

Comparison of Frequency Dependent and Pi Section HVDC Cable Models in the Presence of Harmonics

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Abstract- Understanding harmonic propagation in high voltage transmission lines and cables is important for the design and operation of power systems. The presence of harmonics and other transients in transmission and distribution system pose significant risks to insulation coordination aspects and to the safe and reliable operation of various power system components such as transformers, cables, reactors and filters. In this paper simulations are carried out to study the performance of both classical Pi-section and frequency dependent high voltage cable models under different harmonic distortion conditions. Harmonics of different amplitude and frequencies are superimposed on a 100 kV DC voltage and the frequencies evaluated at both the sending and receiving ends of the cable. Total Harmonic Distortion (THD) values are compared for different levels of harmonic distortion and loading. Current and voltage source harmonics are introduced at the input and the output voltage harmonics are analyzed. The simulation results show individual harmonic amplitudes change for the two models resulting in different THD values. The results presented in this paper will help improve understanding of the potential harmonic propagation within HVDC cables and the harmonic impact on HVDC cable insulation.

I. INTRODUCTION

Transmission lines and cable models are often used as part of the design process of power systems to understand the nature and impact of transient system behavior. Better modelling approaches also help in improved design of protection and insulation of power system equipment. Different types of transmission line and cable models are used for electromagnetic simulations such as the constant parameter model, the Pi section model, the frequency dependent (Mode) and the frequency dependent (Phase) model [1], [2]. The suitability of a certain model depends on the type of study being performed. For example, for power flow simulation, a constant parameter or Pi section model will work, however, for transient simulations these models overestimate the transient phenomena thus more accurate frequency dependent models are preferred [3]. The frequency dependent (Mode) model evaluates line propagation in the model domain considering the frequency dependence of line parameters. However, due to the constant transformation matrices, this model does not fully incorporate transient phenomena and can only be used for modelling balanced and symmetrical systems. The frequency dependent (Phase) model considers full frequency dependence of line parameters in the phase domain and avoids transformation between the model and phase domains. Additionally, the frequency dependent (Phase) model considers the frequency dependence of internal transformation matrices resulting in a more accurate representation of transient phenomena. The frequency

dependent (Phase) model is generally termed the Universal Line Model (ULM) [4], [5].

The transient behavior of transmission lines and cables has been extensively studied in the literature using different types of modelling software [6], [7]. The most common simulation environment used for these studies is PSCAD/EMTDC due to the availability of a variety of models. Some authors have also implemented similar models in MATLAB/ Simulink. The existing transient studies consider step changes and voltage surges. However, a more open question relates to the response of transmission lines and cable models to power frequency harmonics.

The increase in demand for HVDC technology to exploit renewable energy resources such as offshore wind has led to the increase in penetration of power electronic converters in the power system. Power electronic converters offer many advantages along with certain technical challenges. One of the important challenges with the increased use of power electronic converters is the deteriorating power quality due to the presence of harmonics [8]. In the case of HVDC transmission, the presence of harmonics in the transmission lines and cables is either due to the power electronic converters or the background harmonics in the AC systems propagating through the converters [9]. The background harmonics present in the AC system change as energy propagates through the various HVDC elements such as converter transformers, converters, filters and smoothing reactors [10]. The harmonic propagation along the HVDC chain has been discussed briefly in the literature [9], [11], [12] where it has been shown that harmonic magnitude as well as frequency changes occur from the AC to the DC side.

To provide an improved appreciation of the impact of harmonics on power cables, this paper investigates the behavior of classical Pi section and frequency dependent (Phase) cable models exposed to current and voltage harmonics of different frequencies and amplitudes. A further aim is to understand better the response of both models to steady state and transient behavior. The paper has been organized as follows: section 2 presents details related to cable modelling followed by simulation setup in section 3. Section 4 presents results and discussion while section 5 concludes the paper.

II. OVERVIEW OF CABLE MODELS

HVDC power cable propagation behavior is highly non-linear due to the frequency dependence of conductors and ground paths. Therefore, for transient simulations, frequency dependent models are needed. These frequency dependent cable models assist in understanding different phenomena such

as system start up and shut down, faults/short circuits as well as harmonic interactions within the system [13]. The frequency range of interest mainly depends on the type of study undertaken along with the system topology. For harmonic interaction, the frequency range is generally from DC up to a few kHz depending on the order of harmonics to be investigated.

Cable models are generally divided into two types: lumped parameter and distributed parameter models. The lumped parameter model which can be represented with either a T or Pi network is generally used for steady state simulations and short transmission lines/cables [14]. The distributed parameter models are further divided into frequency dependent (Mode) and frequency dependent (Phase) models [15]. The frequency dependent (Mode) model considers the effects of frequency in cable parameters. However, due to the constant transformation matrices, it does not fully incorporate transient phenomena and is best suited for balanced systems. Additionally, frequency dependent (Mode) models do not incorporate low frequency coupling effects with considerable accuracy. This deficiency can be overcome by considering the frequency variation of the transformation matrix within the simulations [16].

III. SIMULATION SETUP

The block diagram of the simulation setup shown in Figure 1 has been implemented in MATLAB/SIMULINK. It consists of a Pi section and frequency dependent (Phase) model connected in parallel to a user controlled current/voltage source. The HVDC cable consists of a conductor, lead sheath, steel armor separated by XLPE insulation layers. The cable parameters are taken from [17]. The frequency dependent (phase) model is implemented MATLAB/Simulink. This type of cable model is based on distributed parameters which has the ability to accurately model transient behavior. The propagation function (H) and characteristics admittance (Y_c) are given as:

$$H = \exp(-\sqrt{ZY}l) \quad (1)$$

$$Y_c = \sqrt{\frac{Y}{Z}} \quad (2)$$

where Y and Z are the frequency dependent shunt admittance and series impedance per unit length respectively and l is the length of cable which is chosen to be 150 km. The total number of Pi sections used was 20. Detailed mathematics of the cable models can be found in [18]. A resistive load is connected to the output of both models. The V block at the input and output represent the location of voltage measurements. Simulations were performed for both voltage and current source harmonics applied at the input terminals and voltage harmonics were monitored at the output. The following mathematical equations were used for simulating the voltage and current harmonics.

$$V(t) = V_0 + V_h \sin(2\pi ft + \theta) \quad (3)$$

$$I(t) = I_0 + I_h \sin(2\pi ft + \theta) \quad (4)$$

where V_0 and I_0 are the DC voltage and current respectively. The harmonic frequency f was varied between 100 and 3000 Hz to simulate up to 60th order harmonics while the harmonic

voltage V_h and current I_h were chosen such that it represents 1% of the DC voltage. This was achieved by superimposing a 1% AC sinusoidal waveform on a 100 kV DC voltage. The frequency of the superimposed sinusoidal waveform was varied to simulate harmonics of different frequencies. For simplicity, the phase angle was chosen to be 0° during all cases. The output voltage was measured in the time domain in the simulation and then a Fast Fourier Transform (FFT) applied to calculate the frequency spectrum of input and output voltages. The sampling frequency was set to 135 kHz to avoid the effect of aliasing. The aim of simulating current source harmonics was to better understand the response of different cable models to current harmonics as the converters may act as a current source. The proposed simulation setup can be used to simulate harmonics of varying amplitude, phase and frequency.

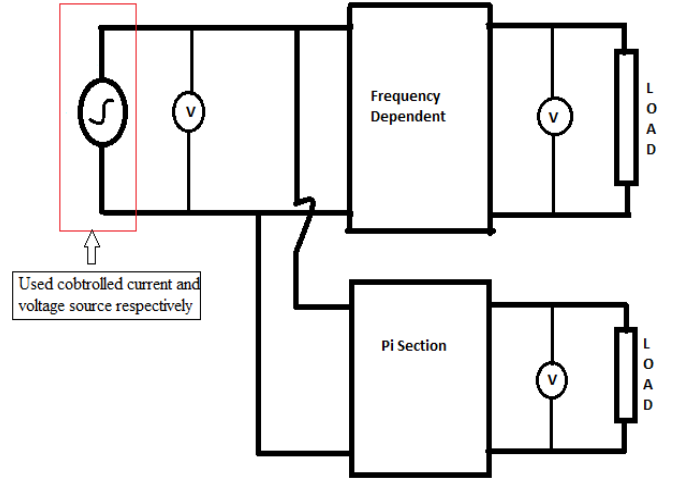


Figure 1 Block diagram of the simulation setup

IV. RESULTS AND DISCUSSIONS

Figure 2 shows the time domain signal of input voltage and output voltage across both Pi section and frequency dependent (Phase) cable models. The input signal to the cables is a step signal with a further step change introduced at 1.0 and 1.2 seconds. The aim of introducing this step change is to understand the response of both cable models to voltage source transients. In reality, any step change in the network will be more controlled and not a sudden increase/decrease but this study will help to appreciate the different responses of cable models and source of disturbances. The output voltage at the receiving ends of the cable can be divided into two parts: transient and steady state; where transient time is defined as the time required for voltage and current signal to reach steady state after the step change. During transient time, a peak of approximately 12% is recorded for the Pi section model while the transient peak for the frequency dependent (Phase) model was around 10%. However, after transient time, the steady state voltage stabilizes around the input voltage.

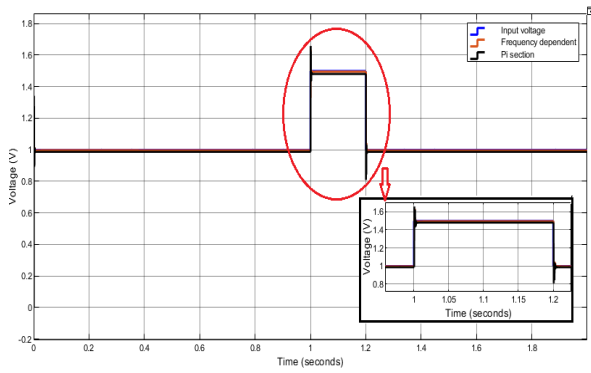


Figure 2 Time domain response to voltage harmonics

Figure 3 shows the time domain waveform of input and output voltages when a current source is used as input. Similar to the previous case, the input signal is a step signal with a further step change introduced at 1.0 and 1.2 seconds. The rationale behind the use of current source is to replicate the behavior of current source converters. One of the visible differences between the two cases is the transient response of the cable models. Although the peak amplitude observed for voltage source harmonics is not present in the case of current source, the transient time is much longer than that for the voltage as input source. Furthermore, it was noted from Figure 3 that the response of the Pi section model is much closer to the input voltage as compared to the voltage output across the frequency dependent model.

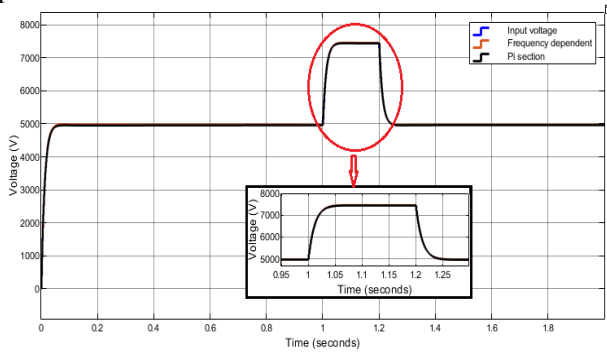


Figure 3 Time domain response to current harmonics

Figure 4 shows the frequency spectrum of output voltages across the Pi section and frequency dependent (Phase) cable models. The voltage at the input consists of 100 kV DC superimposed with 1.0 kV harmonics of varying frequencies. The blue line plotted on the graph at 1.0% shows the input harmonic amplitude. The harmonic frequency was varied to simulate up to 60th order harmonics. Comparing the results of frequency dependent and Pi section models, it is observed that with increase in frequency, the overall harmonic amplitude decreases and is lower than the input harmonic after 50th harmonic. Additionally, the harmonic amplitudes for the Pi section model are greater as compared to frequency dependent model. This difference in amplitudes become more evident with increase in harmonic frequency. These results shows that at low frequencies, Pi section model may be used for harmonic studies but at higher frequencies a frequency dependent (phase) model is more suitable. Another interesting observation from Figure 4

is that the response of cable models to frequency change is not constant but shows a damped oscillatory behavior which is likely due to the frequency response of cable parameters.

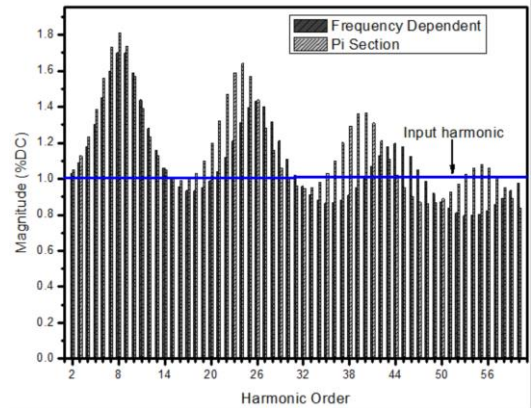


Figure 4 Output voltage frequency spectrum due to current source at the input

Figure 5 shows the harmonic spectrum of output voltage across both cable models when a current source was used at the input terminal. The current source used consists of 200A DC superimposed with 2.0 A. The rationale behind the current magnitudes are to make sure the output voltage across both cable models is 100 kV as was the case for voltage source harmonics. The overall amplitude response of the cable models is different to current source harmonics as compared to voltage source harmonics. Although the harmonic amplitudes are much smaller as compared to input harmonics and voltage source harmonics, the difference between harmonic amplitudes of Pi section and frequency dependent models are very similar. It is evident from Figure 4 and Figure 5 that both cable models have different responses to harmonics. In addition, the effect of current source and voltage source harmonics are different. The reason for introducing current source harmonics at the input was to emulate the behavior of power electronic converters while the voltage source harmonics will help in better understanding the effect of non-linear loads in the network.

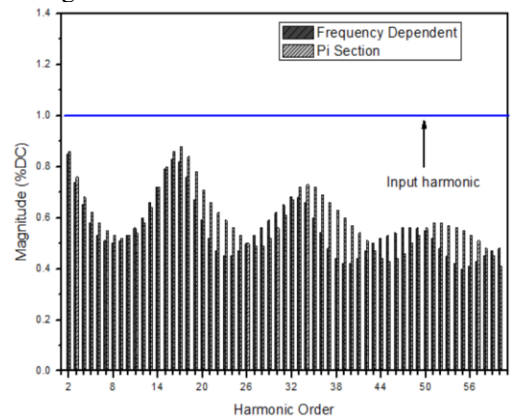


Figure 5 Output Voltage frequency spectrum due to current source at the input

Figure 6 and Figure 7 show the relationship between load and THD (%) for current and voltage source harmonics. For THD calculations, 3rd, 5th and 7th harmonics each with 1% amplitude of the DC voltage were used at the input. It can be observed from these results that for voltage source harmonics, as the load

is increased from 1 to 4 k Ω , the THD increases. However, a further increase in load have minimal effect on THD of output voltages. In the case of current source harmonics, the THD of output voltages decreases with increase in load. This may be due to the change in cable parameters with change in load which result in different harmonic response at the output. These results indicate that the response of both cable models is different to current and voltage harmonics under different loading conditions.

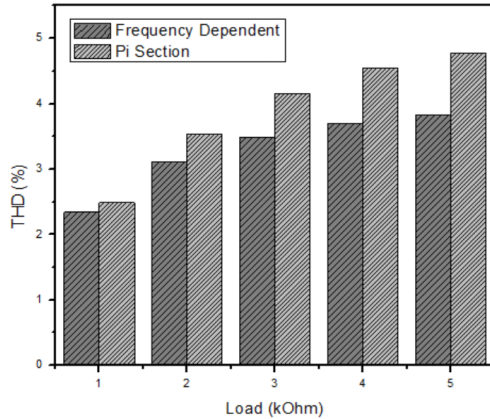


Figure 6 Variation in output THD as a function of load exposed to voltage source harmonics

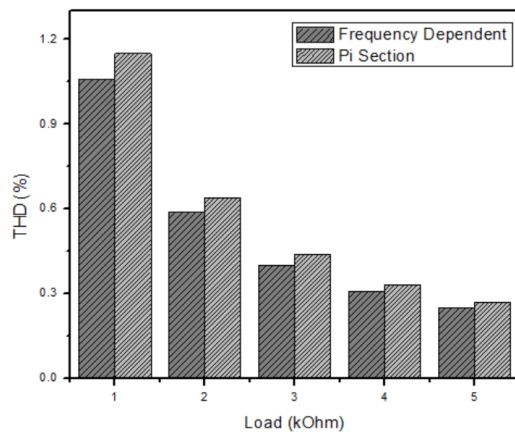


Figure 7 Variation in output THD as a function of load exposed to current source harmonics

V. CONCLUSION

This paper presents a comparison of frequency dependent and Pi section cable models to harmonic distortions. The simulation results show that both cable models have different harmonic response when exposed to similar harmonic distortion at the input terminals. Additionally, the effect of current source and voltage source harmonics are different. It was also observed that the harmonic amplitudes are higher in the case of Pi section model as compared to frequency dependent model and this difference become more evident with increase in harmonic frequency. In terms of time domain response, the current source harmonics takes much longer to settle as compared to voltage source harmonics. These results indicate that a Pi section model overestimate the harmonic amplitudes especially at higher frequencies and therefore choosing the correct cable model is

important for accurate modelling of harmonic distortion in HVDC networks.

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