Frequency Domain Analysis of HVDC Grid Non-unit Protection

Vasileios Psaras, Grain Adam, Graeme Burt

Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow, UK
vasileios.psaras@strath.ac.uk

Keywords: Frequency domain analysis, HVDC grids, HVDC protection, non-unit protection.

Abstract

Owing to the fact that travelling wave propagation in an HVDC grid is a heavily frequency dependent phenomenon, frequency domain analysis has been identified as a useful means of assessing the capabilities and limitations of non-unit protection. This exploits the fact that the main difference between an internal and external fault is the presence of the series inductor in the fault path. The inductor acts as a high impedance element for high frequency components and consequently the transient voltage frequency response in each fault case is recognisably different. On this basis, the investigation in the frequency domain can reveal significant information for protection design purposes. Towards this aim, the transient voltage at the relay location is meticulously represented in the frequency domain by taking into account the transmission medium length and geometry, the number of other attached feeders to the same bus, the converter parameters, the inductive termination, the fault resistance, and the travelling wave behaviour of DC faults. By performing a sensitivity analysis on these parameters, a deeper understanding of their impact on HVDC non-unit protection is obtained. In addition, the factors that can be adjusted to extend the reach of the protection systems are revealed and a generic approach for analytically calculating the protection threshold is developed.

1 Introduction

HVDC grids constitute an attractive option for bulk power transfer over long distances and facilitate the integration of large dispersed offshore wind farms and their interconnection with the onshore AC grids [1]. One of the key enabling technologies for the realisation of the HVDC grid concept is the development of well performing and cost-effective DC protection systems. Owing to the very high rate of rise of fault currents and the under-voltages occurring during DC faults, DC protection systems are characterised by more stringent requirements in terms of speed, selectivity, sensitivity and reliability [2]. Without adequate protection solutions, converter stations may block their operation, resulting in the undesirable loss of power transfer capacity.

Several unit [3, 4], and non-unit protection methods [5–10] have been proposed for protecting DC lines and cables in the literature. However, as the size of the HVDC grids and the lengths of its associated lines and cables are expected to increase in the near future, non-unit protection becomes the preferable option in order to eliminate prolonged undesirable communication delays. The placement of sizeable series inductors in series with DC breakers is one of the practical measures that have been adopted to slowdown the rate of rise of current, thus allowing the breakers to act before the maximum current breaking capability is exceeded. Series inductors not only serve as current limiters that restrain the rate of rise of current, but they also behave as a natural boundary for a range of frequencies of the incident waves generated from DC faults, thus influencing DC voltage and current signatures. This important feature can be exploited to assist non-unit DC fault detection and discrimination [11].

Non-unit protection methods may suffer from sensitivity issues depending on the line length, series inductor size, fault resistance etc. Hence, this calls for a generalised methodology that offers the capability to investigate the practical limitations of non-unit protection and highlight the factors which can be refined to optimise its performance for HVDC grids. Frequency domain analysis of the travelling waves generated during the transient stage of DC faults is a method that can be used to perform such studies [12]. Such analysis overcomes typical issues associated with standard EMT-type software simulations (such as the use of a single network for the validation of protection systems) and offers a more generalised approach to fault characterisation and analysis of HVDC grids.

Therefore, this paper utilises frequency domain analysis in order to perform a comprehensive assessment of the capabilities and limitations of HVDC grid non-unit protection. Recommendations and practical guidelines, which can be used as a basis for designing generalised protection algorithms for fault detection and discrimination of DC faults are offered, based on travelling wave theory principles. The paper is structured as follows. In Section 2, frequency domain analysis of fault voltage travelling waves is implemented with the aim to derive the voltage transfer function at the protective relay location and explain the principles of non-unit protection. Then, the impact of several influencing factors on non-unit protection is presented in Section 3. In Section 4, a methodology on deriving the relay protection setting based on frequency domain analysis is detailed. Finally, conclusions are drawn in Section 5.

2 Frequency Domain Analysis

To facilitate the analysis in this section, a general section of a typical HVDC grid is considered, as illustrated in Fig. 1. The grid section comprises of two terminals with Voltage Source Converters (VSCs) that are connected through a DC line or cable, while further n feeders are connected to terminal bus B1. The feeder is terminated by series inductors at both ends. The protection zone of relay R is the full length of the DC feeder between the two inductors. Based on local measurements, the protective relay should discriminate between a fault at location F_{int} at the remote end of the protected cable (internal fault) from a fault behind the series inductor at location F_{ext} that is right outside the protection zone (external fault).

A solid fault at fault location F_{ext}, is the most difficult case for discriminating and classifying as external as opposed to an internal fault at location Fint with high fault resistance. The main difference between the two faults is the presence of the series inductor, which acts as a natural boundary that alters the transient voltage frequency response of external faults. On this basis, the investigation of the voltage transfer function for both faults can reveal significant information for protection design purposes.

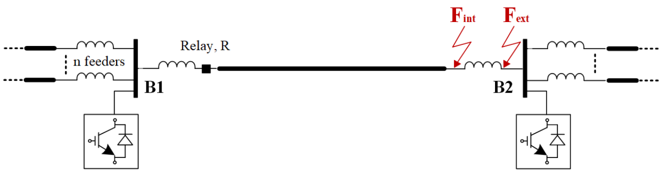

Figure 1: General section of an HVDC grid.

During the transient phase of DC faults, the fault voltage can be described based on travelling wave principles. Owing to the fact that travelling waves are frequency dependent, frequency domain can be used to analyse the fault response of DC faults. The rest of the section presents an approach for deriving the transfer function of the voltage at the relay location with respect to the voltage at the fault point (F_{int} and F_{ext}).

2.1 Cable modelling

Travelling waves that propagate over a cable or overhead line are experiencing attenuation due to the line components. The resistive and inductive components of the medium are heavily frequency dependent and have different values depending on system conditions (steady state, fault conditions etc.). Frequency dependent models are thus required to adequately simulate the response of a transmission medium. These models operate on the basic principle that the frequency dependence of the medium can be sufficiently described by two matrix transfer functions: i) the propagation function *H* and ii) the characteristic admittance Y_c. These functions can be approximated by calculating their values at various points in the frequency domain to derive a set of points, which in turn is approximated by low order rational functions using weighted vector fitting technique [13]. The common form of these functions is

$$f(s) = d + sh + \sum_{n=1}^{N} \frac{C_n}{s - P_n} \tag{1}$$

Where, C_n are the residues, P_n are the poles, *d* and *h* are real constants, and *N* is the order of the rational function. Equation (1) serves as an approximation which is appropriate for use in the frequency domain model. The required inputs of the model are limited to a set of values of cable series impedance Z_s and cable shunt admittance (Y_s) at various frequency points. The characteristic cable impedance (Z_c) is also calculated based on these parameters Z_c=$\sqrt{Z_s/Y_s}$ In this paper, the parameters of (1) are directly obtained through the Line Constants Program (LCP) of PSCAD.

2.2 Converter modelling

The converter technology considered in this study is the Modular Multilevel Converter (MMC). The fault contribution in the initial stage of DC faults of most common MMC topologies, such as the Half-Bridge MMC (HB-MMC), Full-brige MMC (FB-MMC) or Mixed Cell MMC (MC-MMC) is governed by the discharge of the distributed capacitance contained in the sub-modules of the converter. The capacitive discharge stage ends when the IGBTs of the MMC cells are blocked in order to avoid damaging the components. Since the analysis focuses exclusively on the transient phase of DC faults, before converter blocking occurs, only the capacitive discharge stage should be considered. During this stage, the converter impedance can be approximated as a series RLC model, and its frequency domain representation is given by

$$Z_{conv} = R_{eq} + L_{eq} + 1/sC_{eq} \tag{2}$$

where R_{eq}, L_{eq} and C_{eq} are the converter's equivalent resistance, inductance and capacitance respectively. C_{eq} represents the total capacitance of the inserted sub-modules on all three legs of the converter.

2.3 Transient voltage characteristic

To represent the voltage at the measuring point in the frequency domain, the first incident travelling voltage wave generated at the fault location needs to be formulated in the phase domain. The transient voltage measured by relay R is

$$U_r = \mu_{\beta 1} \cdot H \cdot U_f' \tag{3}$$

where $\mu_{\beta 1}$ is the refraction coefficient at bus B1 and U_f' is the voltage wave at the fault point. *H* is dictated by the cable geometry and represents the attenuation voltage and current waves experience when propagating along the cable. The refraction coefficient describes the fraction of the fault voltage wave that passes through the inductor at bus B1 and is transmitted to the network behind the series inductor. The coefficient is calculated as follows

$$\mu_{\beta 1} = \frac{2Z_t}{Z_t + Z_c} \tag{4}$$

where Z_t is the terminal impedance that is calculated as in (5), assuming that all cables have the same characteristic impedance and the same series inductance at both ends.

$$Z_t = Z_{conv} // \frac{(s + Z_c)}{n} + sL \tag{5}$$

When a pole-to-pole (PTP) fault occurs between two transmission cables, the voltage at the fault location falls from the pre-fault nominal voltage Udc to zero. The superposition theorem can be applied to derive the voltage wave at the fault location. According to the theorem, the fault network, which includes a DC voltage source at the fault location with a value equal to the prefault voltage with reverse polarity (U'_f=-U_{dc}), is superposed to the prefault network. Figure 2 displays the equivalent fault-superimposed circuit for an internal PTP fault at location F_{int} and an external PTP fault at F_{ext}.

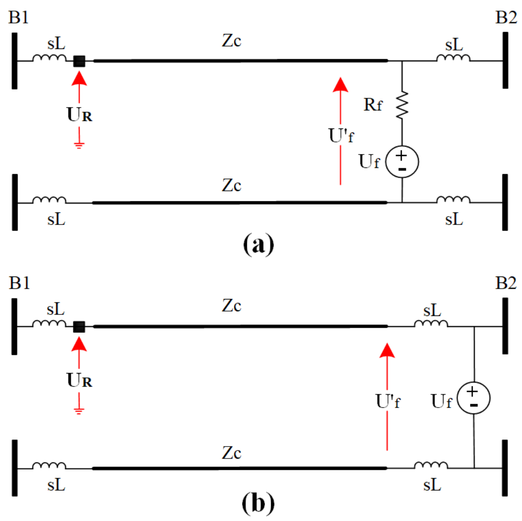

Figure 2: Equivalent fault-superimposed circuit for: (a) a resistive internal PTP fault and (b) a solid external PTP fault.

Based on Figure 2a, the fault voltage wave is expressed as

$$U'_{f,int} = \frac{Z_c//sL}{(R_f + 2Z_c//sL)} U_f \tag{6}$$

Using the superposition theorem in a similar manner for a solid fault at location F_{ext} (Figure 2b), the voltage at the fault point is given by

$$U'_{f,ext} = \frac{Z_c}{2Z_c + 2sL} U_f \tag{7}$$

By substituing (6) and (7) to (3), we can derive the transfer function of the voltage at the relay location with respect to the voltage at fault the fault point (i.e. U_r/U_f) for both fault locations F_{int} and F_{ext}, respectively. The same approach can be followed for deriving the fault voltage waves for pole-to-ground faults. It is worth noting that the analysis is only valid during the transient phase of DC faults, in which the frequency response is mainly determined by the first incident voltage wave. Subsequent travelling waves or other actions such as converter blocking, or breaker tripping are not taken into account. Nevertheless, the available time range is sufficient for the purposes of designing a high-speed non-unit protection method.

2.4 Methodology for investigation of non-unit protection

Design and analysis of non-unit protection can be facilitated by identifying the frequency content of the transient voltage signature resulting from a DC fault. In particular, the comparison between the frequency response of the hardest detectable internal fault (a highly resistive fault) and that of a solid external fault can shed light on the fundamental properties of non-unit protection. Assuming lossless propagation over a DC cable, Figure 3 presents the frequency response of the voltage transfer function under i) an internal solid fault (R_f=0 Ω), ii) a highly resistive internal fault (Rf=100 Ω) and iii) a solid external fault, when 50 mH inductive termination and a constant characteristic impedance of 28 is considered.

It is evident that the fault voltage travelling wave generated after a DC fault at location F_{int} contains higher frequency components than the corresponding fault voltage for an external fault. In particular, there is a critical frequency, beyond which the magnitude response of the transfer function of the internal fault is higher than the magnitude of F_{ext} for all frequencies. This is the main principle of non-unit protection which can be used for the discrimination between internal and external faults by exploiting the higher magnitude of high frequency components in transient voltage. Moreover, the critical frequency can be used as an indicator for determining the lowest sampling frequency for which a non-unit protection method can discriminatively detect DC faults. To maximise the performance of non-unit protection, the low frequency components can be eliminated by utilising filters to manipulate the frequency spectrum of the voltage signature or by selecting signal processing techniques with inherent filtering capabilities (e.g. wavelet transform or short-time Fourier transform).

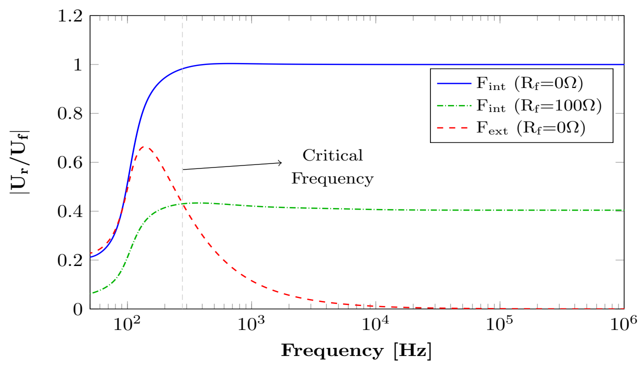

Figure 3: Difference between transient voltage frequency response of internal and external faults assuming undistorted (i.e. H=1) fault voltage travelling waves.

3 Impact of System and Fault Parameters on Transient Voltage Frequency Response

Based on the aforementioned mathematical formulation for the first incident voltage travelling wave, the frequency response of voltage transfer functions for faults at location F_{int} and F_{ext} is analysed with the aim to offer valuable insight into the technical limitations of non-unit protection and an in-depth understanding of the influencing factors. The considered parameters are the fault resistance of the internal fault, the feeder length, the series inductor size, the converter arm inductance and total capacitance as well as the number of healthy feeders attached to the same bus with the faulted feeder. Only cable systems are considered in the analysis and the cable parameters are adapted from [14]. The generic grid section of Figure 1 is considered and Table 1 shows the system parameters, which unless otherwise specified, are used in all studies.

Table 1 System parameters.

Parameter	Value
Cable length	200 km
No. of cables connected at B1	2
DC inductor size	50 mH
Arm resistance	0.08 Ω
Arm inductance	42 mH
Arm capacitance	31.42 μF
Fault resistance	0 Ω

3.1 Fault resistance

Figure 4 shows the frequency response of the voltage transfer function for internal DC faults for various fault resistances. A direct consequence of fault resistance is the damping of magnitude across the whole bandwidth of the transient voltage. Moreover, with increasing fault resistance, the reduction in magnitude becomes more prominent and the critical point is shifted towards a higher frequency, thus transferring the valuable information for HVDC non-unit protection to higher frequencies. Based on these findings, the use of a high sampling frequency allows for the detection of DC faults with higher fault resistances.

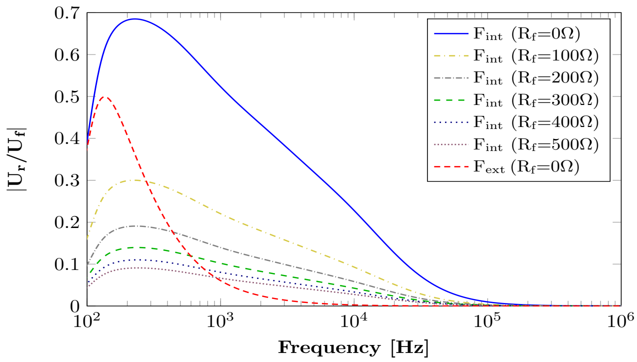

Figure 4: Transient voltage frequency response in the case of a solid external fault and for various fault resistances of the internal fault.

Figure 4 also shows the corresponding frequency response for a solid external fault (R_f=0 Ω). Since the propagation of travelling waves along the cable is the same for solid faults at both F_{int} and F_{ext}, the difference in voltage response is caused entirely by the filtering effect of the inductor. It is evident, that in the case of an external solid fault, the transient voltage attenuates faster in the high frequency region (above 200 Hz in this case) than that of a solid internal fault, in which there is a significant high frequency content. However, for faults with very high fault resistance, the magnitude in the high frequency region becomes indistinguishable from that of the external fault. Therefore, for given cable length and characteristics, there is a limit in the maximal fault resistance that can be detected regardless of the employed non-unit protection method.

Compared to the frequency response of the undistorted fault voltage travelling waves of Figure 3, the shape of the transient voltage characteristic under an external fault is not significantly influenced by the attenuation caused by the cable, while the decay rate of magnitude is only marginally expedited. This indicates that for faults behind the series inductor, the impact of filtering effect of inductive termination is greater than the impact of cable attenuation.

3.2 Cable length

Figure 5 displays the frequency response of highly resistive faults (R_f=100 Ω) at the end of the protection zone and solid external faults just outside the protection zone for different cable lengths. As the length of the cable increases, the magnitude of all transfer functions becomes smaller, while more high frequency components are filtered out due to the low-pass characteristic of the propagation function which becomes more dominant for increasing lengths. This means that the farther the fault location is with respect to the relay location, the lower the sensitivity of the protection due to the attenuation of the travelling waves. To a lesser extent this also true for the magnitude of the transfer function for the external fault. The combined effect is that the available bandwidth for HVDC protection decreases and encompasses more lower frequencies. Moreover, with increasing cable length, the difference between an internal and external fault becomes less distinct and consequently, there is a theoretical maximum length limit, after which the protection method will not be able to differentiate between them. It is worth noting that the effect on critical frequency is minimal and hence, sampling frequency selection can be assumed independent of the length of the protected cable.

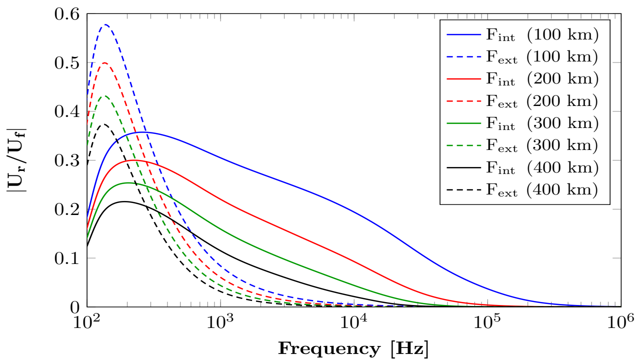

Figure 5: Impact of cable length on the frequency response of DC voltage for internal and external faults.

3.3 Series inductor size

Figure 6 demonstrates the impact of the size of series inductors on the transfer function response for both the internal and the external fault. It is evident that the inductor influences to a great extent the frequency response of both transfer functions. For the internal faults, the high frequency region remains unaffected, since it is primarily determined by the cable characteristics. Nevertheless, the bandwidth is extended significantly in the low frequency region.

For the external faults, the high frequency components of the incident travelling wave are largely attenuated due to the greater filtering effect that is introduced by the the higher size of the inductor. As a result, the magnitude of the transfer function decays faster in the high frequency region. This phenomenon becomes less distinct as the inductor size increases.

In addition, a reduction in the magnitude is caused across the whole bandwidth.

These observations demonstrate the strength of using a series reactor for non-unit protection. The benefit obtained from the use of larger series inductor is that the magnitude of the transfer function for an internal fault is significantly higher when compared to the lower magnitude of the external fault, leading to larger margins and longer time windows for the protection method to effectively discriminate the faulted feeder. Therefore, in the case of a long feeder of several hundreds of kilometres, a larger inductor can be employed to extend the reach of the protection relay and ensure that the whole protection zone is covered. Lastly, due to the more pronounced impact of the series inductor in the low frequency region, lower sampling frequencies may be used.

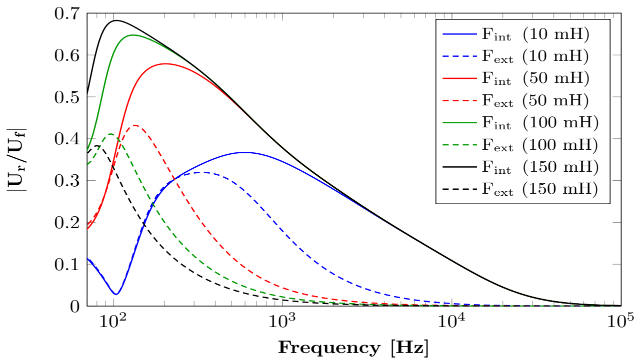

Figure 6: Impact of inductor size on the frequency response of DC voltage for internal and external faults.

3.4 Arm inductance and capacitance

Figure 7 and 8 show the frequency response of transient voltage for different arm inductances and arm capacitances, respectively. The values of these parameters are selected based on typical inductors and cell capacitors used in HVDC grid studies. Both parameters mostly affect the lowest frequencies of the transfer functions. Since the time range considered for HVDC grid protection is in the order of a few milliseconds and based on the previous results which revealed that higher frequency components are of interest for the protection systems, the influence of the converter parameters can be neglected.

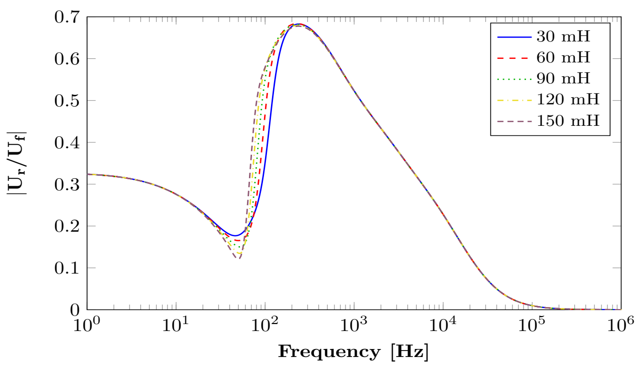

Figure 7: Impact of arm inductance on DC voltage frequency response for an internal fault.

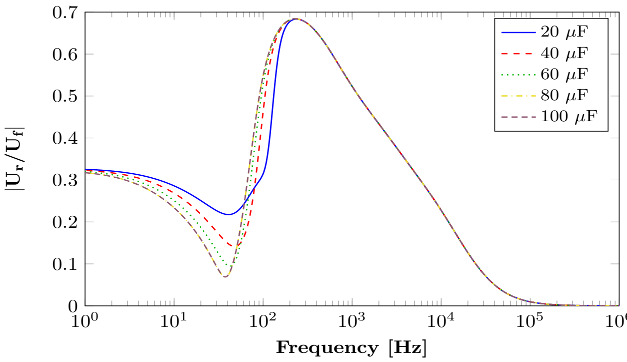

Figure 8: Impact of arm capacitance on DC voltage frequency response for an internal fault.

3.5 Number of cables

The number of non-faulted cables connected to bus B1 is varied from 1 to 4 and the resulting transfer functions are shown in Figure 9, when considering identical characteristic impedance for all cables. It is evident that the influence of the number of the cables on the fault response is limited only to the low frequencies' region. Similar to the previously examined case, its impact on non-unit HVDC protection systems can be neglected without significantly affecting the results of the analysis.

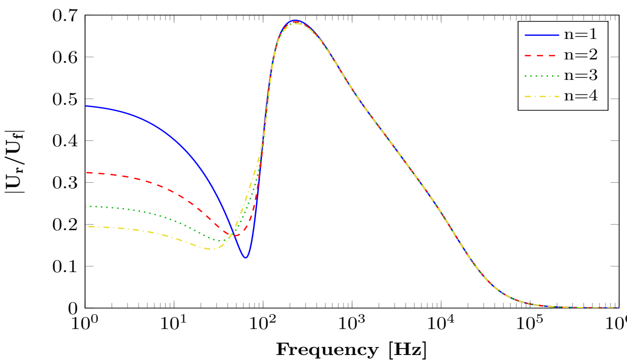

Figure 9: Impact of number of healthy cables on DC voltage frequency response for an internal fault.

4 Protection Setting Determination

Non-unit protection methods do not offer inherent selectivity and they require an optimised protection setting to ensure that the maximum protection reach is achieved and that the method remains robust against external faults and other disturbances. Frequency domain analysis can be used for developing a generalised approach for directly calculating the protection threshold, while avoiding extensive electromagnetic transient simulations. This approach is based on the identification of the most challenging fault that should be discriminated by the protection relay.

As explained before, a solid fault after the series inductor is the hardest fault that should be disregarded by relay R. The application of a step input with a magnitude equal to the pre-fault pole-to-pole voltage at the fault point corresponds to a time-domain representation of the transient phase of PTP DC faults. Based on this approach, the step response of the transfer function for the solid external fault at F_{ext} yields the fault response for the worst-case scenario. By performing the selected non-unit protection method directly on the derived time-domain expression, the corresponding protection setting can be analytically calculated. Only local parameters with respect to the relay are required for the threshold determination.

This procedure shall be applied for the hardest detectable fault for each relay within the HVDC grid. The protection setting may be set equal to the highest calculated threshold of all protective relays. Alternatively, an optimised setting can be applied for each relay separately with the optional capability for dynamically changing its value whenever there is a change in the influencing factors. Moreover, a safety margin shall be included to achieve a trade-off between sensitivity and security. In this way a degree of immunity against noise, measurement errors and other disturbances is also provided. Nevertheless, depending on the non-unit method that is employed, an investigation of the effect of other operating scenarios or external disturbances on the protection system may be necessary in order to ensure maximum reliability.

5 Conclusions

This paper performs a comprehensive analysis of HVDC grid non-unit protection based on frequency domain analysis of DC faults by making use of travelling wave theory principles. By analysing the frequency response of DC voltage for strategically selected fault cases, recommendations and practical guidelines for non-unit protection have been proposed. In particular, the hardest detectable internal fault and the hardest external fault were used to assess the general capabilities and limitations of non-unit protection and to identify the suitable frequency range for differentiating between them. The critical frequency beyond which the impact of the internal fault becomes more distinct is suggested as an indicator for selecting sampling frequency.

Moreover, a sensitivity analysis is performed to reveal the most influential system parameters. The impact on HVDC grid non-unit protection of the converter parameters and the number of healthy feeders attached to the same bus with the faulted feeder was found to be negligible. Cable length and fault resistance are the two main factors that limit the performance of non-unit protection, since the difference between the resulting DC fault voltage signature from internal and external faults may be indistinguishable. It has been shown that by increasing the series inductor size the impact of cable attenuation can be overcome, leading to extended protection reach. Moreover, a methodology has been developed for analytically deriving the protection threshold based exclusively on the prevailing local system conditions. The methodology is applicable to any DC fault detection and discrimination method.

6 Acknowledgements

This work has been supported through the EPSRC Centre for Doctoral Training in Future Power Networks and Smart Grids (EP/L015471/1).

7 References

[1] G. P. Adam, T. K. Vrana, R. Li, P. Li, G. Burt, and S. Finney, “Review of technologies for dc grids – power conversion, flow control and protection,” *IET Power Electronics*, vol. 12, no. 8, pp. 1851–1867, 2019.

[2] V. Akhmatov, M. Callavik, C. Franck, S. Rye, T. Ahndorf, M. Bucher, H. Muller, F. Schettler, and R. Wiget, “Technical guidelines and prestandardization work for first hvdc grids,” *IEEE Transactions on Power Delivery*, vol. 29, no. 1, pp. 327–335, 2014.

[3] N. Johannesson and S. Norrga, “Estimation of travelling wave arrival time in longitudinal differential protections for multi-terminal hvdc systems,” *The Journal of Engineering*, vol. 2018, no. 15, pp. 1007–1011, 2018.

[4] D. Tzelepis, A. Dyśko, G. Fusiek, J. Nelson, P. Niewczas, D. Vozikis, P. Orr, N. Gordon, and C. D. Booth, “Single-ended differential protection in mtdc networks using optical sensors,” *IEEE Transactions on Power Delivery*, vol. 32, no. 3, pp. 1605–1615, June 2017.

[5] J. Sneath and A. D. Rajapakse, “Fault detection and interruption in an earthed hvdc grid using rocov and hybrid dc breakers,” *IEEE Transactions on Power Delivery*, vol. 31, no. 3, pp. 973–981, June 2016.

[6] R. Li, L. Xu, and L. Yao, “Dc fault detection and location in meshed multiterminal hvdc systems based on dc reactor voltage change rate,” *IEEE Transactions on Power Delivery*, vol. 32, no. 3, pp. 1516–1526, June 2017.

[7] D. Tzelepis, A. Dyśko, S. M. Blair, A. O. Rousis, S. Mirsaeidi, C. Booth, and X. Dong, “Centralised busbar differential and wavelet-based line protection system for multi-terminal direct current grids, with practical iec-61869-compliant measurements,” *IET Generation, Transmission Distribution*, vol. 12, no. 14, pp. 3578–3586, 2018.

[8] K. De Kerf, K. Srivastava, M. Reza, D. Bekaert, S. Cole, D. Van Hertem, and R. Belmans, “Wavelet-based protection strategy for dc faults in multi-terminal vsc hvdc systems,” *IET Generation, Transmission & Distribution*, vol. 5, no. 4, pp. 496–503, 2011.

[9] B. Chang, O. Cwikowski, M. Barnes, R. Shuttleworth, A. Beddard, and P. Coventry, “Review of different fault detection methods and their impact on pre-emptive vsc-hvdc dc protection performance,” *High Voltage*, vol. 2, no. 4, pp. 211–219, 2017.

[10] V. Psaras, A. Emhemed, G. Adam, and G. Burt, “Review and evaluation of the state of the art of dc fault detection for hvdc grids,” in *2018 53rd International Universities Power Engineering Conference (UPEC)*, Sep. 2018, pp. 1–6.

[11] W. Leterme, J. Beerten, and D. Van Hertem, “Nonunit protection of hvdc grids with inductive dc cable termination,” *IEEE Transactions on Power Delivery*, vol. 31, no. 2, pp. 820–828, April 2016.

[12] W. Mian, J. Beerten, and D. Van Hertem, “Frequency domain based dc fault analysis for bipolar hvdc grids,” *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 4, pp. 548–559, 2017.

[13] B. Gustavsen and A. Semlyen, “Rational approximation of frequency domain responses by vector fitting,” *IEEE Transactions on Power Delivery*, vol. 14, no. 3, pp. 1052–1061, July 1999.

[14] W. Leterme, N. Ahmed, J. Beerten, L. Ängquist, D. Van Hertem, and S. Norrga, “A new hvdc grid test system for hvdc grid dynamics and protection studies in emt-type software,” in *11th IET International Conference on AC and DC Power Transmission*, 2015, pp. 1–7.