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Design of the Frequency-Dependent DC Line Models for Transient Simulation of MVDC Distribution Networks

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Abstract. In medium voltage direct current (MVDC) distribution networks, distribution lines are relatively short and are often modeled using lumped parameter representations for computational efficiency. However, these models fail to accurately capture traveling wave phenomena, leading to inaccuracies in fault analysis and protective relay coordination. While distributed parameter models provide improved accuracy, they require substantial computational resources. Therefore, an efficient frequency-dependent DC line model is essential to balance accuracy and computational efficiency. This paper presents the design of a frequency-dependent DC line model for transient simulations of MVDC distribution networks. The study considers the ±18.7 kV MVDC distribution network connected to a 22.9 kV AC distribution network, modeled using PSCAD/EMTDC. The frequency-dependent DC line model is developed by analyzing the frequency response of the distributed parameter model and approximating its impedance using rational function approximation. The resulting impedance characteristics are fitted to an RL network, which is then implemented in RTDS for real-time simulation. To validate the model, transient simulations were conducted to compare the frequency-dependent DC line model with the distributed parameter line model. The results demonstrate that the proposed model accurately replicates fault current characteristics and voltage behavior, ensuring its effectiveness in transient analysis. These findings provide a fundamental basis for the transient

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simulation of MVDC distribution networks, contributing to improved fault analysis and system protection strategies.

Keywords; MVDC; distribution networks; frequency-response

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1. Introduction

With the increasing integration of renewable energy sources and the growing demand for efficient power distribution, medium voltage direct current (MVDC) distribution networks have emerged as a promising solution. Compared to traditional AC distribution systems, MVDC networks offer reduced transmission losses, improved power quality, and enhanced controllability. However, accurately modeling and simulating MVDC networks presents significant challenges, particularly in transient analysis.

In MVDC distribution networks, the length of the distribution lines is relatively short, and they are often modeled using lumped parameter models. Although lumped models are computationally efficient, they fail to accurately represent traveling wave phenomena. This limitation poses a significant challenge in transient simulations of DC systems, where fault processes conclude within a few milliseconds. The inability of lumped models to capture high-frequency transient behavior can lead to inaccuracies in fault analysis and protective relay coordination.

While distributed parameter models improve accuracy, they require significant computational resources. Thus, an efficient frequency-dependent DC line model is essential for achieving both accuracy and computational efficiency.

This paper presents the design of a frequency-dependent DC line model for the transient simulation of MVDC distribution networks. Considering the distribution network of Korea, the ±18.7 kV MVDC distribution network was connected to the 22.9 kV AC distribution network.

First, the distribution lines of the ±18.7 kV MVDC distribution network are modeled as a distributed parameter system using PSCAD/EMTDC. The frequency-dependent

DC line model is then developed based on the frequency response of the distributed parameter model, with its frequency characteristics analyzed. The frequency responses are impedance-fitted to the RL network through the rational function approximation.

The designed frequency-dependent DC line model is implemented in RTDS. For performance analysis, transient simulation analysis was performed between the distributed parameter line model implemented in PSCAD/EMTDC and the frequency-dependent DC line model implemented in RTDS. As a result, the frequency-dependent line model had the same fault current characteristics as the distributed parameter line model. The voltage had similar characteristics, which could sufficiently ensure the accuracy of the design. These results can be used as a fundamental study for the transient simulation of MVDC distribution networks.

2. Design of the frequency-dependent DC line models for MVDC distribution networks

The frequency-dependent DC line model was designed based on the frequency response of the distributed parameter model. Figure. 1 shows the distributed parameter model for the ±18.7 kV MVDC distribution network using PSCAD/EMTDC.

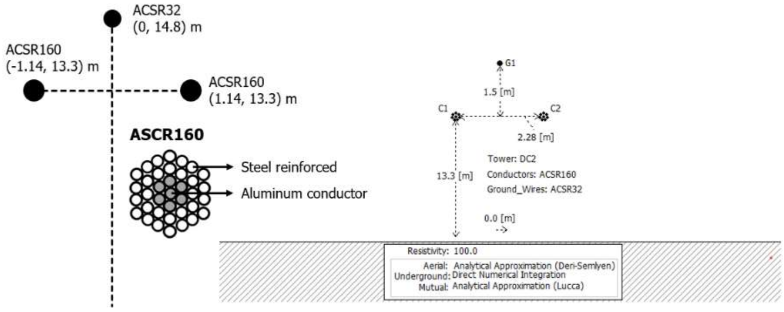


Figure 1. Distributed parameter model for the ±18.7 kV MVDC distribution network.

A frequency response analysis was conducted from 0.01 Hz to 1,000 Hz to capture transient behaviors across both low-frequency and high-frequency ranges. This frequency range was chosen to ensure comprehensive coverage of both steady-state characteristics and low-frequency dynamics, while also accurately reproducing harmonics and transient phenomena to fault analysis of the MVDC distribution networks. The frequency response of the distributed parameter model was converted into a rational transfer function using the vector fitting technique. Vector fitting is one of the most widely used methods for approximating frequency-dependent impedance characteristics of transmission lines with rational functions, ensuring both numerical stability and accuracy in transient simulations [2]. To incorporate frequency dependency, the rational function approximation was transformed into an RL network shown in Figure. 2.

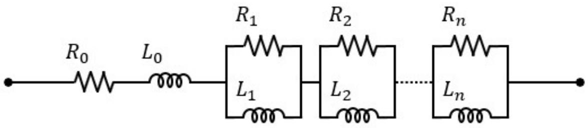
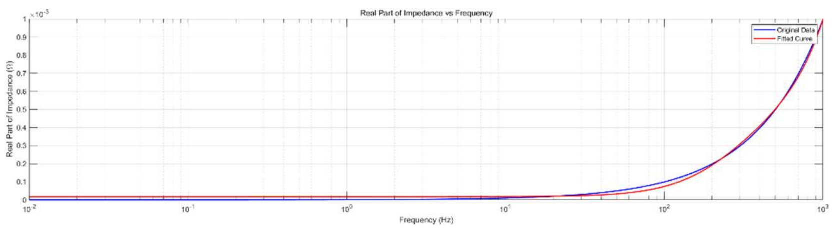


Figure 2. Representation of the RL network.

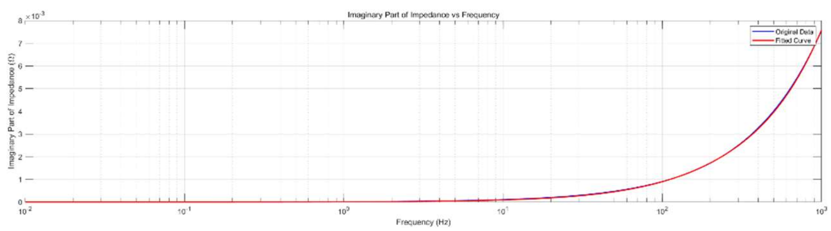
The RL network is used to represent the frequency-dependent impedance while maintaining passivity and ensuring numerical stability in transient simulations [3, 4]. The transfer function obtained through the rational function approximation of the distributed parameter model is converted into the RL network, and the equation is as follows:

$$Z(s) \approx hs + d + \sum_{n=1}^{N} \frac{c_n}{s-a_n} = L_0 s + R_0 + \sum_{n=1}^{N} \frac{L_n R_n s}{L_n s + R_n} \quad (1)$$

The coefficients are determined using vector fitting. A wider frequency range requires more parallel RL networks (n), but increasing n also increases computational time, making it necessary to determine an optimal n through a repetitive process. Vector fitting and the conversion of the RL network were performed using MATLAB. Figure. 3 shows the results of the vector fitting.



(a)



(b)

Figure 3. Vector fitting of the (a) real and (b) imaginary parts of the impedance

Unlike R and L, which are frequency-dependent functions due to skin effect and proximity effect, the capacitance (C) is assumed to remain constant, as it is primarily determined by the conductor geometry and insulation permittivity, which do not significantly vary with frequency. Conductance is considered negligible [6].

Figure. 4 shows the frequency-dependent DC line model. To implement coupling between DC lines, an ideal transformer with a turns ratios of 1:1 was used. Figure. 5 shows the frequency-dependent DC line model for MVDC distribution networks implemented in RTDS.

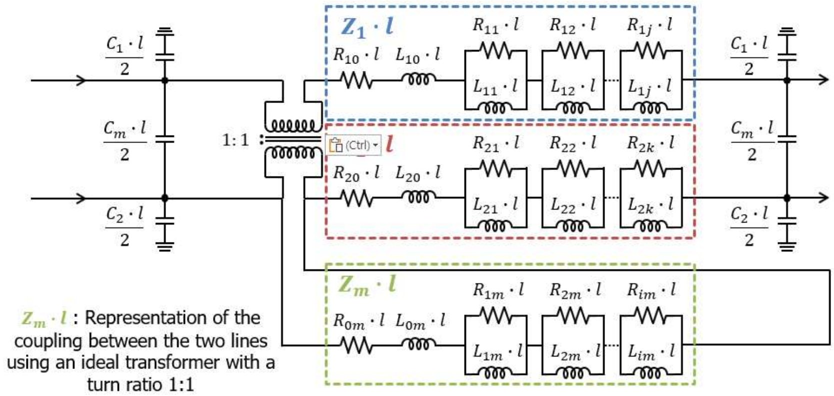


Figure 4. Vector fitting of the (a) real and (b) imaginary parts of the impedance

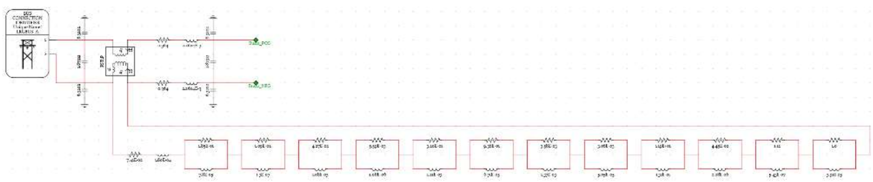


Figure 5. Representation of the frequency-dependent DC line model

3. Results and discussions

A transient analysis of the MVDC distribution network was conducted to analyze the performance of the frequency-dependent DC line model. Figure. 6 shows the configuration of the MVDC distribution network, implemented in PSCAD/EMTDC and RTDS, respectively. Table I shows the parameters of the modular multi-level converter (MMC) used to connect the AC distribution network and the MVDC distribution network.

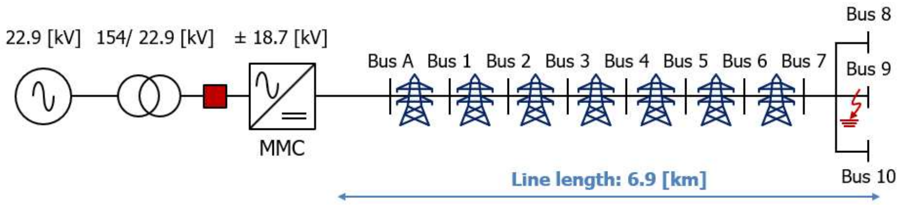


Figure 6. Configuration of the MVDC distribution network

Table 1. Parameter of the MMC FOR MVDC distribution network

Item	Value
Type	Half-bridge
Apparent power	20 [MVA]
Rated DC voltage	37.4 [kV]
Rated AC voltage	154 [kV]
Frequency	60 [Hz]
Ratio of transformer	154/22.9
Number of submodule	20 [EA]
Capacitance of submodule	1900 [μF]
Arm inductance	10 [mH]

The fault location is near Bus 9 as shown in Figure. 6, and the fault type is a ground fault, which is an unbalanced fault. Figure. 7 and 8 show comparisons of simulation results between PSCAD and RTDS. Current and voltage measurements for faults were performed at the DC link of the MMC.

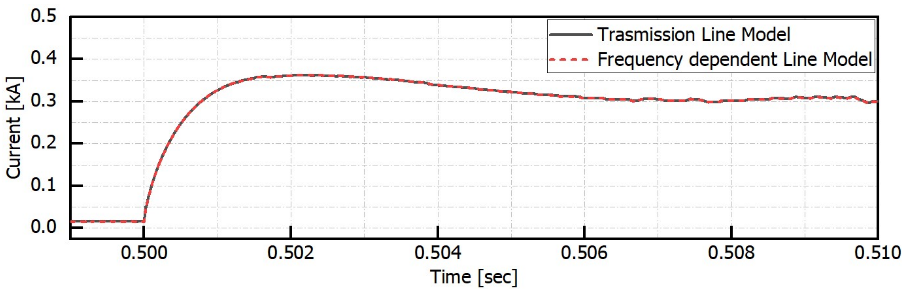


Figure 7. Comparison of distributed parameter model and frequency-dependent line model: Fault current

The fault current of the MVDC distribution network through the frequency-dependent DC line model of RTDS could obtain the same characteristics as the fault current of the MVDC distribution network through the distributed parameter model of PSCAD/EMTDC.

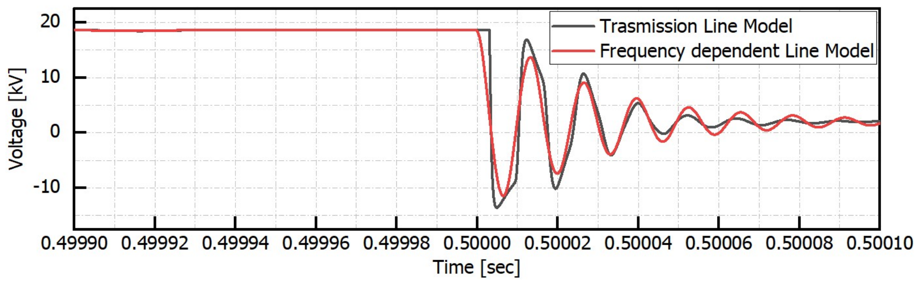


Figure 8. Comparison of distributed parameter model and frequency-dependent line model: Voltage

After the fault, similar characteristics were observed for pole voltages, and sufficiently reasonable results could be obtained.

4. Conclusion

This paper presented a frequency-dependent DC line model for transient simulations of MVDC distribution networks. The proposed model was developed using rational function approximation and implemented in RTDS for real-time simulation. Simulation results demonstrated that the frequency-dependent model accurately replicates fault current and voltage characteristics, ensuring reliability in transient analysis. The proposed method effectively balances computational efficiency and accuracy compared to lumped and distributed parameter models. These findings contribute to improving fault analysis and protection strategies in MVDC distribution networks.

Acknowledgment

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References

[1] Jian Zhang, Xinlong Zheng, Guozhi Chen, Zhigang Zhang, Beibei Xu, "Economic Comparison of VSC-HVDC and HVAC Systems for Connections of Offshore Wind Farms.", Applied Mechanics and Materials, vol. 672-674, pp. 325–330, (2014).

[2] B.Vand Eeckhout, D.Van Hertem, M.Reza, K.Srivastave, R.Belmans, "Economic comparison of VSC HVDC and HVAC as transmission system for a 300 MW offshore wind farm," Europian transactions on electrical power, (2009).

[3] Andersen B, VSC transmission, CIGRE Publication, CIGRE working group B4.37, April (2005).

[4] Brakelmann H. Efficiency of HVAC power transmission from offshore-windmills to the grid. Presented at IEEE Bologna Power Technology Conference, Italy, June (2003).