Electric Power Systems Research 151 (2017) 266–272

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Frequency-dependent models of overhead power lines for steady-state harmonic analysis: Model derivation, evaluation and practical applications

Bikash Poudel, Valentina Cecchi *

Department of Electrical and Computer Engineering, University of North Carolina at Charlotte, Charlotte, NC, USA

ARTICLE INFO

Article history:
Received 15 February 2017
Received in revised form 2 May 2017
Accepted 28 May 2017

Keywords:
Harmonics
Frequency-dependent line model
Steady state analysis
Harmonic power flow
Power system modeling

ABSTRACT

This paper presents a novel frequency-dependent model for electric power lines to be used in harmonic studies. First, the differential equations representing the distributed nature of the line electrical parameters are considered; frequency dependency due to the effect of ground return and the skin effect is then incorporated. These derived equations represent what in this paper is defined as the analytical model, used as benchmark for model comparison. The vector fitting technique is used here to approximate the analytical model and derive a frequency-dependent frequency domain model. A passive circuit realization of the proposed model in a PI structure is presented and can be directly implemented in steady-state analysis tools such as harmonic power flow solvers. This paper then presents the evaluation and verification of the proposed model for multiple test cases. The test cases of unbalanced three-phase lines for overhead and underground conductors are considered. Moreover, to evaluate system-level impacts of the proposed model, the IEEE 13 node test feeder is considered. Through the evaluation of the test results, it is shown that the proposed model is more accurate than currently-used steady state models such as the simple (nominal) PI or the constant PI (with constant parameters calculated at fundamental frequency) models in terms of steady state harmonic voltages and currents at the line terminals. Test results obtained using the proposed model are within comparable accuracy to the ones obtained using the electromagnetic and transient (EMT) model, without having to run computationally expensive time domain simulations.

1. Introduction

Historically, steady state models for electric power lines have been developed under the assumption that only the fundamental frequency (i.e. 50 Hz or 60 Hz) propagates in the system; hence power line model parameters are calculated and calibrated at the fundamental frequency. The assumption of linear power system with only the fundamental frequency in the grid is not accurate; the nonlinearity of the power system has become more pronounced for a number of reasons such as increasing use of power electronic devices, nonlinear and rectifier end loads. These power electronic devices and nonlinear loads are contributing to the injection of a higher level of harmonics in the grid affecting power quality [1].

In order to study the propagation of harmonics in the grid, harmonic power flow (HPF) was introduced by Xia and Heydt in [2]. Since then, various harmonic power flow solution techniques have been proposed [3,4]. Conventional line models, such as the simple PI (nominal PI) model, which are accurate at the fundamental frequency, may not be accurate for harmonic power flow studies [5,6]. This paper presents an accurate frequency-dependent electric power line model which can be seamlessly implemented in HPF to study steady state harmonics propagation.

After the development of commercial digital simulators in 1950s and 1960s [7], various accurate simulation models of transmission lines were proposed [8]. Significant efforts have been invested in developing frequency-dependent transmission line models for electromagnetic transient (EMT) studies [9–13,19,14,15]. EMT simulation software like EMTP-ATP [16] and PSCAD [17] use these models for precise time domain simulations. These models account for harmonics propagation, however they are focused on transient studies. Hence, the simulations are in the time domain and the models cannot be used efficiently for studies in the frequency domain. Performing time domain harmonic power flow simulations for large systems is computationally burdensome, slower in time and

* Corresponding author.
E-mail addresses: bpoudel@uncc.edu (B. Poudel), vcecchi@uncc.edu (V. Cecchi).

http://dx.doi.org/10.1016/j.epsr.2017.05.038
0378-7796/

in many cases unnecessary for steady state analysis. The frequency-dependent line model proposed in this paper yields higher accuracy than commonly used steady state models, resulting in comparable accuracy to EMT models without the need to run expensive time-domain simulations.

A frequency-domain line modeling approach was proposed in [5] and embedded in a harmonic power flow algorithm in [6]. The approach creates a fixed multi-segment lumped parameter model structure for each frequency of interest; however, it does not provide a generic model to be used for all harmonics of interest. In [18], a method to derive a closed form expression for frequency-dependent parameters was presented; the method looks into individual parameter's frequency-dependency, yet again does not provide a generic model structure that could be used in steady state harmonic analysis. A concept of representing three phase lines by cascaded PI was presented in [19]; the circuit representation is in modal domain, unlike the proposed model which is in frequency domain. The work in [20] presents frequency domain models for harmonic calculations, where sequence impedances are considered instead of phase impedances. The work in [21] presents an approach to model three-phase frequency-dependent lines with entirely passive elements using the Padé approximation [22]. These models do not always have a PI structure. A generic frequency-dependent transmission line model based on the vector fitting approximation method [23] was proposed and a single balanced overhead transposed transmission line is considered as the test case in [24]. After this preliminary investigation, a comprehensive frequency-dependent electric power line modeling approach is proposed in this paper, which can model single- and multi-phase, balanced and unbalanced, electric power lines and presents a passive circuit realization for the proposed model. The proposed model is always characterized by a single generic PI structure, thereby making it easily implementable in steady state analysis tools such as power flow algorithms.

The main research goal of this paper is the derivation of a frequency-dependent electric power line model for steady state harmonic studies characterized by a single generic model which can be used for all types of electric power lines. For this task, the objectives can be further detailed as: (1) defining and deriving an analytical benchmark model to evaluate the proposed and other line models, (2) developing a highly accurate frequency-dependent line model characterized by a PI structure, (3) presenting a circuit representation of the proposed model using only passive circuit elements and (4) evaluation and testing of the proposed line model in a number of test cases. The proposed model is compared with the currently-used models such as the simple (nominal) PI and the constant PI (with constant parameters calculated at fundamental frequency) models, as well as with the benchmark analytical model. Metrics for comparison are series impedance, shunt admittance and line terminal behavior (harmonic voltage magnitudes and phases).

This paper is organized as follows. Section 2 discusses background of the steady state transmission line models and highlights limitations of commonly used frequently-used steady state models. Section 3 discusses the derivation of the proposed model. Section 4 presents the proposed line model evaluation in a 2-bus 1-line test case. Section 5 includes the simulation results evaluating the proposed line model in IEEE 13 node test case. Section 6 presents the conclusion of this work summarizing the contributions and briefly discusses the future works.

2. Background: steady state transmission line models

The most commonly used steady state lumped parameter model is the PI model [25]. In simple (nominal) PI model, per unit length parameters are calculated at 60 Hz. For a line of length l, the per unit length line parameters are simply multiplied by l. For the nth frequency of interest, series reactance and shunt susceptance are multiplied by n and series resistance and shunt conductance remain independent of frequency. The constant PI model is similar to the simple PI, except that hyperbolic equations are used to calculate line parameters for line length l, instead of simply multiplying by l. The constant PI model generates error for frequencies other than 60 Hz since the frequency-dependent parameters are calculated at 60 Hz only and the frequency-dependency is kept constant. The limitations of the constant PI model are further discussed by the authors in [24].

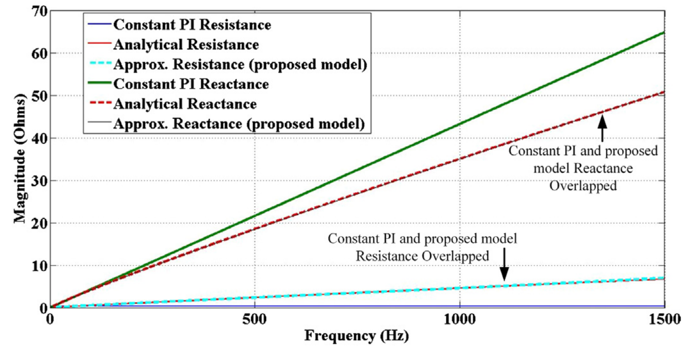

Fig. 1. Line parameter comparison of different models for a unit length line of falcon cable.

The proposed frequency-dependent line model is derived as an approximation of the analytical model. Hence, the analytical model is derived first, and considered as benchmark. The frequency-dependent analytical model is derived by incorporating frequency-dependency due to the effect of ground return path and the skin effect to the distributed parameter line model. In order to account for the effect of ground return, the per unit length series parameters are calculated using Carson's equations [26]. It is noted that alternatively, Deri et al.'s equations [27] can be used. The series line parameters are then adjusted for skin effect using the Bessel function of zeroth order [28] (Chapter 8). The per unit length shunt capacitance is calculated using the method of images. The shunt conductance exists between conductors and conductors to ground, and it accounts for leakage currents along the insulators. Especially for overhead lines, this parameter is very small and is often ignored in the determination of the line shunt admittance element [25] (Chapter 4). Then both shunt and series parameters of the test line are calculated considering uniform distribution of line parameters on a line segment using hyperbolic functions. For N number of frequencies of interest, the analytical model results in N number of exact PI models, each of which is representative of the line at a specific frequency. Impedance vs frequency for an example unit length line of falcon cable type [25] are shown in Fig. 1 for the analytical, the constant PI and the proposed models.

3. Proposed frequency-dependent line model

The proposed model is derived from the analytical model using the Vector Fitting (VF) technique [23]. The proposed model series impedance Z'_p and shunt admittance Y'_p are therefore obtained from the approximation of the analytical model. Z'_p and Y'_p are expressed as the rational pole-residue model, i.e. a transfer function, in the form of ratio of zeros to poles as,

$$Z'_p = \frac{Zr_z(s)}{Pl_z(s)} \text{ and } \frac{Y'_p}{2} = \frac{Zr_y(s)}{Pl_y(s)}, \quad (1)$$

where the subscript z indicates impedance and y indicates admittance, $Zr_z(s)$ is the set of zeros and $Pl_y(s)$ is the set of poles. Hence, the series and shunt elements of the proposed PI-structure model