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

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Abstract. With the continuous increase in power demand and the connection of renewable energy sources in the distribution networks, the need for medium-voltage direct current (MVDC) networkss with improved transfer capacity and flexibility has increased. The simulation time step can be determined based on the physical characteristics of the line. If the time step is too large, the accuracy of the transient simulation will be problematic. Therefore, distribution networks with short lines require shorter time steps to ensure simulation accuracy. However, there is a lack of research on DC line models for transient simulation of MVDC distribution networks. This paper deals with the design of a frequency-dependent DC line model for transient simulation of MVDC distribution networks. Considering the Korean distribution networks, a ±18.7 kV MVDC distribution network connected with the 22.9 kV AC distribution networks was modeled using PSCAD/EMTDC. The DC line model was designed with reference to Korea's 22.9 kV. In order to verify the accuracy of the frequency-dependent DC line model, a distributed parameter DC line model is designed. The distributed parameter DC line model is designed with reference to the 22.9 kV distribution network line in Korea. The frequency characteristics of the distributed parameter DC line model are investigated for the design of the frequency-dependent DC line model. The frequency characteristics are impedance-fitted to the RL-Foster circuit through the rational function approximation. The frequency-dependent DC line and the distributed

parameter DC line model are compared through transient simulation analysis. 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 basic study for transient simulation of the MVDC distribution networks.

Keywords; MVDC; transient simulation; frequency-dependent DC line model

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.
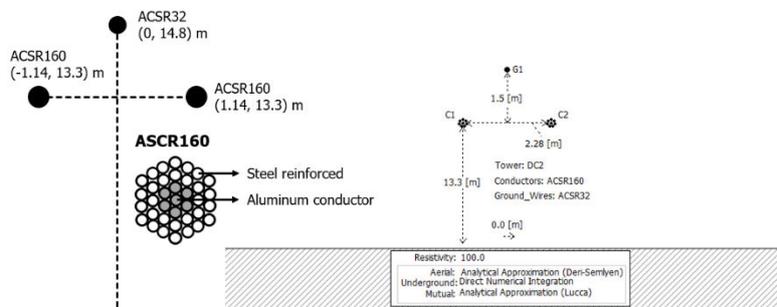

Figure 1.   Distributed parameter model for the ±18.7 kV MVDC distribution network.

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.
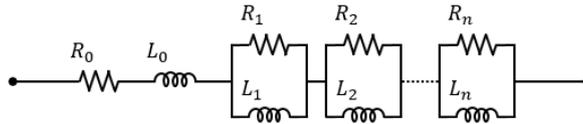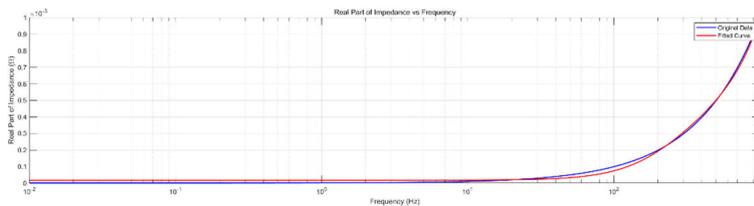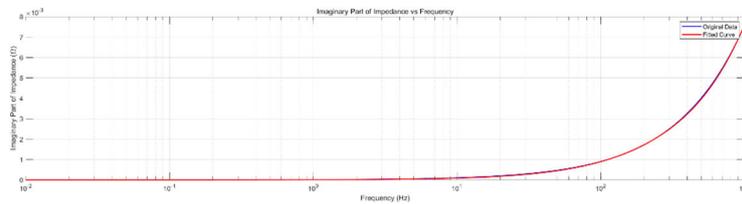

Figure 2.   Representation of the RL network.

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:

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

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

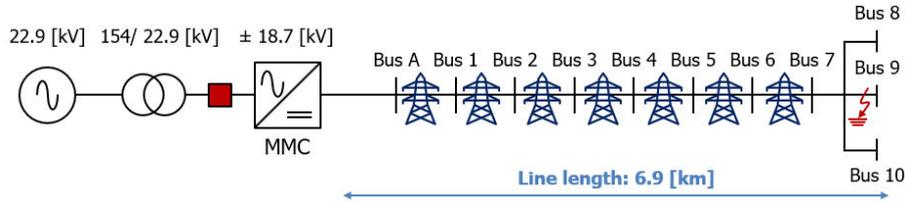Unlike R and L, which are frequency-dependent functions due to skin effect and proximity effect, the capacitance (C) is assumed to remain constant, as it is primarily determined by the conductor geometry and insulation permittivity, which do not significantly vary with frequency. Conductance is considered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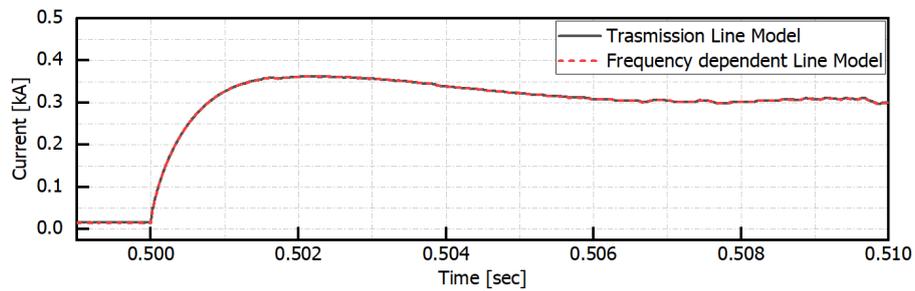

Figure 7.   Comparison of distributed parameter model and frequency-dependent line model: Fault current

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.
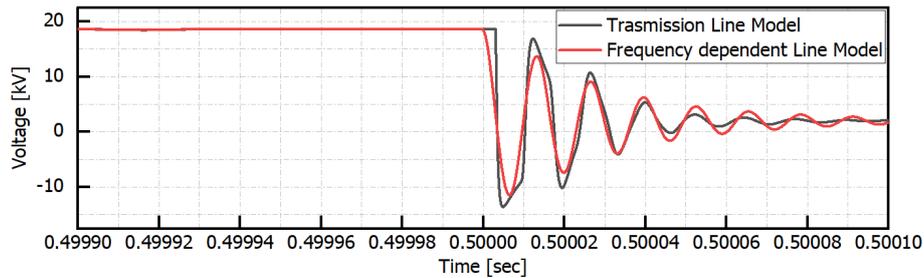

Figure 8.   Comparison of distributed parameter model and frequency-dependent line model: Voltage

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

References

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