Short-Circuit Protection Issues in Converter Topologies for High-Voltage DC Transmission

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Abstract:

The role of power-semiconductor converters in generation and transmission of electric energy becomes more and more important. In addition to well-known thyristor-based grid-commutated high-voltage DC transmission (HVDC), IGBT-based grid-connected inverters start playing an important role. This role will soon be of such importance that the AC-grid stability will depend – beside well-known and experienced aspects – on the reliable operation of these converters and the associated HVDC system.

The main advantages of IGBT-based solutions are independent active and reactive current control as well as superior performance in case of AC-grid faults. Depending on the topology and the control chosen, faults in the DC grid may be critical. The limited thermal overload capability of power semiconductors makes all power-electronic assets very vulnerable to overcurrents – only few milliseconds are available for protective action. In case of short circuits, destruction may result. Counteractive measures are needed and have to be analysed carefully. In this context, safe protection and minimal outage intervals are key issues, needed effort and life-cycle costs also have to be considered. This paper analyses risks and counteractive measures with special regard to a modular multilevel converter based on bipolar modules.

1 Introduction

Today, the majority of high-voltage DC-transmission systems (HVDC) use thyristor-based grid-commutated converters. These systems are well-known and offer high efficiency, but are vulnerable to short circuits on the AC side of the transmission system, with the converter feeding energy into the AC grid. Extensive filter circuits secure safe and grid-compatible operation. Short circuits within the DC-transmission line can easily be controlled. Overhead lines for DC transmission are usual – weather-effected short circuits can be handled easily. Oil-free cables supporting the high voltages used by modern systems are not available.

While offering many advantages, these transmission systems have four major drawbacks:

- No black-start capability. A stable grid with high short-circuit power has to be available for operation.
- The amount of reactive power required for the operation of the grid-commutated converters and its dependency on the point of operation.
- The tripping of the transmission system in case of AC-grid faults on the fed end of the transmission line.
- The need for large filters at both AC terminals of the transmission line.

With regard to this, self-commutated converters offer a very interesting alternative, especially for wide-range energy transport in Europe. While having higher losses within the converter stations, active and reactive power can be controlled independently, reactive power even separately at both ends of the transmission line. The converters provide black-start capability and – if constructed as modular multilevel converters with a resulting high number of voltage levels [1] – do not need filters at all, if designed and controlled adequately. Faults within the AC grids can be handled easily on both sides of the transmission line. The desired behaviour of the converters can be implemented by suitable control algorithms within relatively wide boundaries.

Most of the suggested topologies suffer from one drawback: Short circuits within the DC-transmission line quickly lead to very high currents and cannot be controlled by the converters themselves. Due to the fact that the currents are only limited by (low) resistances of all components, such short circuits are severe. Due to DC operation, the inductances are relevant only dynamically. As long as cables are used for DC transmission, relatively simple countermeasures can be taken, because short circuits are rare and usually severe in themselves. With regard to cost and efficiency, long-distance transmission strongly suggests overhead lines instead of cables – at least for the majority of the distances. Consequently, weather-effected short circuits will be frequent and call for special attention. Several suggestions exist for mitigating the consequences of DC short circuits. The underlying principle and the advantages and disadvantages of the most prominent solutions are discussed in the following. For the sake of simplicity (and because they are quite generally accepted by now), in all cases modular multilevel converters (MMC) are assumed to be used. Conventional two- or multilevel converters would, however, face identical problems. The basic solutions discussed in general and commented in this paper are:

- DC circuit breakers.
- Thyristor-based bypasses to those diodes of two-quadrant MMC modules which have to conduct the short-circuit current in case of a DC short circuit.
- Use of four-quadrant MMC modules (or modules with similar properties).

2 Detailed problem statement

2.1 Aspects of power-electronic devices in case of short circuits

If overhead lines are used for energy transmission, various types of short circuits are to be expected on a more or less regular basis. Safe operation and fast recovery from such short circuits is crucial for reliable operation of the AC grid. Depending on the chosen power-electronic topology, short circuits can be handled easily or not. A basic example for a power-electronic topology is given in Fig. 1: The diode bridge transfers energy from

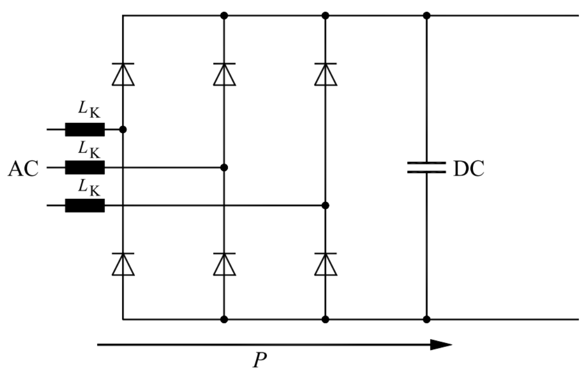

Figure 1: 6-pulse diode bridge with capacitive smoothing

the three-phase AC grid to the DC capacitor and a DC load connected to this capacitor. The resulting power flow and the resulting non-active power are natural ones, no control is possible. Consequently, the AC grid supplies energy, a small amount of reactive power (fundamental frequency non-active power) and a considerable amount of non-active power caused by current harmonics of higher frequency.

With regard to short circuits, AC-side and DC-side faults have to be treated separately. Short circuits on the AC-grid side reduce the available voltage, but are not harmful to the circuit itself. Depending on the type of short circuit, the DC voltage decreases or becomes in the worst case zero. A DC-side short circuit is really critical. On the one hand, the charge of the capacitor quickly drives high current into the short circuit. On the other hand, the diodes force a low-impedance connection from the AC grid to the DC side. Currents are limited only by the grid impedance and the commutation inductances. The resulting current will destroy the diodes within few milliseconds – a circuit breaker on AC or DC side would have to react within these few milliseconds and limit or switch off the current. This is not feasible with conventional circuit breakers. Even conventional fuses are too slow – they prevent physical destruction of the plant as a whole by overheating or fire, but not the destruction of the silicon wafers within the diodes which have a very low thermal capacity.

Whenever power-electronic devices are used, short-circuit protection is obviously an issue of importance. The gravity of the issue depends, of course, on the probability of such a short circuit. With a closely guarded DC link inside an appliance, short-circuit probability is nearly zero, common practice does not use protective measures – consequently accepting the (relatively low) risk of damage to the device. The longer the DC link extends in plants, e.g. using bus bars or even cables, the more important protective measures will be. All conceivable protective measures have severe disadvantages with regard to functionality and/or cost. In case of the diode bridge introduced above, thyristors replacing the diodes would solve the main part of the short-circuit problem. This is of special importance with regard to conventional HVDC systems.

2.2 Conventional HVDC systems

Conventional HVDC systems use line-commutated converters. The basic structure – reduced to the aspects relevant for this paper – is given in Fig. 2: The left-hand side of the structure is very similar to the diode bridge treated previously. However, replacing the diodes by thyristors introduces the option to control the mean value of the DC-link voltage by means of the control angle of the thyristors. Mean value zero and even negative mean values (given continuous current flow) can be realized. In this way, reaction to a short circuit on the DC side is safe and simple: The control angle is adapted appropriately and fast. As discussed in context of the diode bridge, short circuits in the left-hand-side AC

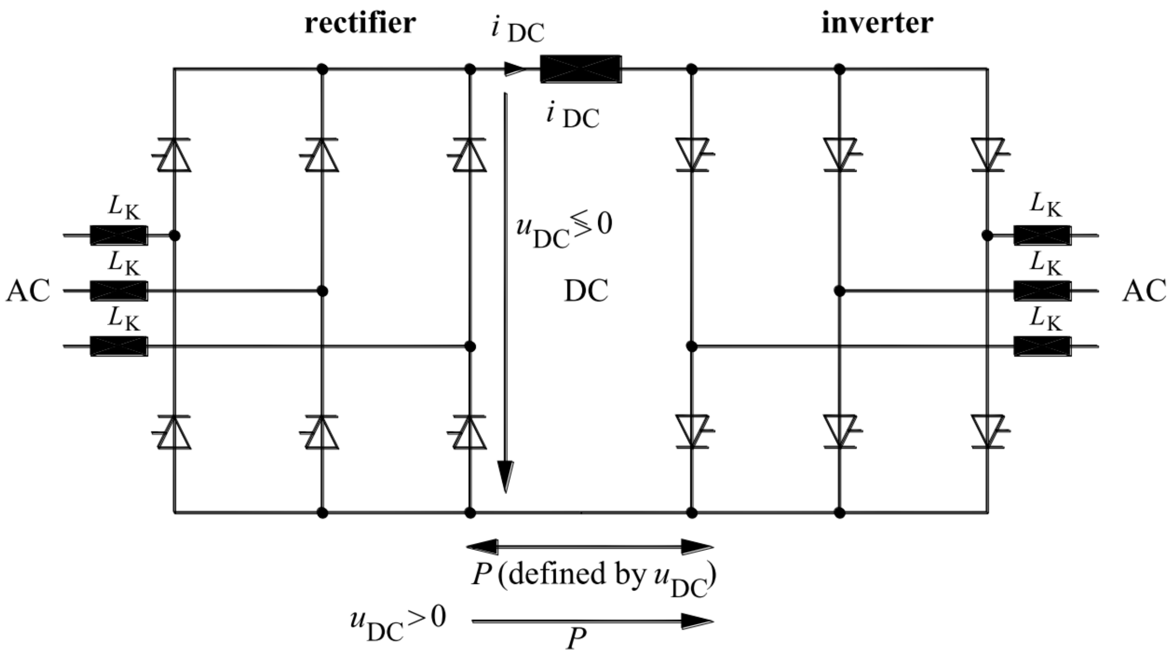

Figure 2: Basic structure of a conventional HVDC system

grid at presumed rectifier operation of the thyristor bridge do not present any problem. Energy transfer will be reduced or cease totally, but the HVDC system is not in danger of destruction. Short circuits on the receiving right-hand-side AC grid, however, are critical again. They immediately lead to a commutation failure, causing the currents to increase quickly. Countermeasures are needed to cope with this event – causing the transmission system as a whole to trip.

The converters used for conventional HVDC transmission are line-commutated converters. They require a certain amount of reactive power for commutation which depends on the control angle of the thyristors and the magnitude of the current flowing. Consequently, magnitude and sign of the reactive power are given and cannot be chosen freely.

2.3 Self-commutated (IGBT-based) HVDC systems

As discussed above, many advantages (compared to few disadvantages) suggest self-commutated HVDC systems for DC-transmission systems. The basic structure of such a system based on conventional converter topologies is given in Fig. 3. The self-commutated structure of both converters allows free adjusting of the reactive power in both AC grids. This reactive power is even completely independent of the active power being transmitted (if not exceeding the power rating of the converters). Short circuits on the AC side can be handled without any problem due to the properties of self-commutated converters. Suitably defined reactive power injection helps in stabilising the AC grid.

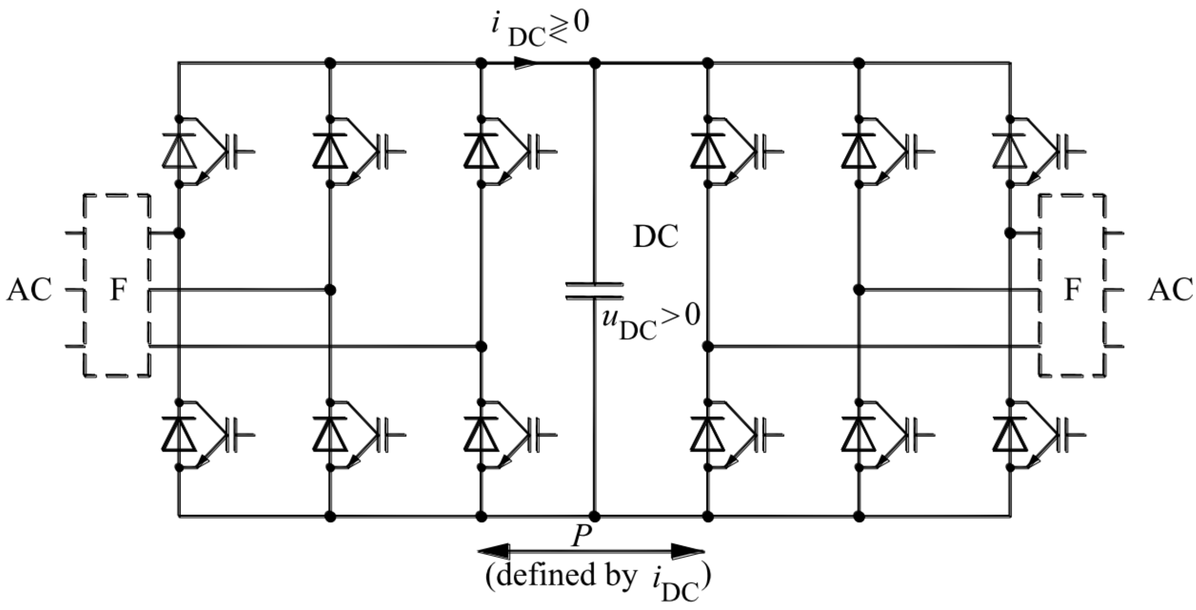

Figure 3: Basic structure of a HVDC transmission system (conventional self-commutated converters)

Comparing Fig. 3 with the diode bridge seen in Fig. 1 shows that each of the AC grids is connected to the DC link by a diode bridge. Additionally, an IGBT is connected anti-parallel to each of the diodes. The control of the converters is based on deliberately switching the IGBT and so controlling the voltages and currents. This requires a DC-link voltage well above that resulting from the diode bridges alone, else the diodes would switch on their own. This becomes fatal in case of a short circuit on the DC side: The DC-link voltage quickly drops below the diode-defined DC-link voltage – a high short circuit current identical to that of a diode bridge results, even if all IGBT are switched off. DC-link short-circuit protection is very critical.

With regard to realization the structure shown in Fig. 3 poses some challenges. The two most important aspects are: Linking the core elements by structures with low parasitic inductance and realising a smooth and at the same time high converter voltage on the AC side with acceptable filter effort. These challenges are hard to meet with a structure as shown in Fig. 3. Therefore, since some years a structure (Fig. 4) avoiding these challenges has been coming more and more into the focus of HVDC applications. This structure employs modules which are of comparatively simple construction and can be connected in series to reach the needed voltage level. A detailed description of the properties of this relatively new structure is not within the scope of this paper. Here, the discussion of the structure concentrates on those aspects relevant for short-circuit protection. The structure in Fig. 4 consists of six identical arms p1, p2, p3, n1, n2 and n3.

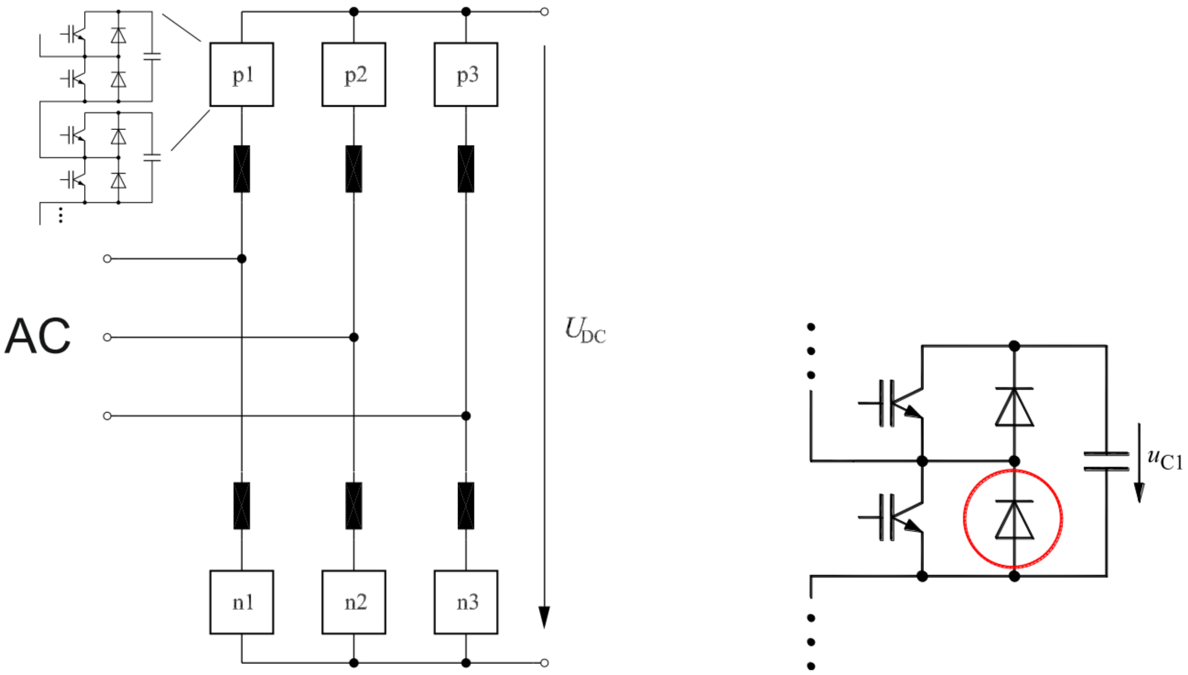

Figure 4: Left-hand side: Structure of a modular multilevel converter (MMC)
Right-hand side: Two-quadrant-converter module with uncontrollable diode path in detail

Each of these arms comprises in its basic form a series connection of a freely selectable number of two-quadrant converter modules [1]. The advantage of simple modules and free scalability by series connection in many applications is far more important than the drawback of single-phase energy conversion imposed by the structure. Also, the number of voltage levels can be very high, leading to quasi-sinusoidal AC voltages and quasi-filterless and in some applications even transformerless grid connection. With all these properties, short circuits on the DC side can still not be controlled. As detailed on the right-hand side of Fig. 4, an uncontrollable diode path connects AC terminals with DC terminals, leading to high currents in case of short circuits on the DC side. Due to the fact that the capacitors are no longer part of the short-circuit path, a small advantage is gained. In consequence, the energy stored within the capacitors is not touched by the short circuit.

A modified version of the MMC employs four-quadrant converter modules (Fig. 5), e.g. for STATCOMS [2] or railway interties [3]. The structure is still the same as shown on the left-hand side of Fig. 4. But with four-quadrant-converter modules, two major advantages result: On the one hand, no direct diode connection links AC and DC side of the converter. With all IGBT switched off, any conceivable current charges the capacitor. In this way, the capacitor voltage counteracts any undesirable rise of currents, even in case of DC-link short circuits. On the other hand, switching the IGBT allows positive capacitor voltage, zero voltage, or negative capacitor voltage between the terminals of each module, independent of the direction of the current flow. In this way, the converter freely controls the DC-link voltage between maximum positive and maximum negative voltage values – quite like the options known from the grid-commutated thyristor converters. In total, short circuits on the DC link can easily be handled by this topology as well as short circuits on the AC side.

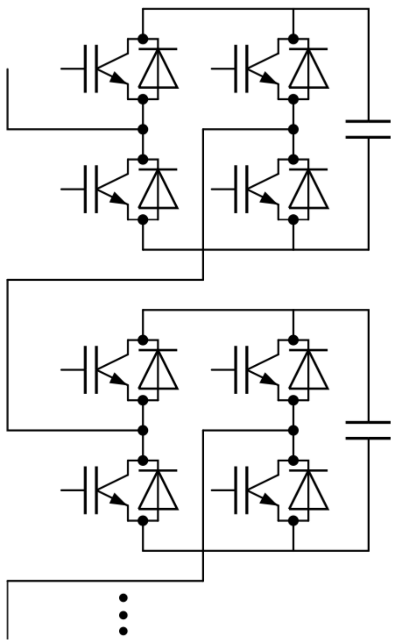

Figure 5: Four-quadrant-converter modules in series connection

3 Mitigation of DC-link short circuits

With regard to the challenges resulting specially from DC-link short circuits, as detailed above, several mitigation methods are under discussion. The most important of these are discussed here.

3.1 DC circuit breaker

With regard to known concepts, DC circuit breakers seem to be the logical way. They counteract the cause of the problem directly where it emerges. Taking a closer look, they are by far the most unfavourable alternative. Large DC circuit breakers are known from DC railway traction. Already for the relatively low voltages of DC railways ($\leq$ 3 kV), they are very bulky elements. AC circuit breakers use the zero-crossing of the current to extinguish the arc – in case of DC circuit breakers huge constructions are needed for this purpose. With regard to voltages in the range of 400 kV and currents in the range of 2000 A, conventional technology will no longer be suitable for constructing such circuit breakers. Power electronics, possibly in combination with quenching circuits, might be used. However, if power electronics would be used for turn-off, losses should have to be reduced by conventional circuit breakers in parallel. Prior to switching off the DC current by power electronics, these conventional circuit breakers would have to be opened, commutating the current to the power-electronic devices, which would then be switched off. The size, effort and cost of such a device would be enormous, still leaving open many questions as to functionality. Some of these questions and consideration are:

- Power-electronic devices survive currents exceeding the nominal current for few milliseconds only. Consequently, current limitation within few milliseconds is needed. This is far more challenging than usual operation of circuit breakers which will need some 30 ms to 60 ms for current limitation. In addition to the problematic DC case, very fast reaction would be required.
- At DC, the impedance is given by ohmic resistance only. (Stray) inductances only limit the slope of the current – not the maximum value reached. In DC grids, much higher short-circuit currents are to be expected than in case of AC operation.
- It is known practice to limit the slope of current by deliberately inserting chokes into the circuit. However, if a rise of current from 2000 A to 4000 A within 20 ms at 400 kV would be the limit, the required inductance would be 4 H (linear up to at least 4000 A, therefore to be realized as air coil). Should the DC circuit breaker react within 10 ms and the current be allowed to rise to three times the nominal current within this time, still 1 H would result. Dimension, loss and cost of such a choke are not to be neglected.
- With these considerations it is highly probable that a thyristor bypass to the endangered diodes (as in the Transbay Cable project realised by SIEMENS [1]) would be required in addition to a DC circuit breaker. This would, however, cause the converter to trip and go out of operation. Further consequences are listed below in the subsection covering the thyristor-based bypass.
- The energy stored in the DC cables and in additional chokes and the energy rushing into the system from the AC side has to be dissipated as heat within the DC circuit breaker. Such a device would, however, have to base on more or less adiabatic elements, cooling would be slow. Consequently, only very few turn-off events would be allowed within a period of some minutes. In the event of a DC-overhead line under bad weather conditions, this could soon lead to a situation where the transmission

line would be out of operation – waiting for the circuit breaker to cool down to operating temperature.

3.2 Thyristor-based bypass

As an alternative to the DC-circuit breaker, conventional or fast AC circuit breakers on the AC side of each converter can be combined with thyristor-based bypasses to the diodes affected by DC-side short circuits. The cost of such a solution, compared to a DC circuit breaker, is very low. Due to the fact that the DC circuit breaker is very likely not able to shut off a short circuit without interrupting operation of the converter, the disadvantages are small, if at all existent. The concept of thyristor bypasses has already been used e.g. in the Transbay Cable project realised by SIEMENS [1]. However, in this project cables connect the stations, no overhead lines are employed on the DC side. Consequently, short circuits on the DC side are associated with major faults in the system – shut-down of the plant in such cases is acceptable. On the DC side, conventional disconnectors can be used to disconnect defective DC-line sections at zero current – no DC-circuit breakers are required. No large additional chokes on the DC side are required. The main considerations concerning this concept are:

- Firing the bypass thyristors protects the converter, until the AC-side circuit breaker cuts off power. However, the converter is disconnected from the AC grid; no reactive power can be supplied.
- Each emergency shut-down in case of DC-side short circuit heats up the thyristors adiabatically due to the restricted cooling possibilities. In case of too high temperature, the plant cannot go into operation.
- The plant is completely shut down with the AC circuit breaker open. A pre-defined switch-on procedure is required to restore normal operation.
- The turn-on procedure does not allow to increase the DC-side voltage slowly. Due to the diodes and the requirements from capacitor pre-charging of the modules, a stepwise voltage rise on the DC side is unavoidable. In case of persisting short circuit, this solution is not optimal, but acceptable.

3.3 Four-quadrant converters as basic structure of MMC modules

As detailed above, four-quadrant converter modules allow optimized short-circuit reaction in case of AC-side and DC-side short circuits. The converter itself remains under full control, even in case of a DC-side short circuit, reactive power can be controlled on the AC side. This permits stabilization of the AC grid. Such a feature is of particular importance because the DC-side short circuit cuts of the energy transmission, causing a considerable lack of power on the inverter side and a considerable overshoot of available power on the rectifier side of the DC transmission line. The resulting voltage drop / voltage increase can be mitigated by reactive power supplied via the converter. With all converters remaining in controlled operation, the DC voltage can be increased as desired after a pre-defined time interval known to be sufficient for arc clearing and de-ionization of the environment of the failure. In this way, the fastest possible restoring of energy transmission is guaranteed. On the DC side, conventional disconnectors can be used to isolate defective DC line sections at zero current – no DC circuit breakers are required. No additional chokes or filters are required on the DC side. The number of short circuits which can be cleared within a time span is not limited, if the converter control suppresses currents exceeding the nominal current effectively. Considerations concerning this concept are:

- Slightly increased losses within the converter stations
- Slightly increased cost for the converter stations

4 Conclusion

The analysis of this paper demonstrates that modular multilevel converters (MMC) with four-quadrant converter modules (and some variants of these modules with similar properties) present the only currently known topology which remains in controlled converter operation under short circuits on AC and DC side. All other topologies, including thyristor-based HVDC transmission, trip in case of certain short-circuit events. They need countermeasures to survive short-circuit events without destruction. These countermeasures generally disrupt normal mode of operation, also for the control, and lead to tripping of the main switches. Reactive power control, if available at all, is lost together with the loss of energy transmission. With fault clearance, the converter system has to be put into normal operation again – usually requiring time-consuming initialization procedures. Heating up of semiconductors taking up energy mainly adiabatically may introduce further delays before resuming operation. With regard to the suggested solutions and taking into account efficiency, cost and reliability, DC circuit breakers might be regarded as the least promising alternative.

In case of MMC with four-quadrant converter modules, normal operation can be re-established very quickly, for example after lightning-effected short circuits in case of overhead DC transmission. The use of expensive and far less suited DC circuit breakers is not required. Moreover, in case of DC-link short circuits, full reactive-power control is still maintained at both ends of the transmission line. This allows to mitigate the results of sudden power outage caused by the short circuit in the DC link by generating suitable reactive currents on both ends of the transmission line, independent of each other and optimally chosen with regard to the state of the grid on each side.

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