COMPARISON OF HVDC LINE MODELS IN PSB/SIMULINK BASED ON STEADY-STATE AND TRANSIENTS CONSIDERATIONS

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ABSTRACT

Transmission lines are a vital link in HVDC transmission systems. Transients originated in the lines themselves (e.g., short circuits, lightning) or originated in the substation equipments (e.g., rectifier, inverter) propagate from one part of the HVDC system to another through the transmission lines. This paper presents a summary of the main transmission line models currently in use for steady-state and transients simulations on an HVDC link. Simulations have been performed comparing frequency and time domains performance of distributed parameters line model and (π) sections line model. The limitations of these models are explained. General guidelines are suggested regarding the area of applicability of the models in SIMULINK.

Keywords: *HVDC Transmission, Transmission line models, Steady-state and transients analysis, Simulink*

1. INTRODUCTION

Matlab/Simulink is a high-performance multi-functional software that uses functions for numerical computation, system simulation, and application development. Power System Blockset (PSB) is one of its design tools for modelling and simulating electric power systems within the simulink environment. It contains a block library with common components and devices found in electrical power networks that are based on electromagnetic and electromechanical equations. PSB/Simulink can be used for modelling and simulation of both power and control systems. PSB solves the system equations through state-variable analysis using either fixed or variable integration time-step. The linear dynamics of the system are expressed through continuous or discrete time-domain state-space equations. It also offers the flexibility of choosing from a variety of integration algorithms. To this end, many families of models are made available to the user [1],[2],[3].

In PSB/Simulink, two models of transmission lines for simulation in the time domain are [3]:

1. (π) sections line;
2. Distributed parameters lines.

Although for frequency domain studies transmission lines modeled with (π) lines can be precise, in the time domain, particularly for long lines (where propagation travel time spans many time steps), precision suffers. (π) line sections are more useful for very short transmission lines where the propagation travel time (τ) is less than a step time (Δ t).

The distributed transmission line model operates on the principle of traveling waves. A voltage disturbance will travel along a conductor at its propagation velocity (near the speed of light) until it is reflected at the end of the line. In a sense, a transmission line or cable is a delay function. Whatever is fed into one end will appear at the other end after some delay, perhaps slightly distorted. The calculation step time (Δ t) of the simulation should be less than the propagation time (τ) .

General guidelines regarding the areas of applicability and the limitations of the discussed models in Electromagnetic Transients Program (EMTP), has been presented in [4] and [5]. In this paper, a simulation compares the frequency and the time domains performance of distributed parameters line model and (π) sections line model on a 12-pulse HVDC (High Voltage Direct Current) system.

2. HVDC SYSTEM MODEL IN PSB/SIMULINK

The HVDC system modelled, using the Simulink package, is based on a point-to-point DC transmission system. The DC system is a monopolar, 12-pulse converter using two universal bridges connected in series, rated 1000 MW (2 kA, 500 kV) at the inverter. DC interconnection is used to transmit power from a 500 kV, 5000 MVA, 60 Hz network to 345 kV, 3 000 MVA, 50 Hz network. The converters are interconnected through a 300 km transmission line and 0.5 H smoothing reactor. The converter transformer (Wye grounded / Wye / Delta) is modelled with three-phase transformer (three-Windings). The tap position is rather at a fixed position determined by a multiplication factor applied on the primary nominal voltage of the converter transformers (0.9 on rectifier side; 0.96 on inverter side). The configuration of the system is given in figure 1. The AC networks, both at the rectifier and inverter end, are modelled as infinite sources separated from their respective commutating buses by system impedances. The impedances are represented as L-R/L networks having the same damping at the fundamental and the third harmonic frequencies. The impedance angles of the receiving end and the sending end systems are selected to be 80 degrees. This is likely to be more representative in the case of resonance at low frequencies [6],[7].

From the AC point of view, an HVDC converter acts as a source of harmonic current. From the DC point view, it is a source harmonic voltage. The order n of theses characteristic harmonics are related to the pulse number p of the converter configuration: $n = kp \pm 1$ for the AC current, and $n = kp$ for the direct

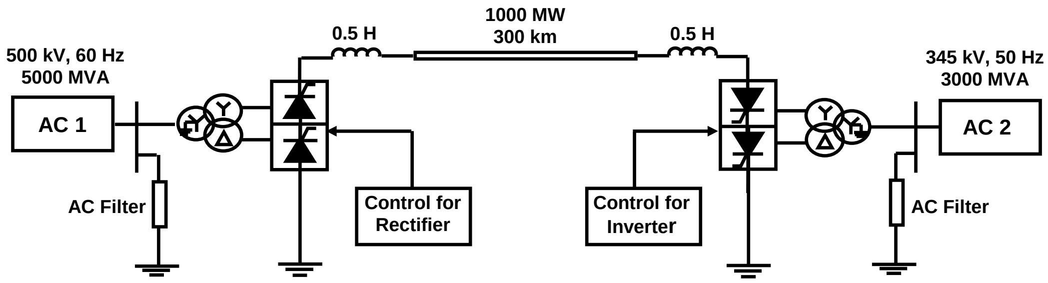


Fig. 1 HVDC system model

voltage, k being any integer. In the example, p = 12, the injected harmonic are: 11, 13, 23, 25 on the AC side, and: 12, 24 on the DC side [8].

3. TRANSMISSION LINE MODELS

The simulation is performed with two different line models:

- (π) sections line
- Distributed parameters line

3.1. (π) sections line

For a transmission line, the resistance, inductance and capacitance are uniformly distributed along the line. An approximate model of the distributed parameters line is obtained by cascading several identical (π) sections as shown in the figure 2. Unlike the distributed parameters line block, which has an infinite number of states, the (π) sections linear model has a finite number of states that permits to compute a linear state-space model.

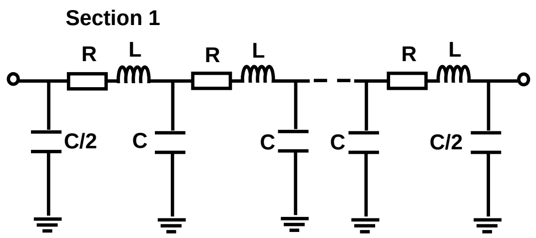


Fig. 2 (π) sections line

The number of sections to be used depends on the frequency range to be represented.

3.2. Distributed parameters line

The distributed parameters line block implements an N-phase distributed parameters line model with lumped losses. The model is based on the Bergeron's travelling wave method [4],[5]. The Bergeron method is based on a distributed LC parameters travelling wave line model with lumped resistance. This model produces constant surge impedance and is essentially a single frequency model. The Bergeron method can be used for any general fundamental frequency impedance studies. The Bergeron Model represents the L and C elements of a (π) section in a distributed manner (not using lumped parameters like (π) sections). It is roughly equivalent to using an infinite number of (π) sections except that the resistance is lumped).

In this model, the lossless distributed LC line is characterized by two values (for a single phase line) [9]:

- The surge impedance $$Z_C = \sqrt{\frac{L}{C}}, \tag{1}$$
- The phase velocity $$\upsilon = \frac{1}{\sqrt{LC}}, \tag{2}$$

The model uses the fact that the quantity e+Zi, where e is line voltage and i is line current, entering one end of the line must arrive unchanged at the other end after a transport delay of τ

- $$\tau = \frac{l}{\upsilon}, \tag{3}$$

where: l is the line length.

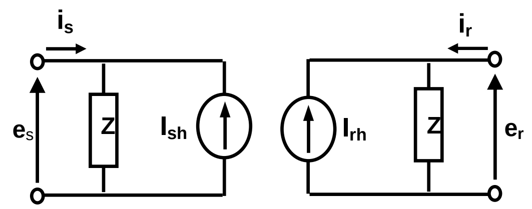


Fig. 3 Distributed parameters line

By lumping R/4 at both ends of the line and R/2 in the middle and using the current injection method of the Power System Blockset, the following two-port model is derived:

$$I_s h(t) = \left(\frac{1+h}{2}\right)\left[\frac{1}{Z}e_r\left(t-\tau\right) + hi_r(t-\tau)\right] + \left(\frac{1-h}{2}\right)\left[\frac{1}{Z}e_s(t-\tau) + hi_s(t-\tau)\right] \tag{4}$$

$$I_R h(t) = \left(\frac{1+h}{2}\right)\left[\frac{1}{Z} e_s\left(t-\tau\right) + h i_s(t-\tau)\right] + \left(\frac{1-h}{2}\right)\left[\frac{1}{Z} e_r(t-\tau) + h i_r(t-\tau)\right] \quad (5)$$

where:

$$Z = Z_C + \frac{R}{4}, \quad (6)$$

$$\tau = l\sqrt{LC}, \quad (7)$$

$$h = \frac{Z_C - \frac{R}{4}}{Z_C + \frac{R}{4}}, \quad (8)$$

Z_C: The characteristic or surge impedance [Ω].
R: The total line resistance [Ω]
τ : The travel time of the line [s]
L: Inductance [H/unit length].
C: Capacitance [F/unit length].

4. SIMULATIONS AND COMPARISONS

In order to demonstrate the applicability and the limitations of these models, a simulation compares the frequency and time domains performance of distributed parameters line model and (π) sections line model on a 12-pulse HVDC system. The time step used for the simulation is 50 μs. The results and analyses are presented in this section.

4.1. Frequency domain

1) Frequency response of the AC systems: Figure 4 shows the magnitude, seen from the busbar where the filter is connected, of the combined filter and AC network impedance as a function of frequency.

Notice the two minimum impedances on the Z magnitudes of the AC systems, these series resonances are created by the 11^{th} and 13^{th} harmonic filters. They occur at 660 Hz and 780 Hz on the 60 Hz system (550 Hz and 650 Hz on the 50 Hz). The low principal natural frequency, coinciding whit the parallel resonance at 188 Hz on the rectifier side and 120 Hz on the inverter side, is a determining factor in the development of overvoltages and interaction with the DC system.

2) Frequency response of the DC system: Figure 5 illustrates the magnitude of the impedance as a function of frequency of the DC system, as seen from the rectifier. It is composed by the two smoothing reactors and the DC line (300 km), represented by two (π) sections, or distributed parameters line (the two impedances are displayed on the same graph). The distributed parameters line shows a succession of poles and zeros equally spaced, every 492 Hz. The first pole occurs at 246 Hz, corresponding to frequency:

$$f = \frac{1}{4\tau}, \quad (9)$$

where: τ = 1.013 ms (for l = 300 km).

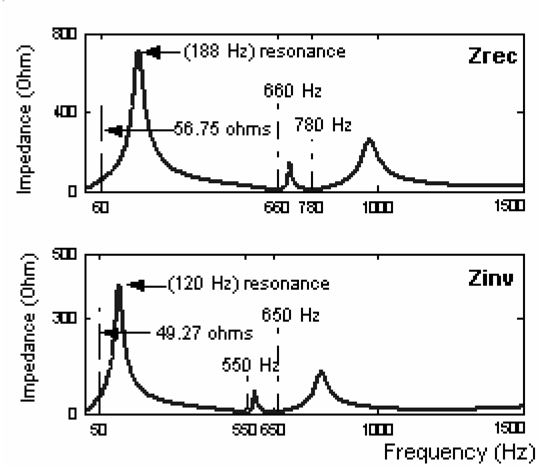


Fig. 4 Positive-sequence impedances of the two AC networks

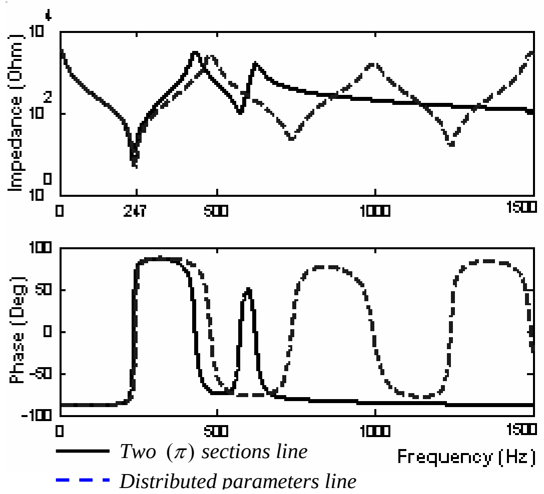


Fig. 5 Positive-sequence impedance of the DC line (300 km)

The (π) sections line only shows two poles because it consists of two (π) sections. Impedance comparison shows that a two (π) sections line gives a good approximation of the distributed line for the 0-247 Hz frequency range. In transient studies with (π) sections, it is important to consider whether a line should be represented by one or several sections. This is dependent upon:

1. The travelling time (τ).
2. The frequency of response required from the simulation model.
3. The length of the line (l).

2-1) The travelling time (τ): At light speed, a wave may travel 15 km over 50 ms. If the length of the transmission line is less than 15 km when (Δ t = 50 ms), then one (π) section is adequate to represent the line (figure 6). If the line is longer than 15 km, two or more (π) sections should be cascaded in series.

2-2) The frequency of response required: A good approximation of the maximum frequency range represented by the (π) line model is given by the following equation:

$$f_{\max} = \frac{N\upsilon}{8l}, \qquad (10)$$

where: N is the number of (π) sections

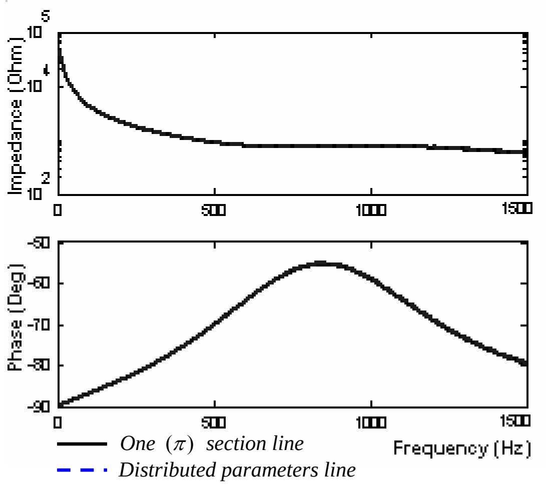


Fig. 6 Positive-sequence impedance of the DC line (15 km)

For a 300 km aerial line having a propagation speed of 296112 km/s (approximately the speed of light), the maximum frequency range represented with a single (π) section is approximately 123 Hz. For studying interactions between AC and DC system, this simple model could be insufficient.

For switching surge studies involving high frequency transients in the kHz range, much shorter (π) sections should be used. In fact, accurate results would probably only be obtained by using a distributed parameters line model. If (π) sections have to be used for some reason on long lines, the use of 10 (π) sections for a long line is adequate (figure 7).

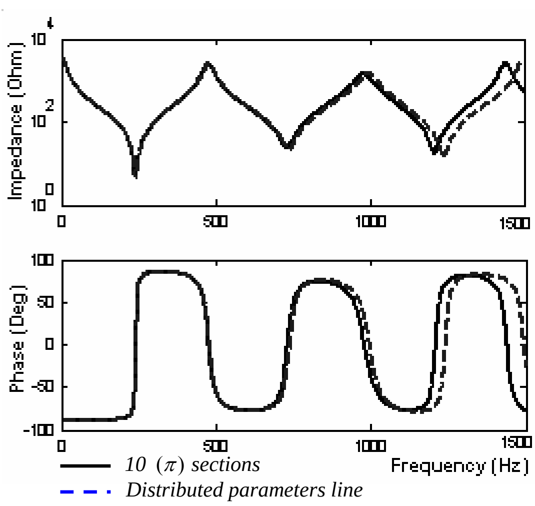


Fig. 7 Positive-sequence impedance of the DC line (300 km)

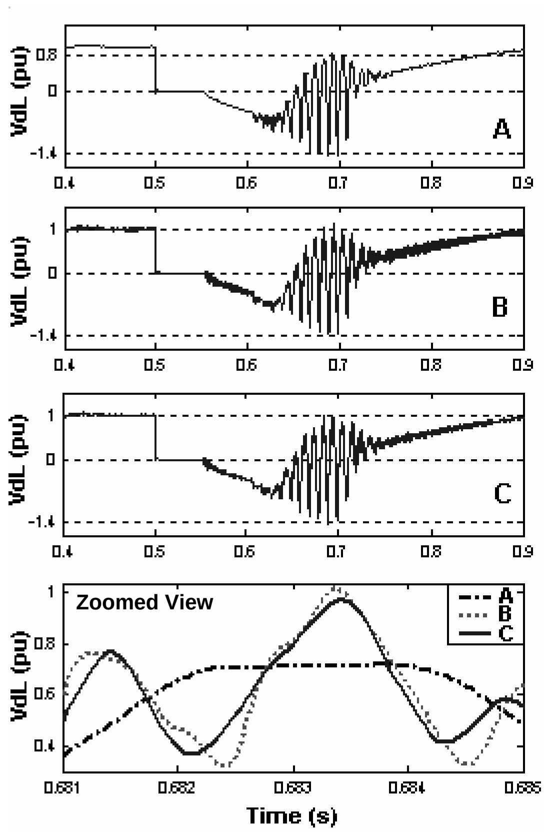
4.2. Time domain

A DC line fault was applied for three different DC line model (300 km):

- First case: one (π) section line.
- Second case: six (π) sections line.
- Third case: distributed parameters line.

For each of the transient case considered above, plots of the DC voltage at the rectifier side are given (figure 8). At fault application (t = 0.5 s), the DC voltage falls to zero at the rectifier. Then, at t = 0.55 s the rectifier α firing angle is forced to 165º by the protection system. The rectifier now operates in inverter mode. The DC line voltage becomes negative and the energy stored in the line returned to the AC network, causing rapid extinction of the fault current at its next zero-crossing.

From these results we can conclude that for the distributed parameters line and the six (π) sections line, the overvoltages at DC line (after fault cleaning) are identical. We can observe that the response of the one (π) section line model does not match the results of the other models. Also it fails to duplicate the maximum peak overvoltages which are shown for both the distributed and the six (π) sections line models. This is because the one (π) section line is not accurate enough to represent the high frequency transients.



(A) One (π) section line
(B) Six (π) sections line
(C) Distributed parameters line

Fig. 8 DC line fault on the rectifier side

5. CONCLUSION

This paper provides some general guidelines regarding the areas of applicability and the limitations of discussed models in Simulink.

A simple (π) section model cannot give the correct impedance at higher frequencies; it is suitable for very short lines where the travelling wave models cannot be used. The (π) sections models are generally not the best choice for transient solutions, because travelling wave solutions are faster and usually more accurate

The Bergeron transmission line model should generally be chosen over an equivalent (π) sections whenever the lines are sufficiently long, so that the propagation time (τ) (approximately the light speed) is accounted for in the simulation time step (Δ t). For a general simulation time step of 50 µs, lines over 15 km could be represented by the Bergeron model (assuming travel time as the light speed), or by much shorter (π) sections.

The Bergeron model has an important advantage over (π) sections. It does not introduce an artificial resonance at high frequencies as do lines modelled with a limited number of (π) sections. In comparison to the (π) sections line model, the distributed parameters line model represents wave propagation phenomena and line end reflections with much better accuracy.

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APPENDIX

Data for the system model:
Firing angle: $\alpha = 17°$ (for the rectifier); $\alpha = 142°$ (for the inverter).

1- <u>Rectifier end</u>: The rectifier end AC system 1 representing a strong system (SCR = 5), consists of one source with an equivalent impedance of:

$R = 26.07\ \Omega$, $L_1 = 48.86$ mH, $L_2 = 98.03$ mH.

2- <u>Inverter end</u>: The inverter end AC system 2 representing a weak system (SCR = 3), consists of one source with an equivalent impedance of:

$R = 20.56\ \Omega$, $L_1 = 47.48$ mH, $L_2 = 92.82$ mH.

3- <u>DC line parameters</u>:

Rdc = 0.015 Ω/km, L = 0.792 mH/km,
C = 14.4 nF/km

4- <u>Details of AC system representation</u>