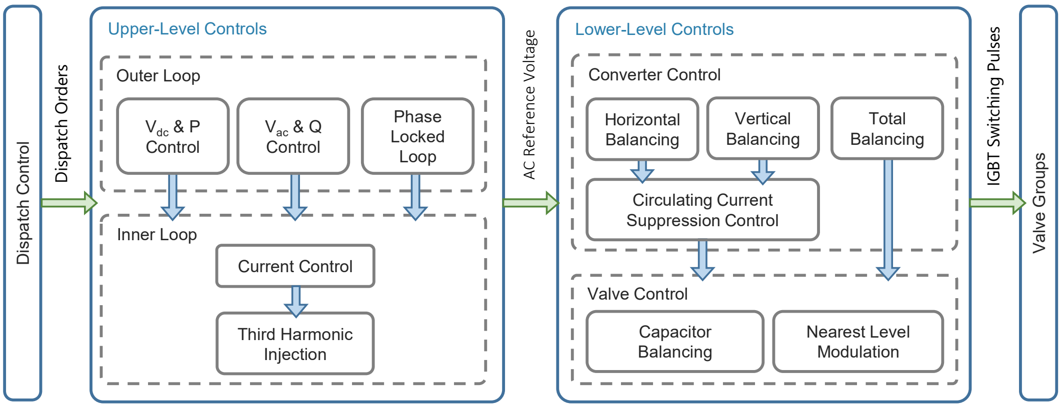

Figure 2: Control Structure

Lower Level Control

The lower level controls ensure a stable operation of the converter. First, the energy transfer between the AC and DC side is managed to maintain a constant level of stored energy and therefore a constant level of total submodule voltage within the converter [8]. Moreover, the energy differences between the phases, between the upper and the lower arms and between the submodules within each arm need to be minimised, to minimise submodule voltage fluctuations. Since full-bridge converters can be controlled during DC fault events and actively control the fault current, their control requires a very high level of dynamic performance during faults. A common dynamic control approach is to control the *total energy balancing* via the DC component of the arm currents and to control the *horizontal* and *vertical balancing* via a cascaded control in the α/β/0 reference frame [8]. Nevertheless, similar controls can be designed in a decoupled double synchronous reference frame ($d/q/0^{\pm}$) reference frame. The so-called *Circulating Current Suppression Control* (CSCC) is used as inner control loop with *horizontal* and *vertical balancing* as outer control loops [8]. By varying the circulating and negative sequence current components the internal energy balancing can be realised with these controllers.

The reference arm voltages $v_{u;l}^*$ are generated by a summation of the upper level voltage e_{AC}^*, the CCSC voltage v_Z^* and half of the reference DC voltage v_{DC}^*, since the DC voltage is normally generated equally in the upper and lower arms (cf. Figure 2). Finally, the reference arm voltages are converted into firing signal for the power electronic switches by a *nearest level modulation* (NLM) method [7]. An even capacitor voltage distribution within each arm is ensured by a *capacitor balancing algorithm* (CBA) [7].

3. METHODOLOGY

3.1. Blocking concept for full-bridge MMC with continuous reactive power supply

The objective of the developed concept is to enable converter blocking and thereby DC fault current interruption with continuous reactive power supply to the AC grid. In case of a single pole-to-ground fault, only the submodules of the arms, which are directly connected to the faulty line need to be blocked to interrupt the fault current, as depicted in Figure 3. This operation is called *partial blocking* within this paper. Thus, the other arms can stay in operation and provide the required reactive power. Nevertheless, the reactive power provided by the arms in continuous operation has to rapidly increase from $Q_{u,l}^* = 0.5\ Q^*$ to $Q_{u,l}^* = 1\ Q^*$ during *partial blocking* operation. To ensure a minimal disruption in the reactive power supply at the PCC the response time of the reactive power controller should be sufficiently small. Since no active power is transferred during fault operation, the full reactive power can be generated within half of the converters arm without overloading the MMC.

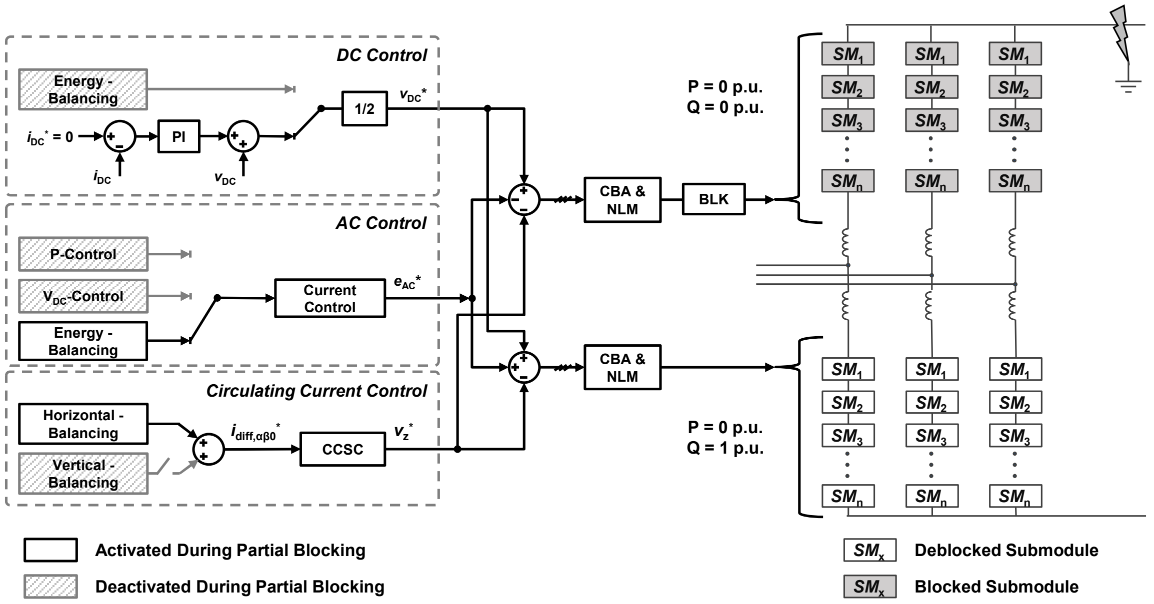

Figure 3: Partial blocking control concept

An important aspect of the *partial blocking* concept is to ensure a stable energy and capacitor voltage balancing of the unblocked arms. As described in section 2.2 standard MMC control concepts manage the *total energy balancing* via the DC side. Since no power is transferred via the MMC during fault operation the *total energy balancing* needs to be controlled via the AC side. Therefore, an additional energy balancing controller, which is selected during *partial blocking* operation, is added to the outer loop of the AC control, as shown in Figure 3. Since the active power is now controlled via the AC side, the DC control needs to directly control the DC voltage of the pole, which is not connected to the fault. This is achieved by a PI control (cf. Figure 3). To ensure, that no current flows from the AC to the DC side, a DC current zero controller is added to the DC reference voltage v_{DC}^*. During *partial blocking* operation, the capacitor voltages of the blocked arms cannot be controlled and remain almost constant (beside the self-discharge of the capacitors). Thus, the *vertical balancing* cannot fulfil its function of matching the upper and lower arm voltages and the controller is deactivated, as shown in Figure 3. The *horizontal balancing* remains in standard operation and manages an equal distribution of the total energy across the three arms in operation.

In addition to single pole-to-ground faults, the concepts can be used for the blocking of faults with multiple pole involvement. Even though these faults are less likely than single pole-to-ground faults, especially in cable systems, the faults have to be taken into account during the design of a DC line protection system. During a pole-to-pole fault, either the upper or the lower arms are blocked and the other arms remain in operation to continuously provide reactive power. In case of a pole-to-pole fault, *partial blocking* is sufficient to interrupt the fault current path. Although a fault current path cannot be completely interrupted by *partial blocking* during a pole-to-pole-to-ground fault (cf. Figure 4), the DC fault current can be eliminated by eliminating the DC voltage component of the arms, which are still connected to the fault. Nevertheless, the main, usually low ohmic, fault current path between the DC lines can be interrupted using *partial blocking.*

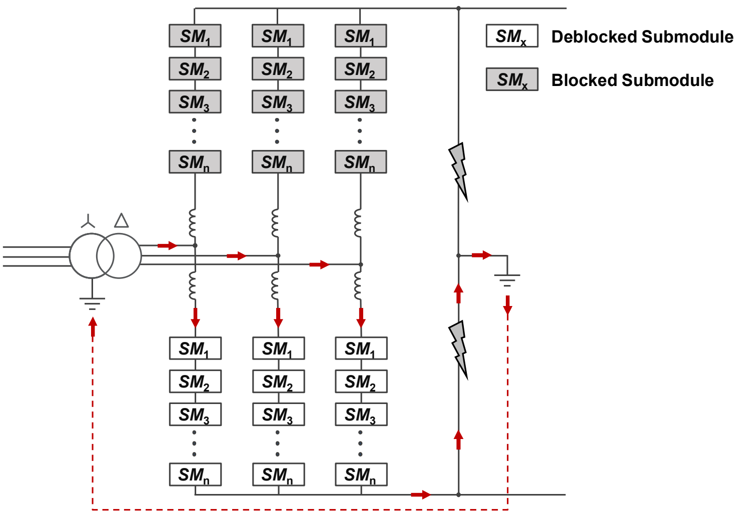

Figure 4: Fault current path in case of a pole-to-pole-to-ground fault

4. SYSTEM MODEL

The *partial blocking* control concept is investigated in a monopolar point-to-point HVDC transmission system as depicted in Figure 5. All simulations are carried out in PSCAD|EMTDC™ with a solution time step of $\Delta t = 5\ \mu s$. The model's components are described in detail within the following subsections.

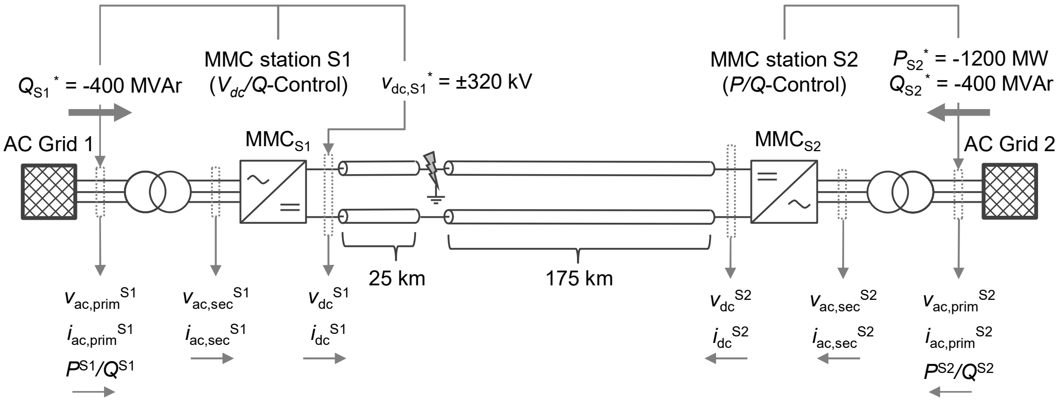

Figure 5: Investigated HVDC transmission system

The test system consists of two converter stations (S1and S2) connected via a transmission line over a length of $l_{line} = 200$ km. The monopole configuration comprises of two conductors P and N. During normal operation, S1 operates in DC voltage control mode (V_{dc}-Control) and S2 in active power control mode (P-Control). To show that a continuous reactive power support can be achieved with *partial blocking*, the S1 and S2 are operated in constant reactive power control mode (Q-Control). The MMCs are modelled using a *Detailed Equivalent Circuit Model (Type 4)* [7]. Since individual submodule switching states and capacitor voltages of the converter are represented, the model can be used for transient fault studies [7]. The station ratings are depicted in Table I. $P^{S1/S2}$ and $Q^{S1/S2}$ are the instantaneous active power and reactive powers at the connection point between the converter and the AC grid 1 and 2. All powers are defined towards the converters.

The transmission lines are modelled either as 2000 mm² copper cables rated for a DC voltage of $V_{dc,r} = 320$ kV or as 4-bundle aluminium conductors (Al/St 265/35) OHL using a *Frequency Dependent Line Model* [9]. As a simplified fault detection method an undervoltage protection relay triggered at $v_{UV} = 0.5$ p.u. in combination with a time delay of $\Delta t_{det} = 0.5$ ms is used.

Table I: MMC stations ratings

Parameters	**Values**
Rated DC voltage $V_{\mathrm{DC,r}}$	± 320 kV
Rated active power P_{r}	1200 MW
Rated reactive power Q_{r}	400 MVAr
Primary transformer voltage $V_{\mathrm{prim,r}}$	400 kV
Secondary transformer voltage $V_{\mathrm{sec,r}}$	450 kV
Arm inductance L_{arm}	0.15 p.u. = 75 mH
Arm resistance R_{arm}	150 mΩ
DC pole inductance L_{dc}	10 mH
Number of submodules per arm n_{sm}	350
Rated submodule capacitor voltage $V_{\mathrm{sm,r}}$	2.7 kV
Submodule Capacitor C_{SM}	7.5 mF

5. SIMULATION RESULTS

5.1. Partial blocking of a pole-to-ground fault in monopolar HVDC systems

The developed blocking concept is presented in detail with an exemplary P-pole to ground fault with a fault resistance of $R_{\mathrm{flt}} = 0.5\ \Omega$ in a cable system. As shown in Figure 5, the location of the fault is $x_{\mathrm{flt,S1}} = 25$ km (from S1) and it occurs at $t_{\mathrm{flt}} = 1$ s. In the following, the simulation results at station S1 are presented in detail, since the fault current is highest at this station. The fault is detected after $\Delta t_{\mathrm{det,S1}} = 0.65$ ms at station S1 and the arms connected to the P-pole are blocked, while the arms connected to the N-pole remain in operation. As depicted in Figure 6, the DC current is successfully interrupted after *partial blocking* is initiated. The reactive power supplied to AC grid 1 remains almost constant, beside a dynamic disturbance caused by the transient response of the reactive power of the arms connected to N, which step from $Q_{\mathrm{n}}^{*} = 0.2$ p.u. to $Q_{\mathrm{n}}^{*} = 0.4$ p.u. The DC voltage drop of line N is caused by the discharge of the cable, as it would be in case of *standard blocking* as well. Since the power transfer is stopped, the DC line cannot be charged during blocking operation. The voltage oscillation on line P occurs due to travelling wave reflections between the blocked converter and the fault location. A detailed comparison between the DC currents during *standard* and *partial blocking* is shown in section 5.3.

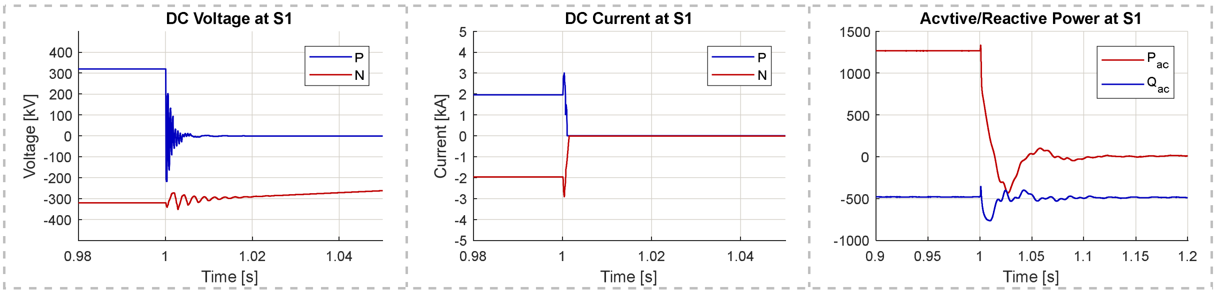

Figure 6: DC voltage (left), current (middle) and instantaneous AC active/reactive power during an exemplary P-G fault with *partial blocking*

Figure 7 depicts the arm currents, the average capacitor voltages and the voltages and currents at the secondary side of the transformer. The current flow in the arms connected to the faulty pole P is interrupted immediately once blocking is initiated. The maximum arm current of $I_{\mathrm{arm,max}} = 2.4$ kA is caused by the transient fault current before blocking. After this transient process, the arm currents are limited and the energy balancing with the arms can be maintained. A reduction of the transient SM overvoltage is possible by increasing the DC line reactor or the SM capacitors. Apart from a transient overvoltage, the secondary side transformer voltages and currents do not exceed their normal operation values. Moreover, no DC voltage component can be observed. Thus, it is concluded that *partial blocking* does not harm the transformer more than standard blocking.

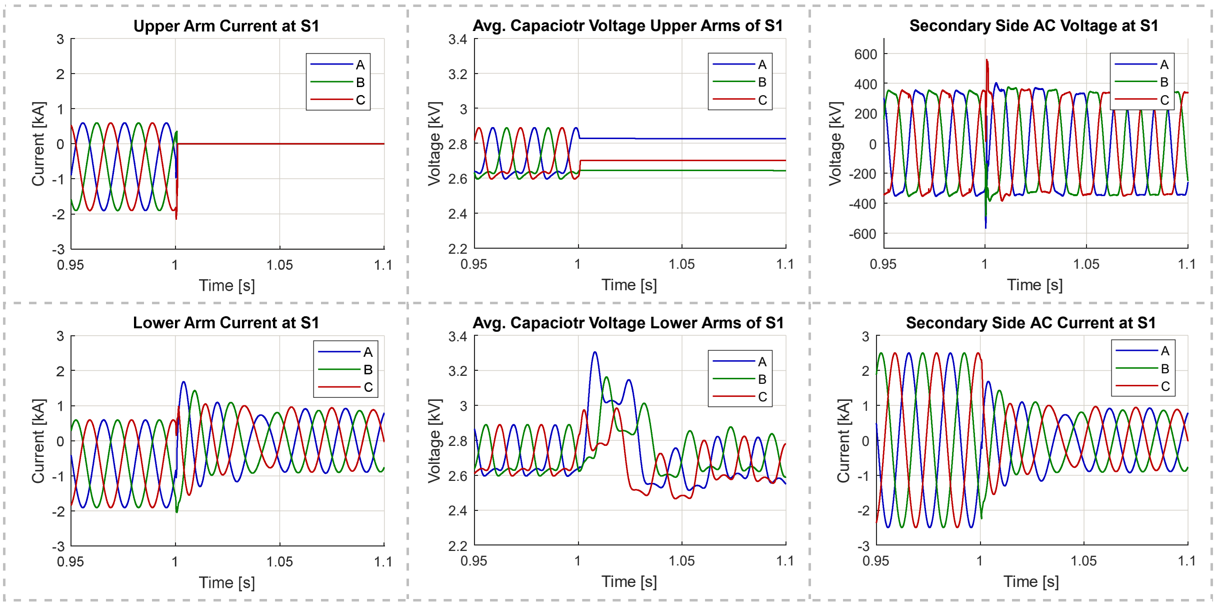

Figure 7: Converter internal values during an exemplary P-G fault with *partial blocking*

5.2. *Partial blocking of a pole-to-pole-to-ground fault in monopolar HVDC systems*

Partial blocking can also be used for the interruption of pole-to-pole faults with ground involvement (P-P-G), as Figure 8 depicts. Even though the only half of the submodules connected to the fault (c.f. Figure 4) are blocked, the DC current of both lines can be limited to values close to zero with *partial blocking*, while the reactive power controllability can be maintained.

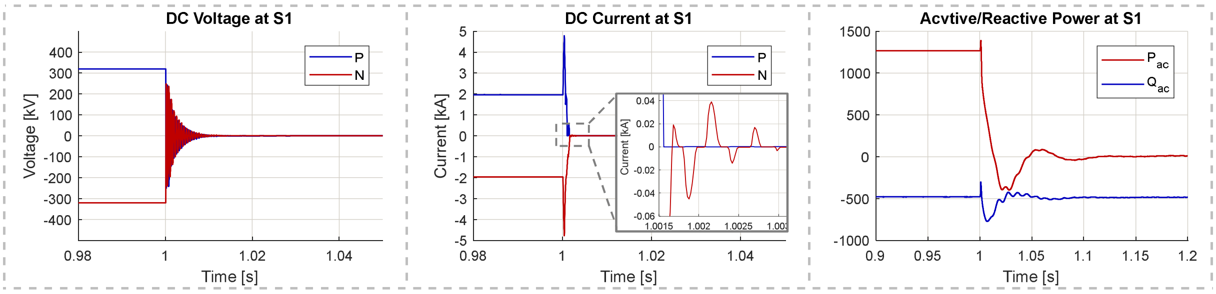

Figure 8: DC voltage (left), current (middle) and instantaneous AC active/reactive power during an exemplary P-P-G fault with *partial blocking*

To show that *partial blocking* does not harm the converter in case of a P-P-G fault, the converter internal currents and voltages are depicted in Figure 9. The maximum arm current of $I_{\text{arm,max}} = 2.9$ kA is caused by the transient line voltage drop and does not differ from the maximum arm current for *standard blocking*. A reduction of the arm surge currents can be achieved by an increase of the DC reactor or a faster fault detection. Similar to the P-G fault presented in section 5.1, the energy balancing with the arms can be maintained after a transient process. Beside a transient overvoltage, the secondary side transformer voltages and currents do not exceed their normal operation values. Moreover, no DC voltage and current components stress the transformer. Therefore, it is concluded that *partial blocking* can be used for the interruption of DC faults with multiple pole involvement. A detailed comparison between the DC currents during *standard* and *partial blocking* is shown in section 5.3.

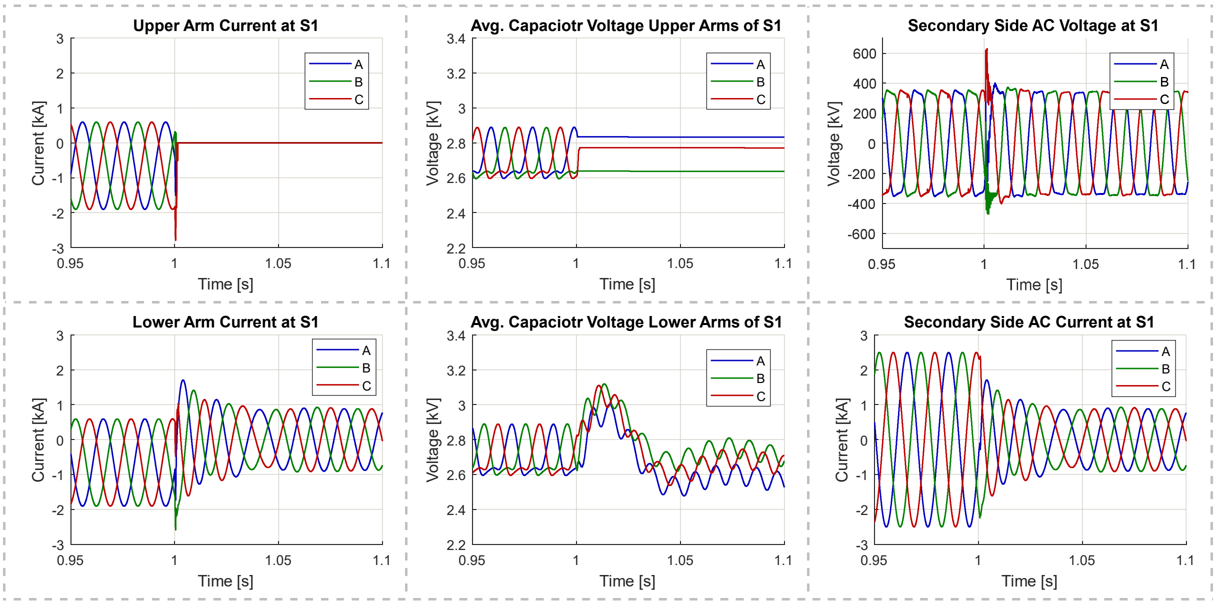

Figure 9: Converter internal values during an exemplary P-P-G fault with *partial blocking*

5.3. Comparison of standard and partial blocking

Finally, a comparison between *standard* and *partial blocking* regarding the DC current after blocking is presented in Figure 10 for the cable as well as the OHL system. During both faults, the currents i_P of the positive pole are almost the same for both blocking concepts, since the SMs connected to this conductor are also blocked during *partial blocking*. However small differences between the currents i_N of the negative line for *standard* and *partial blocking* are visible, since the DC current component is only suppressed by control instead of SM blocking in case of *partial blocking*. Nevertheless, these differences are not considered to be critical. Moreover, is it shown that the DC currents in case of P-G and P-P-G faults within an OHL based HVDC system are very similar for *partial blocking* and for *standard blocking*. Thus, converter blocking with a continuous reactive power supply is achieved in both transmission system types.

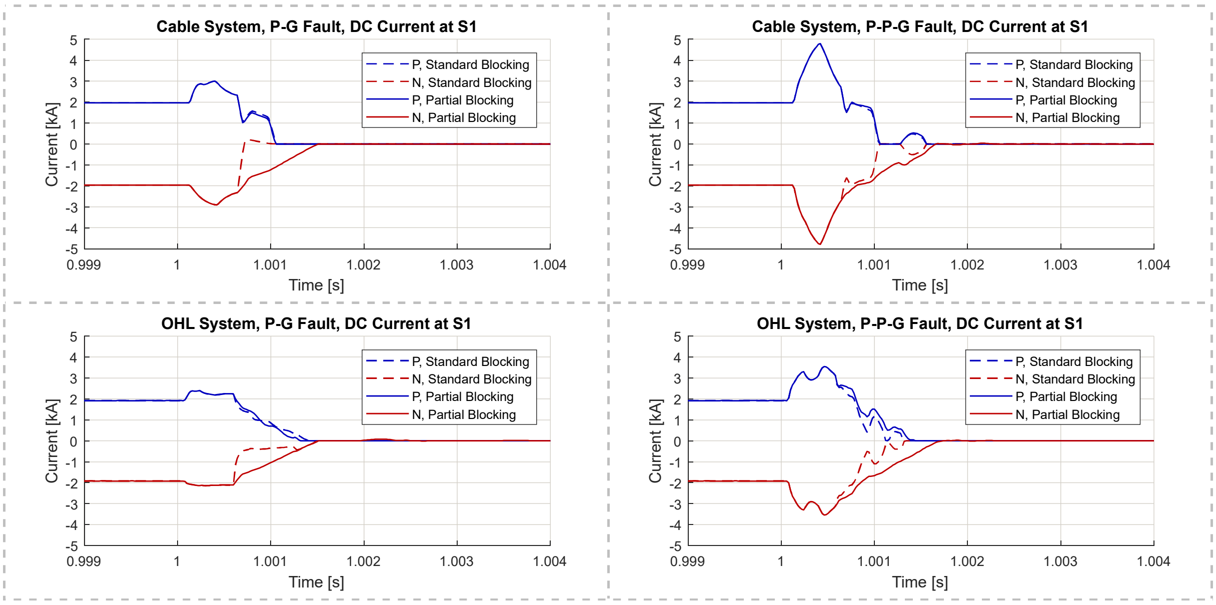

Figure 10: Comparison of *standard* and *partial blocking* for an exemplary P-G (left) and P-P-G fault (right) in a cable (top) and OHL (bottom) point-to-point HVDC system

6. CONCLUSIONS

It is shown that the proposed *partial blocking* concept has a similar DC fault current interruption characteristic as *standard blocking* of full-bridge based converters. Apart from a transient process, *partial blocking* enables a continuous support of reactive power to the adjacent AC grid. Even though the fault current path of pole-to-pole-to-ground faults cannot be completely interrupted by *partial blocking*, the concept can also be used for faults with multiple pole involvement utilising the MMC's fault current controllability. Additionally, the concept is suited for cable and overhead line applications. Compared to fault current control methods *partial blocking* has the benefit of an instant current interruption in case of P-G and P-P faults as well as a significantly faster fault current suppression in case of P-P-G faults compared to fault current control methods. Especially during faults caused by atmospheric impacts in OHL based systems, converter blocking is an efficient way to reduce the energy input into the fault arc and thereby accelerate the recovery process. Thus, *partial blocking* of the MMC can combine the benefit of fast fault clearance, grid recovery and continuous reactive power control. Moreover, the concept can be integrated in multi-terminal protection strategies based on full-bridge converters as primary or as backup and internal converter protection.

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