Impact factors of modular multilevel converters on the second zone of distance protection

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***Abstract*—The introduction of an increasing number of converters in the existing AC systems has led to a series of challenges. One of them is securing the stability of the existing AC grids in case of faults. This work reviews existing contributions on the impact of modular multilevel converters (MMC) on the AC distance protection, especially on its second zone. Based on this analysis, study cases are derived to compare the impact of an MMC on the distance protection to other impact factors. Thereafter, a differentiation between the factors resulting from the chosen system configuration and the impact of the MMC is given. The results show that there is an impact of the MMC on the second zone due to the given system topology. However, the impact of the MMC on the impedance measurement does not exceed the variation due to other impact factors, because of its limited fault current contribution capability. Depending on the previously existing system conditions, the impact of an MMC inserted as intermediate infeed into an existing line is negligible in a meshed AC grid due to its limited short circuit current contribution.**

***Index Terms*—Distance Relay – Fault detection – Voltage source converters.**

I. INTRODUCTION

To achieve a reduction of emitted carbon dioxide, more renewable energy sources are integrated into the existing AC systems with a large share of these renewables being integrated via converters. A prominent example are offshore wind power plants. With offshore wind farms being located further offshore, the need to connect them to the mainland via high voltage direct current (HVDC) transmission arises. In Europe, there are already several offshore wind farms connected to the high voltage AC (HVAC) grid via HVDC links. The connections are based on the MMC technology [1]. The phase-out of power plants with synchronous generators and the shift to converter-interfaced energy sources lead to several challenges: Lower system inertia, possible power quality issues, a less secured power production, more controllable elements in the grid and, more specifically, a possible impact on the existing line protection system [2]. The latter is in the focus of this work.

The protection of the existing HVAC transmission grid is based on the characteristic behavior of solidly earthed meshed AC grids fed by large synchronous generators. In case of a fault in the transmission system, the synchronous generators instantaneously contribute a high current exceeding the steady-state current several times. To ensure reliable fault detection and voltage stability, the short circuit power (SCP) of the HVAC grids is designed to be sufficiently high while at the same time ensuring the safety of components. In the central European grid, the SCP goes up to several tens of GVA and AC circuit breakers can break faults currents of up to 63 kA [3].

The detection of faults is achieved mainly by distance protection relays, which do not only allow fault detection, but can also provide fault localization and back-up protection for neighboring lines. They measure the resulting impedance in case of a fault, which is reduced in comparison to load conditions. The distance protection accomplishes fault detection in 1-2 cycles of the fundamental frequency. Subsequently, the AC circuit breakers take 2-3 cycles for opening. To ensure the stability of the system in case of a line fault, a maximum fault clearing time of 140–250 ms is set in the corresponding grid codes [4].

Contrary to the synchronous generators, the short-circuit contribution of an MMC depends on its specific converter design and its controls. The maximum short-circuit contribution of converters is limited by the current carrying capability of the power electronic components. Consequently, their current infeed capacity in case of faults is only marginally higher or the same as their rated current. Furthermore, their active and reactive power infeed does not depend on the system impedance but can be adapted according to the chosen control sets and grid code requirements within the current limits of the converter [1].

There are several publications indicating a negative impact on the second zone of distance protection relays when integrating MMCs, i.e. faults occurring at the limit of the second and third zone are localized in the third zone. This paper investigates to which degree the indicated impact is based on the characteristics of the converter and its controls, how other impact factors, such as load flow and fault resistance, compare to the impact of the MMC and which aspects are based on the topological network configuration.

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The paper is structured into five sections. Section 2 gives the background on AC systems under fault, MMC converter controls under AC faults, the relevant grid code requirements in Europe and distance protection relays. Section 3 describes the investigation framework including the models and scenarios implemented in EMTDC|PSCAD. Section 4 then presents the resulting impact of the analyzed scenarios on the second zone of the distance protection and section 5 discusses the results and concludes the paper.

II. BACKGROUND

A. Characteristic fault response of high voltage AC grids

High voltage AC transmission grids are typically solidly earthed at the transformer star point. This leads to high fault currents in the affected phases and little voltage displacement of the healthy phases in case of a fault. The main fault current contribution stems from the synchronous generators connected to the transmission grid. The current response of a synchronous generator depends on its construction and the fault and line impedances. Faults close to the generators exhibit a high initial fault current with a significant DC component. The short circuit power of high voltage AC grids at any given point is commonly specified using formula (1).

$$S_k'' = \sqrt{3} \cdot U_\mathrm{N} \cdot I_k'' \qquad (1)$$

Where U_N defines the nominal voltage level without fault, and I_k'' is the initial fault current. This is a fictional value as the high fault current and nominal voltage will not occur at the same time [3].

B. MMC control under AC fault conditions

In contrast to synchronous generators, voltage source converters do not have an inherent AC fault response. Their response depends on their controls and the current limits of the power electronic components. The MMC is typically controlled using a cascaded vector control allowing independent control of the active and reactive power [1]. This includes a V_AC control mode, which can be used to implement dynamic voltage support during AC faults. Furthermore, a current limiter is commonly included, which ensures that the combination of the references for active and reactive current contribution do not exceed the maximum current capability of the converter. It can also be used to give preference to active or reactive current contribution [1].

AC faults close to a converter station result in a reduction of transferable active power between the AC and DC system and consequently a power imbalance. For the existing HVDC connections of offshore wind power plants, an AC onshore fault leads to an increase in the DC voltage because the wind power plant keeps feeding the DC system. To alleviate this DC overvoltage, dynamic breaking systems (also called DC choppers) are installed at the onshore stations. In case of overvoltages, they convert the excess energy into heat in a resistor or surge arrester controlled by a hysteresis control [1].

C. Grid Code requirements for HVDC systems

A first “Network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules to the AC system” has been suggested by ENTSO-E and have been legislated by the European commission in August 2016. Based on this, national implementations were drafted in the following two years. The following paragraphs state the main requirements with regard to the behavior during AC faults from the EU legislation. In addition, more detailed requirements from the German implementation are used as a reference [5].

As a basic requirement, a voltage-time characteristic is given that represents the conditions during which the converters have to be able to stay connected to the AC system. Meeting this requirement is often referred to as Fault Ride Through (FRT) capability [5].

In addition to staying connected to the AC system during reduced voltage levels for a certain period, article 19 states the requirements with regard to the short circuit contribution during faults. If the system operator (SO) specifies it, the HVDC system shall have the capability to provide a fast fault current contribution. The exact specifications have to be defined by the SO and the transmission system operator (TSO). Furthermore, it leaves the possibility to specify a requirement for asymmetrical current injection [5].

Article 22 defines the requirements on the dynamic reaction during voltage changes: Following a step change in voltage, the converter should achieve 90 % of the required change of output currents in a maximum time period of 0.1 s and should settle at the specified value after a maximum of 1 s. Article 23 states that priority can be given to active or reactive power contribution during faults [5].

In the German implementation, priority is given to reactive power support and the infeed is specified in positive and negative sequence components. Furthermore, the required reactive contribution should reach 90 % within 50 ms and 100 % within 80 ms with a maximum deviation of -5 % to +15 %. The relation between the voltage drop (U-U_ref) and the additional reactive current contribution (Δi_B) is given in (2). The parameter k can be varied between $k = 2\ldots6$ for the positive sequence. For the negative sequence, k can either be equal to the positive sequence’s k or 0 [6]. The specification in negative sequence components is taken into account to ensure the maximum fault current contribution from the converter in case of asymmetric faults [4].

$$\Delta i_\mathrm{B} = k \cdot (U - U_\mathrm{ref}) / (U_\mathrm{n}/\sqrt{3}) \qquad (2)$$

D. Distance protection relays

Distance relays calculate the impedance resulting from the voltage and current measurements at the relay location. In case of a fault in an HVAC system, the voltage drops and the current rises leading to a decline in the calculated impedance. Based on the resulting resistances and reactances, a plane is defined, which separates load from fault conditions as shown in Figure 1. The shown characteristic is called quadrilateral. It allows independent setting of the resistive and reactive reach of the protection relay [7]. The plane is divided into several zones, representing different lengths of the line to be protected and being associated with different tripping times. Commonly the first protection zone covers between 75 % and 85 % of the line. The length of the line to be covered is defined by the reactance setting as the determined resistance is also influenced by the fault resistance. Zone 1 does not cover 100 % of the line to give a security margin accounting for measurement and relay uncertainties. The second zone typically covers up to 125 % of the line and has a delay of several 100 ms. The third zone has a delay of up to 3 s [7].

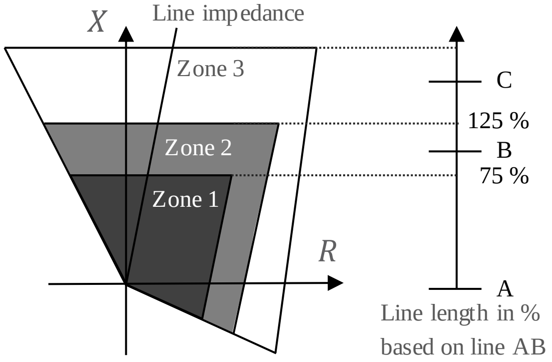

Figure 1: Quadrilateral R-X plane with different zonal settings

The second zone of the distance protection can be used to provide back-up protection. In case of a breaker failure at one end of a faulted line (e.g. at the beginning of line BC in Figure 1), the distance relay at the adjacent line (here: at busbar A) should trip after the defined time delay, if the resulting fault impedance is in the second zone. This is the protection zone many publications identified to be in danger of mal-operation in case of connection of MMCs [8], [9], [10]. The following section will give an overview of the used system topologies, identified influences and proposed remedial actions in these publications.

E. *Review of previous publications*

In the above mentioned publications, MMC are put under scrutiny with regard to their impact on the second zone of AC line protection. For this purpose, a small section of an AC grid is often analysed, as shown in Figure 2, where an additional MMC is connected along a given radial line [8], [9].

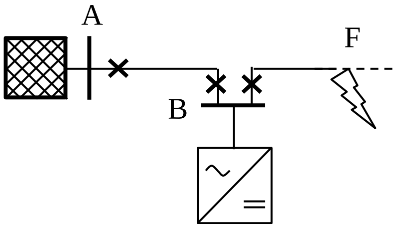

Figure 2: Analysis of the MMC impact based on a small section of an AC grid

In the investigations, the impact of the MMC on the back-up distance protection in location A is examined in case of a fault at position F (presenting the limit of the second zone). The studies conclude with the statement that the connection of the MMC results in an increase in the calculated impedance leading to a fault impedance determination in the third protection zone. As a remedial action, a control scheme of the MMC is proposed ensuring that the ratio between the currents from line AB and BF stays the same [8]. In the analyzed cases, this leads to no fault current contribution from the MMC, such that the connection of the MMC has no influence on the measured impedance. The impact of a change of, the MMC's control mode is investigated in [9], e.g. using active or reactive power priority. The respective investigations conclude that the R-X planes need to be changed for the connection of the MMC. A detailed analysis, however, is not given.

In [10], the IEEE 39-bus system is investigated, wherein two generators are replaced by an HVDC system. Previous to the integration of the HVDC system into the AC network, the second zone boundaries are defined based on a single measurement for a selected fault case. When integrating the HVDC system, it is found that the now determined fault reactance exceeds the previously set boundary. One assumption of the investigation is that the converter contribution of the reactive power support is faster than the generators control scheme. The exact timings are, however, not elaborated.

In general, the previous publications lack information on the assumed short circuit power of the represented sources and grids. Furthermore, other influencing factors, like the fault resistance or load flow are not compared to the influence of the MMC. This paper aims to fill this gap.

F. *Effects on distance protection*

To put the identified impact of the MMC on the second zone of the distance protection into perspective, general impact factors on the distance protection relay are discussed in the following.

One impact factor is the feeding of the fault from two sides, as illustrated in Figure 3, which is commonly the case in meshed systems [11]. The impedance determination in this case at relay A is given in (3).

$$Z_\mathrm{D} = \frac{x}{l} \cdot Z_\mathrm{L} + R_\mathrm{F} + \frac{I_\mathrm{B}}{I_\mathrm{A}} \cdot R_\mathrm{F} \tag{3}$$

The measurements at each side are influenced by the additional contribution of the respective other side. The higher the fault resistance, the higher the difference in amplitude between the two current contributions, and the higher the load flow prior to the fault, the more impact can be noted on the calculated impedance. This results in a calculated impedance value different from the "ideal" value, which is only composed of the fault and line impedances [7].

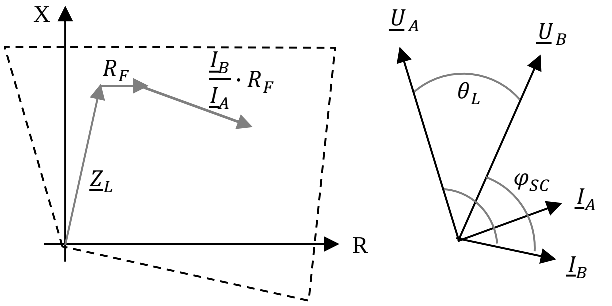

Figure 3: Impact of double-sided infeed on the impedance caluclation [12]

Another aspect to be considered is the intermediate infeed effect, which describes an impact on the impedance determination in the second protection zone. In meshed system topologies, additional fault current sources are often located between the distance relay and the fault on an adjacent line, c.f. Figure 4. In case there is an additional infeed somewhere along the line, the impedance calculated by relay A includes the voltage drop along line AB and the voltage drop along the line section AF. The voltage drop along the line section AF is increased because of the additional current contribution from the intermediate source [7].

The impact of the intermediate infeed on the measurements depends, among other factors, on the relation of the short-circuit strengths at point A and B. In case $SCP_A >> SCP_B$, the resulting impact is very low and vice versa. In case both systems have a low SCP, the impact is high and, in case both systems have a high SCP, the impact is low [13].

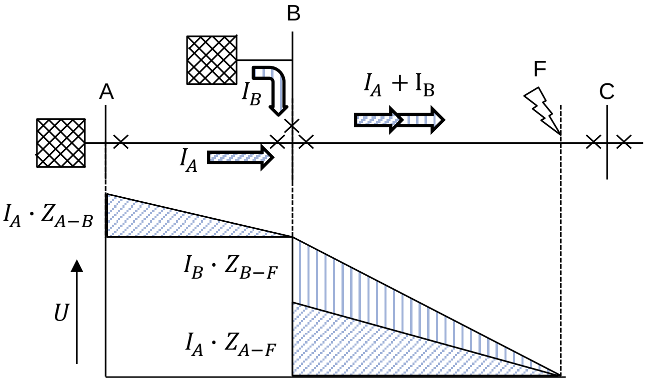

Figure 4: Impact of the intermediate infeed effect on the impedance calculation

III. INVESTIGATION FRAMEWORK

A. Scenario definition

As discussed above, the pre-fault load flow, the fault resistance and the considered grid topology are relevant impact factors, which are independent of the converter.

To analyze the impact of an MMC as intermediate infeed and compare it to the other relevant system parameters, the topology shown in Figure 5. In a first step, line BC is disconnected to compare the behavior of an MMC under different control modes and the typical behavior of the high voltage AC grid. In a second step, the MMC is disconnected with both lines in operation to study the other impact factors independent of the MMC. In a third step, the MMC is re-connected.

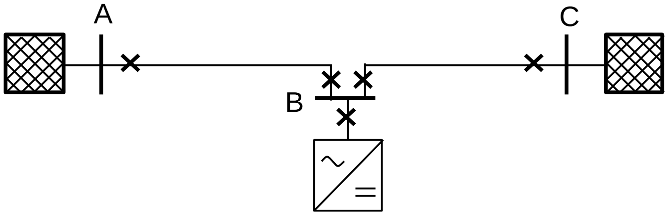

Figure 5: Considered basic grid topology

The networks at A and C are represented by a Thévenin equivalent with exemplary short-circuit powers of 30 GVA and 5 GVA and an X/R ratio of 10 [11], [3]. 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 load flow is varied from 0 MW, to the natural power of 600 MW, and to 80 % of the maximum thermal load of this setup of ca. 1500 MW. Furthermore, both load flow directions are taken into account; from A to C and vice versa.

Within this network, a three-phase fault is applied at 25 % of line BC representing a fault at the border of the second zone for the relay at A. The fault resistance is varied between $R_F = 0\ldots20\ \Omega$.

B. MMC model and control

The half-bridge MMC in symmetrical monopole configuration is represented by a type 4 detailed equivalent model with a cascaded state vector control based on the CIGRE benchmark model [1]. The main parameters of the converter are chosen based on existing offshore HVDC connections in Germany and are summarized in Table I.

To show the impact of different control modes, the following load flow and control settings are chosen: The active power mode is V_{DC} control as this is typical for the onshore station of an offshore link. The power flow infeed is varied between 0 MW and 400 MW. The latter reduced infeed is chosen to highlight the limited fault current contribution capacity during an AC fault. The reactive power mode is varied between the Q control mode with reference Q = 0 MVAr and V_{AC} control mode with $V_{AC,ref} = 400$ kV.

TABLE I. CONVERTER PARAMETRIZATION

Parameter	Rating
Rated station power	1256 MVA
Rated active station power	1200 MW
Rated DC pole voltage	±320 kV
Rated AC voltage at the MMC	350 kV
Rated DC pole current	1.875 kA
Number of submodules per arm	350
Rated submodule voltage	1.9 kV
Submodule capacitance	8.8 mF
Arm resistance	80 mΩ
Arm inductance	42 mH
Converter output inductance	10 mH
Star point reactor	5000 H, 5 kΩ

C. Distance protection implementation

The implemented distance protection uses a quadrilateral characteristic, as discussed in section II.D. 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, which are then used to calculate the impedances. As the components work ideally, an additional delay of one cycle is added to represent the communication and calculation time. The measured values are represented per unitized based on the impedance determined for a fault current loop of a solid three-phase 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 shown in Figure 8 and Figure 9.

IV. SIMULATION RESULTS

A. *Comparison of MMC and HVAC grid under fault conditions*

In a first step, a comparison between the AC sources with different short-circuit powers and the MMC in V_{AC} control mode and no pre-fault current contribution is carried out. The resulting current of phase A for a 3-phase fault with $R_{\mathrm{F}} = 5\ \Omega$ at $t = 2$ ms is shown in Figure 6. The current contribution from the network representation rises instantly to $\hat{\imath}_{30} = 18$ kA for SCP = 30 GVA and to $\hat{\imath}_5 = 10$ kA for SCP = 5 GVA. The MMC does not contribute instantly to the fault current; there is a delay of ca. 60 ms until the maximum contribution equal to the rated current is achieved. In comparison to the contribution from the grid representation, there is a phase shift of 90° as the converter does only feed in reactive power. When analyzing the time frame relevant for fault detection (the first 1-2 cycles of the fundamental frequency), there is a distinct difference in the contributions from the grid representations and the MMC. The contribution from the grid representations occurs instantly, leading to a significant fault current infeed in this time frame. In contrast, the current contribution from the MMC is negligible in the first cycles due to the needed time for the controls to act on the change. The maximum fault current contribution from the MMC is only reached after the detection is expected to take place – albeit in line with the grid code requirements.

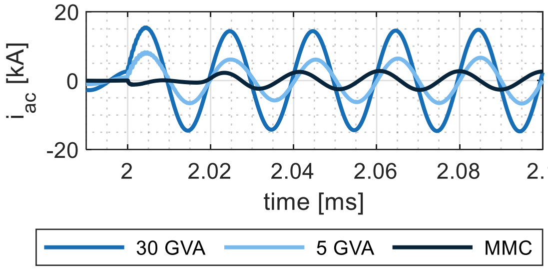

Figure 6: Comparison of MMC and AC grid fault current contribution

B. *Contribution of MMCs for different controls*

Figure 7 shows the contribution from the MMC for a fault at 25 % of line BC with $R_{\mathrm{F}} = 5\ \Omega$ for different control modes and pre-fault load flows. In V_{AC} control mode, the contribution from the MMC always leads to the contribution of the rated current. The rated current is reached after ca. 60 ms. In case of no pre-fault load flow, the steady-state contribution of the MMC in *Q* control mode is negligible as the reference is not changed due to the voltage change. According to the European network code this is an allowable situation in case the *Q* control mode is chosen as the reactive power mode. In case of a pre-fault load flow of 400 MW, the converter contributes rated current. In comparison to the current contribution in V_{AC} control, there is a phase shift of 90°, because only active power is transferred. When taking into account that the fault detection usually takes place in the first 10 ms - 40 ms for faults in the first zone, the contribution of the MMC has not reached its steady state nor the maximum current contribution for any of the control modes or pre-fault power flows during this time.

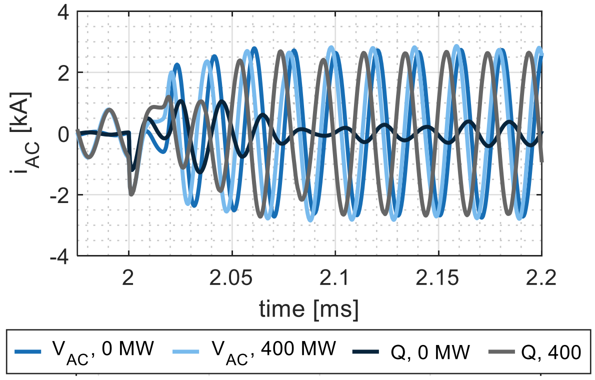

Figure 7: Comparison of MMC contribution for different control modes

C. *Impact factors on the distance protection without MMC*

To show the impact of load flow and fault resistance on the second zone of protection, Figure 8 shows the resulting reactances and resistances determined at relay A, when the MMC is disconnected. For faults with near zero fault resistance there is no influence of the load flow and the reactance value is measured as 1.25 pu representing the exact fault location. When increasing the fault resistance, there is, on the one hand, a shift of the resistive part to higher values. On the other hand, the impact of the load flow increases, such that the reactive component for the same fault resistance and fault location is influenced leading to under- or overreaching of the distance relay depending on the load flow direction. While the combination of a fault with $R_{\mathrm{F}} = 20\ \Omega$ and a load flow close to maximum thermal rating can be considered an extreme case, also faults with $R_{\mathrm{F}} = 5\ \Omega$ and a load flow at natural power lead to a deviation from the ideal value of 1.25 p.u. for the reactance.

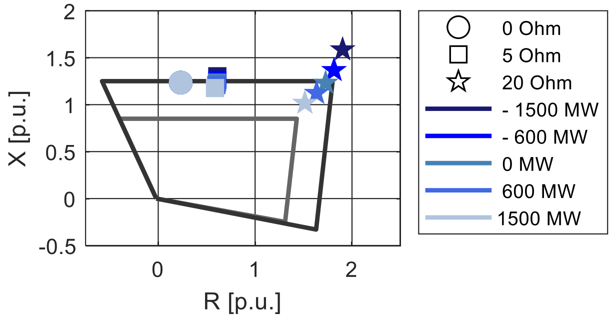

Figure 8: Impact of fault resistance and load flow on relay A

D. *Impact of MMC as intermediate infeed*

In the following, the same fault cases are studied with an MMC connected at terminal B. To separate the impact of the MMC on the load flow and only show the impact of the current contribution of the MMC as intermediate infeed during a fault, the MMC does not feed in active power before the fault. The converter is in V_{AC} mode, such that there is a current contribution from the MMC in case of a fault. In Figure 9, the cases including the MMC are displayed in black in addition to the previous cases. The shown impedances are evaluated when the measured impedance is constant over time, i.e. the current contribution from the MMC has reached its steady state. As can be seen, the impact of the MMC increases with the fault resistance – similar to the previously shown effects. However, the range, in which the MMC changes the measured impedance, could also be caused by a change in load flow or fault resistance – impact factors that also exist without the MMC. Overall, there is no significant amplification of the range, in which inductance and resistance are calculated because of the MMC as intermediate infeed source.

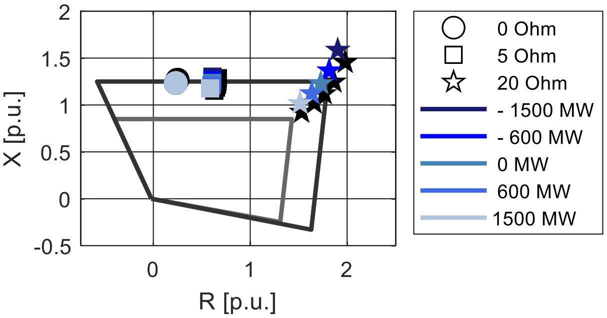

Figure 9: Impact of the MMC as intermediate infeed on relay A

V. Discussion and Conclusions

As shown for the given system set-up, the impact of an MMC as intermediate infeed in an existing meshed HVAC grid is rather small and lies in the same range as other impact factors that need to be taken into account when parametrizing the distance protection in AC systems – even without intermediate infeed. This is mainly due to the fact that the MMC has a small short circuit current contribution in comparison to the existing HVAC grids.

As the converter does not have an inherent fault response, the current contribution of the MMC is very low in amplitude during the time frame commonly assumed for fault detection with existing AC relays in the first protection zone; the maximum current contribution only occurs after a certain delay due to the control and its associated measurement and communication scheme. While this is not critical in the above cases, where the MMC is connected as an intermediate infeed into an existing strong AC grid, the connection of an MMC at a remote line end represents a more critical scenario for fault detection with distance relays [14].

Another topic of interest with regard to FRT is the control of the MMC and its current contribution during asymmetric faults. There is not yet a standard control for the asymmetric fault current contribution [15]. The FRT of a converter for unbalanced faults represents a challenge with regard to the converter internal energy balancing, but also because the fault current contribution from the MMC does not correspond to the typical AC fault current profiles.

Acknowledgment

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References

[1] Cigré Working Group B4.57, “Guide for the Development of Models for HVDC Converters in a HVDC Grid,” Cigré, Dec. 2014.

[2] ENTSO-E, "High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS)," ENTSO-E, Brussels, BE, Mar. 2017, [Online]. Available: https://docstore.entsoe.eu/Documents/Network%20codes%20documents/Implementation/CNC/170322_IGD25_HPoPEIPS.pdf

[3] D. Oeding and B. R. Oswald, *Elektrische Kraftwerke und Netze*, Springer, ed. 7, München, 2011.

[4] ENTSO-E (2016, Nov), "Fault current contribution from PPMS & HVDC," ENTSO-E, Brussels, BE, [Online]. Available: https://docstore.entsoe.eu/Documents/Network%20codes%20documents/Implementation/CNC/IGD-Fault_Current_Contribution.pdf

[5] *Network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules,* COMISSION REGULATION (EU) 2016/1447, Aug. 2016.

[6] *VDE Technische Regeln für den Anschluss von HGÜ-Systemen und über HGÜ-Systeme angeschlossene Erzeugungsanlagen (TAR HGÜ)*, VDE-AR-N 413, Mar. 2018.

[7] G. Ziegler, *Numerical Distance Protection: Principles and Application*, Publicis, Erlangen, 2011.

[8] M. Zolfaghari, R. M. Chabanlo, M. Abedi and M. Shahidehpour, “A Robust Distance Protection Approach for Bulk AC Power System Considering the Effects of HVDC Interfaced Offshore Wind Units," in *IEEE Systems Journal*, vol 12 (4), p. 3786 -3795, Dec 2018.

[9] C. Teixeira and H. Leite, “The influence of a VSC based HVDC link on distance protection relay assessed by CAPE software,” in *2017 IEEE Manchester PowerTech*.

[10] L. He, C. Liu, A. Pitto and D. Cirio, "Distance Protection of AC Grid With HVDC-Connected Offshore Wind Generators," *IEEE Transactions on Power delivery*, vol. 29(2), pp. 493-501, Apr. 2014.

[11] *Messrelais und Schutzeinrichtungen – Teil 121: Funktionsanforderungen für den Distanzschutz,* DIN EN 60255-121, Jan. 2015.

[12] C. Gererstorfer, S. Stukelj and W. Gawlik, "Schutz in Netzen mit leistungselektronischer Einspeisung – Betrachtungen zu Einflussgrößen auf die Distanzmessung von Distanzschutzgeräten," *Elektrotechnik & Informationstechnik*, vol. 133, pp. 381-387, Aug. 2016.

[13] M. Kuflom, P. Crossley and M. Osborne, "Impact of ‘intermediate’ sources on distance protection of transmission line," in *Proc. The 14th International Conference on Developments in Power System Protection*, pp. 913-914, 2018.

[14] A. Hooshyar, M. A. Azzouz and E. F. El-Saadany, "Distance Protection of Lines Emanating From Full-Scale Converter-Interfaced Renewable Energy Power Plants—Part I: Problem Statement," in *IEEE Transactions on Power Delivery*, vol 30 (4), p. 1770 - 1780, 2015.

[15] J. Li, G. Konstantinou, H. R. Wickramasinghe and J. Pou, "Operation and Control Methods of Modular Multilevel Converters in Unbalanced AC Grids: A Review," in *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol 7 (2), p. 1258 - 1271, Jun 2019.