THE APPLICATION OF LINE PROTECTION RELAYS IN HIGH VOLTAGE AC TRANSMISSION GRIDS CONSIDERING THE CAPABILITIES AND LIMITATIONS OF CONNECTED MMCS

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Abstract

The increase in the number of grid connected converters along with the decommissioning of conventional power generation integrated via synchronous generators will lead to a change of the transmission system behaviour under faults. This paper reviews the possible behaviour of Modular Multilevel Converters (MMCs) under AC faults, considering different grid conditions and control objectives as well as the resulting impact on the line protection functionality. One main result is that typical distance protection relays will mal-operate when installed at radial line ends terminated by MMCs due to the different short circuit powers of the MMC and the grid, the flexible phase angle of the MMCs AC side current and the changed current profiles under asymmetrical faults compared to HVAC systems fed by synchronous generators. For cases in which the MMC is connected at busbars with multiple outgoing lines, its impact depends on the short circuit power of the connected nodes. However, even for low short circuit powers of the surrounding grid, both distance and differential protection work reliably as the MMC does not significantly change the characteristic behaviour of the AC transmission grid.

1. Introduction

The increasing integration of HVDC connected power sources like remote offshore wind farms into the transmission grid has led to a re-evaluation of the proper functionality of common AC protection relays, especially distance protection, as the converters exhibit different behaviour under AC faults in comparison to synchronous generators. The reaction of state-of-the-art voltage source converters (VSC) connected to the HVAC transmission system, namely the Modular Multilevel Converter (MMC), under AC line faults is defined by the control system and the converter's internal limitations. The latter arise due to the limited current-carrying capability of the power electronic devices within the converters and typically limit the AC side currents to 1 - 1.2 p.u. [1]. With regard to the controls, three aspects are of major importance when evaluating the MMC performance concerning distance protection functionality. The first aspect is the time delay between the impact of the AC fault at the converter terminals and the corresponding reaction of the converter. Contrary to synchronous generators, which react instantaneously to the voltage drop, there is a delay in the reaction of the converter due to the control and measurement system. Secondly, the active and the reactive power contribution of the MMC is not dependent on the impedance between the fault and the MMC, but the MMC can flexibly adjust its active and reactive power contribution – (given a non-zero fault resistance) [2,3]. Thirdly, there exists no standard yet how to control the MMC during unbalanced faults and the current profiles achieved with proposed controls can deviate significantly from the characteristic AC grid fault behaviour [4]. In this paper, the impact of the different possible control modes and the resulting current profiles are investigated with regard to their impact on typical AC line protection functions to complement investigations published previously, which either focus on control under unbalanced conditions or the distance protection functionality. Moreover, both distance and differential protection are taken into account. Furthermore, the location of the MMC within the grid, i.e. at radial lines ends or at a busbar with several outgoing lines is varied.

1.1. *Line protection in HVAC transmission grids*

Distance protection is considered state-of-the-art for AC transmission lines, as it does not need communication and can provide additional back-up protection for neighbouring lines. Distance protection relays calculate the phase-to-ground impedance for each phase and the three phase-to-phase impedances on the basis of local current and voltage measurements. Under fault conditions, the calculated impedance drops and falls within characteristic zones in the RX plane for systems based on synchronous generators. A typical quadrilateral characteristic of numerical distance protection relays is shown in Figure 1 [5].

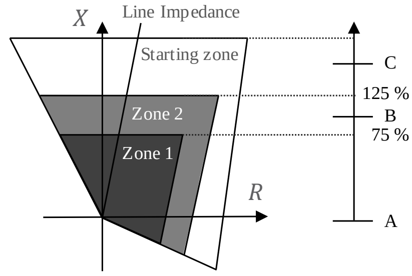

Figure 1 Quadrilateral R-X plane with different zonal settings

It consists of several zones corresponding to a certain part of the line. Typically the first protection zone, which sends a trip signal immediately, covers 75 – 85% of the line. The second zone provides back-up protection for up to 25 % of the neighbouring line and trips with a delay of around 300 ms. Full selectivity, i.e. covering 100% of the line, is not possible, because of measurement and line parameter uncertainties [5].

The impedance calculated by the distance relay depends on the fault conditions for the different types of faults in meshed AC systems. The fault current contribution from both sides will lead to an additionally calculated component apart from the line and fault impedance, c.f. Figure 2. This error term $\underline{I}_B / \underline{I}_A \cdot R_F$ is influenced by the fault resistance, the difference in magnitude between the current contributions from each side and the angle between both sides [5].

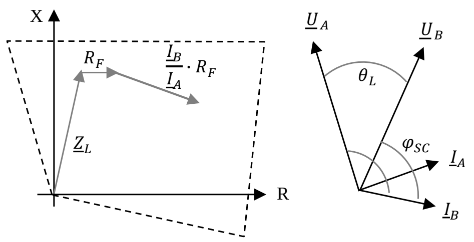

Figure 2 Calculated impedance components [5]

In case of HVAC transmission grids without integrated HVDC converters, the fault current contribution from both sides is typically similar and the phase angle after the fault stays similar to the pre-fault value according to the power flow. Correspondingly, the calculated impedance only changes marginally. This can be accounted for in the design of the quadrilateral characteristic and the definition of the zones [5].

An additional relay typically used in AC transmission systems is the differential protection. It calculates the differential current between the line ends for each phase. If the current is greater than a threshold (taking into account measurement inaccuracies), the relay trips. Contrary to the distance protection, the differential protection requires communication between the line ends, but it is thereby fully selective [5].

1.2. Requirements on converters during AC faults

The requirements on the behaviour of converters connected to transmission grids during AC faults have evolved over time with the increased integration of converters. The main network codes considered for this paper are the HVDC network code prepared by the ENTSO-E and published by the European Commission as well as the corresponding national implementations. The most basic requirement under fault conditions is for the converter to stay connected to the transmission grid during voltage sags at its AC point of connection (PoC) for a certain voltage level and time [7]. Most recent national implementations require the converter to stay connected during zero voltage for at least 140 ms. This time corresponds to the maximum allowed fault clearing time in the first protection zone for balanced and unbalanced faults. While the ENTSO-E's HVDC grid code demands the capability of fast fault current contribution for symmetrical (3-phase) faults if specified by the system operator, the requirement to provide asymmetrical current injection in the case of asymmetrical faults is left open [7]. The fault current contribution has been further specified in some national implementations, most of which now require reactive fault current contribution to support the voltage. Detailed requirements are given in the published German implementation including separate specifications for positive and negative sequence and the respective timings: The rise time to 90 % of the required additional reactive current should be below 50 ms and the settling time should be smaller than 80 ms. The overall control objective stated is to counteract the negative sequence voltage of the grid to the maximum amount possible. In addition, a non-current based reference system should be available for future systems [8].

1.3. MMCs under AC fault conditions and their impact on AC line protection functionality

The control of MMCs under unbalanced AC faults has been the subject of manifold investigations. The focus of each investigation and the correspondingly proposed control concepts differ. Aspects often studied are e.g., the limitation of the converter internal stresses during faults, the alleviation of DC side 100-Hz ripples during unbalanced faults, the internal energy balancing and fast fault current contribution [4]. To allow appropriate control under unbalanced faults, a decoupled control of positive and negative sequence in combination with an appropriate internal energy balancing is needed.

The impact of MMCs on AC line protection has been the subject of investigations focussing on the functionality of distance protection installed at lines terminated by MMCs [3,6]. However, these investigations have not yet taken into account the different possible behaviours of MMCs under varying control concepts for unbalanced faults. A major difference exists between a control using negative current suppression to reduce the stresses on the MMC's components and a dedicated negative sequence current injection. Furthermore, the impact of MMCs on the surrounding grid and its protection has not yet been assessed, i.e. when the MMCs are not connected at a radial line end.

2. Methodology and Investigation framework

To assess the performance of both distance and differential protection for different control objectives of the MMC for different grid conditions, a test system in PSCAD|EMTDC is built up. The following provides a short overview of the implemented models and system parameters.

2.1. AC grid modelling

The AC grid is modelled similarly to the requirements given in IEC 60255-121 by Thévenin equivalents, as commonly done for AC fault studies [9]. To assess the impact of a changing short circuit contribution, the short circuit power (SCP) - a fictive and grid condition dependent value defined as $S_k'' = \sqrt{3} \cdot U_N \cdot I_k''$ - is varied to 5 GVA and 30 GVA [10]. An overview of the assumed values is given in Table 1. The overhead lines are based on the Danuba tower design with four conductors of 264-AL1/34-ST1A in each phase and represented by a frequency dependent phase model [1]. Each line is 40 km long.

The grid layout is shown in Figure 3; a three terminal system is used to represent the infeed from the two line ends. At each line end either an MMC or a Thévenin equivalent is connected.

Table 1 AC grid modelling

Thévenin equivalent parameters		Rating
Rated AC voltage	$V_{AC,r}$	400 kV
Short circuit power	S_k''	5 / 30 GVA
X/R		10
Z_0 / Z_1		1.33

For the investigation of the MMC behaviour at a line end, an MMC is connected to busbar 1, with the other sources at busbar 2 and 3 being Thévenin equivalents. As a reference case, the MMC is replaced by another Thévenin equivalent. In a second analysis, Thévenin equivalents are connected to busbar 1 and 3 only and the effect of the connection of an MMC at busbar 2 is investigated. Faults with a fault resistance of 2 Ω are simulated at 25 % of line 1-2 and at 25 % of line 2-3. Three phase-to-ground faults, phase-to-phase faults and phase-to-ground faults are taken into account. To be able to study the effect of the MMC on the system and protection without further impact factors, the power flow is set to zero in all cases.

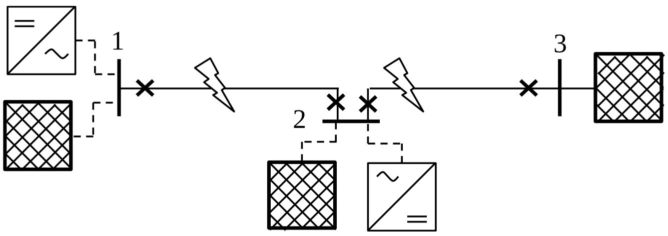

Figure 3 Considered AC grid topology and MMC locations

2.2. *AC Protection modelling*

The implemented distance protection uses a quadrilateral characteristic, as discussed in section 1.1. The measurement and calculation scheme is implemented as follows: A Fast Fourier Transformation is used to extract the 50-Hz component of the current and voltage measurements at each line end, which are then used to calculate the phase-to-ground and phase-to-phase impedances. The measured values are represented per unitised based on the impedance determined for a solid fault at the end of the respective line. To account for different fault resistances, the resistive characteristic of the protection polygons is enlarged. The implemented quadrilateral characteristics for the first and second zone are for example shown in Figure 5. While this impedance evaluation describes the main functionality of distance protection, distance relays implemented in the field also contain algorithms for assessing the directionality of the fault and have special algorithms for selecting the faulted phase. These functionalities are not in the scope of this paper.

The differential protection is implemented as a dual slope relay in PSCAD, taking into account the measurement uncertainties. It is also based on the evaluation of the 50-Hz components.

2.3. *Converter modelling and parametrisation*

The converters are modelled as a type 4 detailed equivalent model [1] in symmetrical monopole configuration with half-bridge submodules. They are connected to the AC grid via a wye-delta transformer with a grounded star point on the primary side. The main parameters of the converters are chosen based on existing offshore HVDC connections in Germany and are summarized in Table 2.

Table 2 Converter modelling

Converter station parameter		Rating
Rated power	S_r	1265 MVA
Rated active power	P_r	1200 MW
Rated DC pole voltage	$V_{dc,r}$	± 320 kV
Rated DC current	$I_{dc,r}$	1.875 kA
Rated AC voltage	$V_{ac,r}$	400 kV
Arm inductance	L_{arm}	42 mH
Number of SM per arm	n_{sm}	350
Rated submodule voltage	$V_{sm,r}$	1.9 kV
Submodule Capacitor	C_{sm}	8.8 mF
IGBT repetitive peak current	$I_{IGBT,max}$	3.0 kA

2.4. *Converter control*

The control concept is based on the cascaded state vector control of the CIGRE benchmark model [1]. It includes a PLL in the decoupled double synchronous reference frame (DDSRF) to accurately control positive and negative sequence components. The upper level controls are implemented in dq reference frame. The positive sequence i_{d+} and i_{q+} references are generated either based on V_{DC} or V_{AC} references respectively. For negative sequence current suppression, the negative sequence references i_{d-} and i_{q-} are set to zero. For a dedicated negative sequence current injection, they are calculated based on the negative sequence voltage measured at the converter terminals, according to [11]. These references are fed into the current controller which is also implemented in the DDSRF allowing independent control of positive and negative sequence currents. The circulating suppression control is implemented in alpha-beta reference frame for the suppression of DC side ripples in case of unbalanced AC faults.

2.5. *Assessment of protection performance*

The performance of distance protection encompasses several aspects, firstly the relay has to detect the fault, e.g. based on a starting zone, secondly the correct lines should be identified as faulted, thirdly the calculated impedance should be in the correct protection zone, i.e. resulting in the correct selection of the faulted line(s) and correct timing of the tripping signals. To allow distinct single phase opening of the AC circuit breaker, as is used for single phase-to-ground faults in some countries, only the respective phase-to-ground line should be identified as faulted. Furthermore, the trip signals for faults in the first zone should be sent without further delay, while second zone faults should not be tripped without the corresponding time delay. Moreover, the calculated impedance will go through some transients before settling at the final value.

This time dependent development affects the point in time when the trip signal is sent.

For the differential protection, the calculated differential currents are evaluated.

3. AC line protection performance at lines terminated by MMCs

In the following the behaviour of the system for the connection of an MMC at busbar 1 for 2-Ω faults at 25 % of line 1-2 at $t = 5$ ms is compared to the connection of a grid equivalent with SCP = 5 GVA at the same location. The line, colour and marker styles for all plots in this paper are as follows:

Linestyle	—	Solid: MMC	- -	Dashed: Grid
Colour	—	Grey: SCP = 5 GVA	—	Blue: SCP = 30 GVA
Marker	●	Circle: MMC	■	Square: Grid

3.1. *Three-phase-to-ground faults*

The resulting voltage and current profiles for a balanced three-phase-to-ground fault are shown along with the calculated R and X values for the phase1-phase2 impedance in Figure 4. The other calculated line-to-line impedances show a similar behaviour apart from the existing OHL line imbalances. The current contribution of the MMC is delayed, smaller in magnitude and shifted in phase in comparison to the grid equivalent. In consequence, the calculated resistance and reactance need a longer time to settle at the final values. The resulting impedance in the RX plane and the differential current values are shown in Figure 5. The RX plane and differential current plot contain additional fault cases for SCP = 30 GVA to give a more representative overview. The impedances are evaluated Δt = 60 ms after fault occurrence.

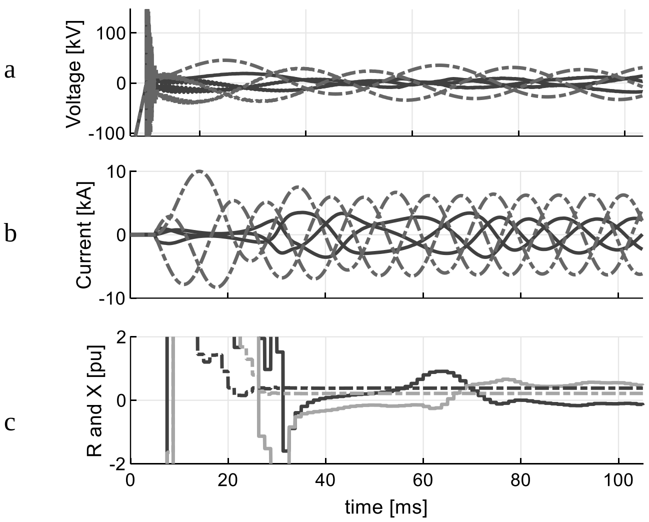

Figure 4 Comparison of a) voltage, b) current and c) impedances at busbar 1 for MMC and Thévenin equivalent

The delay of the current contribution and the reactive power support of the MMC lead to a calculation of the impedance outside the first distance protection zone. Consequently, the distance protection will not trip or trip with a delay under these circumstances. The differential current calculated is exceeding the threshold in all cases, leading to correct operation of the differential protection.

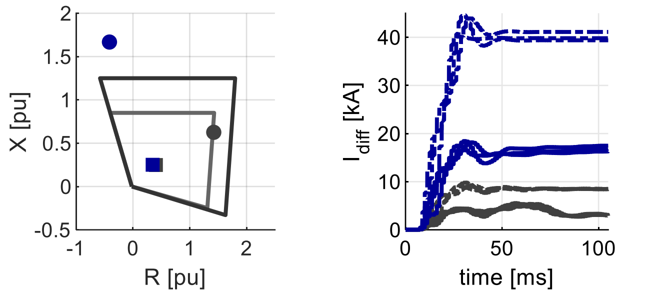

Figure 5 Calculated impedance and differential currents

3.2. *Phase-to-phase faults*

Phase-to-phase faults have a characteristic current and voltage profile in HVAC transmission grids: The faulted phase voltages are in phase and the faulted phase currents have a 180° phase shift, c.f. Figure 6a and b. However, when using an MMC with negative sequence current suppression control, the MMC supplies a balanced three phase current after some transition period. The transition period leads to a delay in the settling of the calculated impedances by the distance relay. Moreover, for SCP = 30 GVA of the surrounding grid, the impedance is located outside the protection characteristic leading to non-operation of the relay. The differential protection works reliably based on the calculated differential current (c.f. Figure 7).

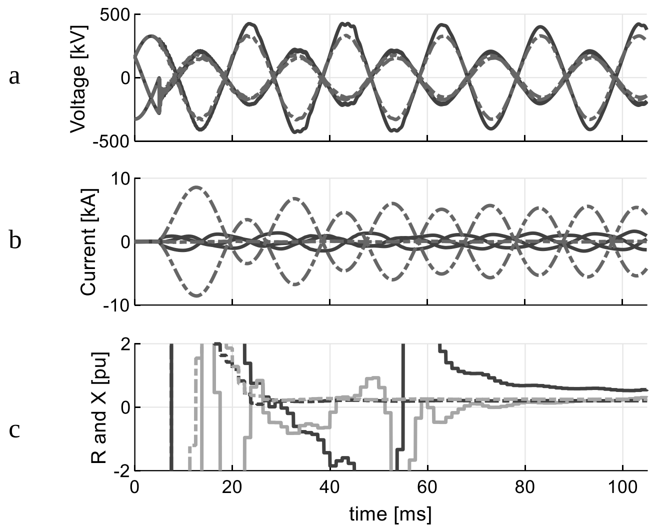

Figure 6 Comparison of a) voltage, b) current and c) impedances at busbar 1 for MMC and Thévenin equivalent

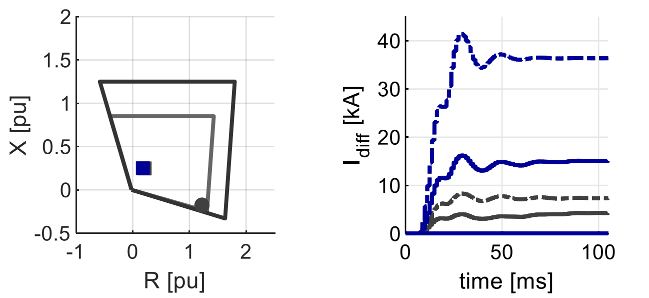

Figure 7 Calculated impedance and differential currents

3.3. *Phase-to-ground faults*

Phase-to-ground faults are the most likely fault type in transmission systems. They characteristically feature a low voltage and a high fault current on the faulted phase. Moreover, they exhibit a high zero sequence current. This zero sequence component in combination with the wye-delta transformer is the reason for the asymmetry in the currents at the MMC terminal even with negative sequence current suppression control. The calculated impedances settle at the final value within the protection zone within one cycle due to the zero sequence component. For the exemplary chosen case with negative sequence current injection (in light green), the calculated resistance and reactance get reduced, leading to a mal-operation of the relay.

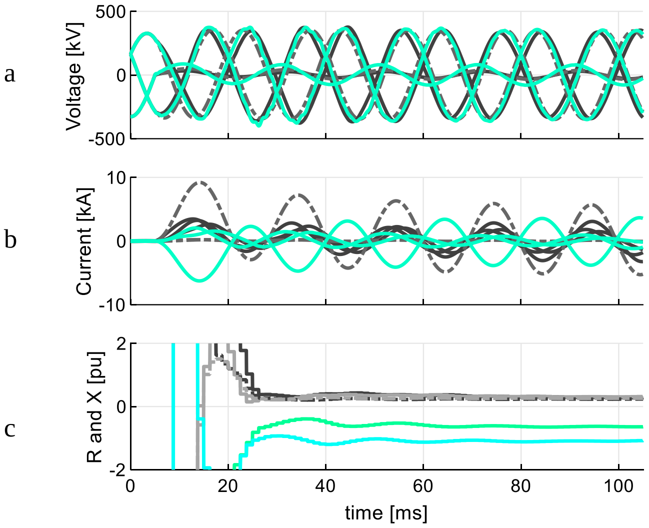

Figure 8 Comparison of a) voltage, b) current and c) impedances at busbar 1 for MMC and Thévenin equivalent

The resulting impedances of the faulted phase-to-ground loop fall within the RX plane for negative sequence current suppression, c.f. Figure 9. The calculated differential currents lead to selective tripping of the differential relay for all cases.

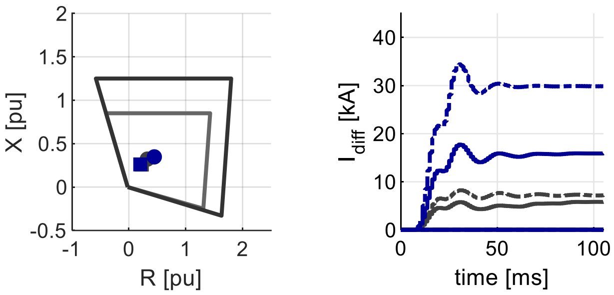

Figure 9 Calculated impedance and differential currents

4. AC line protection performance at busbars with MMCs

In the following, the behaviour of the system for the connection of an MMC at busbar 2 for 2-Ω faults on line 2-3 is compared to the system without the MMC at busbar 2 for the different types of faults. The shown measurements are taken at the left line end of line 2-3. The order of analyses is reversed due to different key results.

4.1. *Phase-to-ground faults*

The resulting voltage and current profiles for a phase-to-ground fault are shown in Figure 10 for different short circuit powers and a control with negative sequence current suppression. As can be seen the current and voltage profiles – albeit changing in magnitude due to the additional star point to ground connection of the converter transformer - largely represent the typical profiles of HVAC transmission grids as discussed in section 3.3, even though the output current profiles of the MMCs are the same as in in section 3.3 using the negative current suppression control. Correspondingly, the calculated impedances are very similar to the scenario without the MMC and settle at their final values in under two cycles, c.f. Figure 10c and Figure 11.

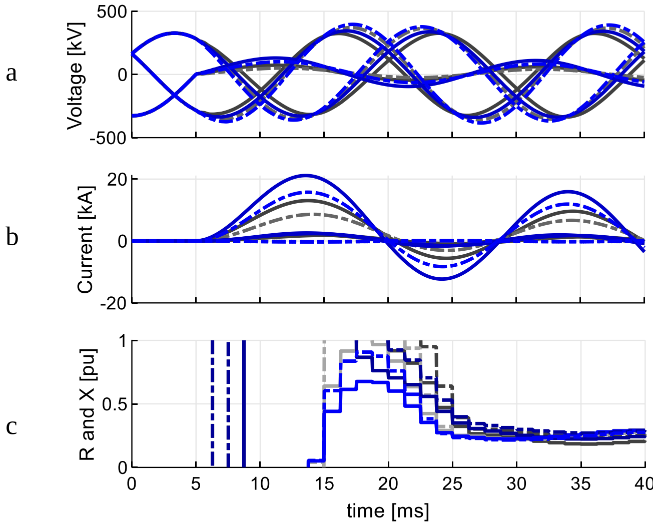

Figure 10 Comparison of a) voltage, b) current and c) impedances at line 2-3 with and without the MMC

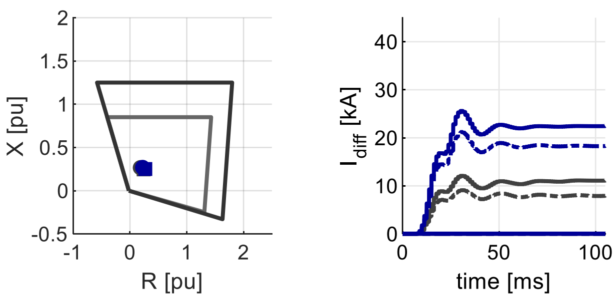

Figure 11 Calculated impedance and differential currents

4.2. *Phase-to-phase faults*

Similarly to the results for phase-to-ground faults, the voltage and current profiles at the line end correspond to the typical behaviour of HVAC transmission grids under integration of the MMC. Exemplarly the measured currents at line 2-3 are shown in Figure 12. Even though the negative current suppression is activated, leading to largely different current profiles at the MMC terminal, the resulting impact on the line current is marginal. This also results in very similar impedance measurements and differential currents as shown in Figure 13.

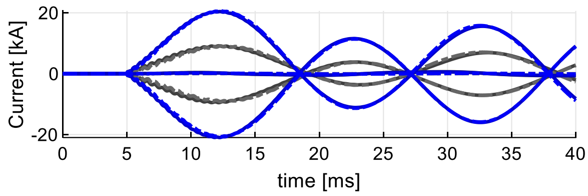

Figure 12 Current at line 2-3

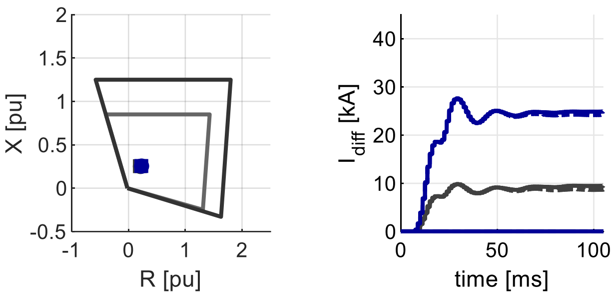

Figure 13 Calculated impedance and differential currents

4.3. Three-phase-to-ground faults

In case of balanced faults the current and voltage profiles are similar to the system without MMC integration. Correspondingly, the calculated impedances and differential currents are similar as shown in Figure 14. The impedance measurement is changed slightly due to the reactive power support.

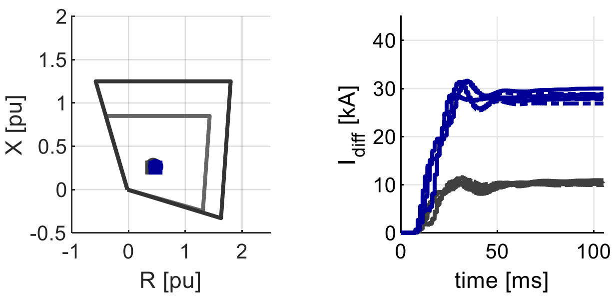

Figure 14 Calculated impedance and differential currents

5. Conclusion

MMCs are designed for high voltage and high power applications, offer flexible control over active and reactive power and are able to adjust the positive and negative sequence currents. However, when considering fault scenarios, the MMCs will always be limited in their current contribution to approximately their rated current, have a delay in fault current contribution and the discussed controls will lead to uncharacteristic current profiles.

If the MMC is the only source of short circuit current for a relay, the application of distance protection relays is not advised based on the given results. Regardless of the fault type, zone 1 faults might not be identified, thus leading to a loss of selectivity. The differential protection works selectively in all analysed cases.

If there is additional short circuit current contribution from the surrounding grid, which still displays the characteristic behaviour of solidly grounded AC systems, the impact of the MMC is small and both distance and differential protection operate selectively.

Acknowledgements

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