Electrical Power and Energy Systems 44 (2013) 908–915

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

Digital filtering of oscillations intrinsic to transmission line modeling based on lumped parameters

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ARTICLE INFO

Article history:
Received 10 April 2012
Received in revised form 1 August 2012
Accepted 9 August 2012
Available online 27 September 2012

Keywords:
Transmission lines
Electromagnetic transients
Digital signal processing
FIR digital filter

ABSTRACT

A correction procedure based on digital signal processing theory is proposed to smooth the numeric oscillations in electromagnetic transient simulation results from transmission line modeling based on an equivalent representation by lumped parameters. The proposed improvement to this well-known line representation is carried out with an Finite Impulse Response (FIR) digital filter used to exclude the high-frequency components associated with the spurious numeric oscillations. To prove the efficacy of this correction method, a well-established frequency-dependent line representation using state equations is modeled with an FIR filter included in the model. The results obtained from the state-space model with and without the FIR filtering are compared with the results simulated by a line model based on distributed parameters and inverse transforms. Finally, the line model integrated with the FIR filtering is also tested and validated based on simulations that include nonlinear and time-variable elements.

1. Introduction

One of the most important characteristics in power system modeling is the frequency dependence of the electrical parameters. To study the electromagnetic transients of electric power devices, the variation in their parameters as a function of the frequency should be accurately considered by taking into account the fact that the transient conditions in power systems are composed of a range of low to high frequencies, up to approximately 1 MHz [1].

In general, transmission lines can be modeled directly from their electrical parameters in the frequency domain or by using an equivalent representation by lumped elements directly in the time domain. The first modeling approach is developed from the two-port representation of the line in the frequency domain, and the time-domain results are obtained by applying inverse transforms [2]. Although the distributed-parameter models are considered to be an accurate representation of the transmission systems, these models are not a typically used or practical. The main disadvantage of this type of representation is the difficult integration with other nonlinear and time-variable elements (e.g., switching, capacitors, corona effect, disruptive discharges, surge arresters, etc.). Furthermore, the models included in the well-established Electromagnetic Transient Program (EMTP) and the Alternative Transient Program (ATP) (as well as several other derivatives of these two programs) are completely implemented in the time domain, which enables the insertion of time-variable elements in the simulation process [3,4].

Since the 1970s, several researchers have investigated transmission line models implemented directly in the time domain. Currently, several time-domain models exist, and many improvements, such as real-time applications and improvements to the well-established models in the literature, have been proposed to address the new trends. A classic example of a time-domain model using lumped parameters is the well-known cascade of π circuits. This model is widely used to represent transmission lines directly in the time domain for research or didactic purposes. Furthermore, a detailed profile of the currents and voltages along the line can be obtained from the representation by a cascade of π circuits and the inclusion of time-variable elements in the simulations. These features are the main advantages of the line representation by lumped parameters over the representation by distributed parameters [5].

The three-phase representation by a cascade of π circuits is a practical implementation that enables easy interaction of the line model with many other power devices and common electromagnetic phenomena in power systems. In addition, this type of model can be represented by state matrices and solved by numeric or analytical integration methods [5,6].

Another positive aspect of modeling with the lumped elements approach is that this approach can easily be implemented by using most programs based on the EMTP/ATP, both commercial and open-source, or by using any other computational language.

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http://dx.doi.org/10.1016/j.ijepes.2012.08.050

Simulations performed from models of lumped elements are relatively accurate for a wide range of frequencies, thus enabling most simulations that consider possible transient conditions in transmission lines and power systems [6]. However, this paper addresses one of the main disadvantages associated with the representation by lumped parameters, which is the error that occurs due to the continuous function discretization, such as the longitudinal/transversal parameters of the line and the continuous function representing the simulation time [2].

The development proposed in this paper describes an original and nonconventional correction method based on the integration of an Finite Impulse Response (FIR) digital filter in the three-phase line modeling using state equations. Thereafter, the results obtained from the FIR-filtering-integrated line model are compared with the results from simulations performed from the same model without the FIR digital filter and with results obtained from a well-established model by distributed parameters.

2. Line representation by frequency-dependent lumped elements

An equivalent section of transmission line can be represented by a frequency-dependent π circuit. This statement is based on the procedure described by Gustavsen and Semlyen using *vector fitting* to include the frequency-dependent line parameters directly in the time domain [7]. Using this procedure, several transmission line models for symmetrical and asymmetrical configurations have been described in the literature [5,6]. This equivalent frequency-dependent π circuit is described as follows.

In Fig. 1, the terms $R_0, R_1, R_2, \ldots, R_m$ represent resistances, while $L_0, L_1, L_2, \ldots, L_m$ represent inductances. The terms G and C refer to the shunt conductance and shunt capacitance, respectively. The time-variable values V_{k-1} and V_k are the shunt voltages on the sending end and on the receiving end of the k-th π section, respectively. The terms I_{k0} and $I_{(k+1)0}$ are the currents in the k-th and $(k+1)$-th Π circuits. Thus, the differential equations of the circuit described in Fig. 1 are given as follows.

$$\frac{dI_{k0}}{dt} = \frac{I_{k0}}{L_0}\left(-\sum_{j=1}^{m} R_j\right) + \frac{1}{L_0}\left(-\sum_{j=1}^{m} R_j I_{kj}\right) + \frac{1}{L_0}V_{k-1} - \frac{1}{L_0}V_k \quad (1)$$

$$\frac{dI_{k1}}{dt} = \frac{R_1}{L_1}I_{k0} - \frac{R_1}{L_1}I_{k1} \quad (2)$$

$$\frac{dI_{km}}{dt} = \frac{R_m}{L_m}I_{k0} - \frac{R_m}{L_m}I_{km} \quad (3)$$

$$\frac{dV_k}{dt} = \frac{1}{C}I_{k0} - \frac{1}{C}I_{(k+1)0} - \frac{G}{C}V_k \quad (4)$$

The terms $I_{k0}, I_{k1}, I_{k2}, \ldots, I_{km}$ are the currents in the lumped inductances $L_0, L_1, L_2, \ldots, L_m$, respectively.

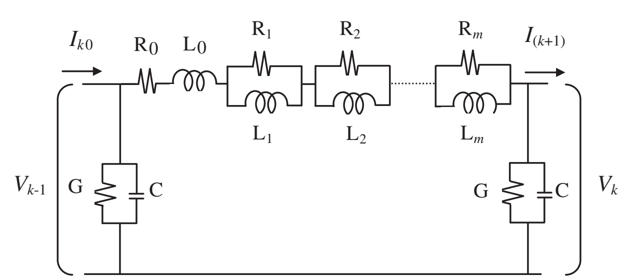

Fig. 1. Frequency-dependent π circuit representing the k-th line section.

In the formulation expressed by Eqs. (1)–(4) and extended to a cascade with n frequency-dependent π section, a system composed of $n(m+2)$ differential equations completely describes the current and the voltage profiles along the line. This system is usually represented in state space in the following form [5].

$$[\dot{X}] = [A][X] + [B]u(t) \quad (5)$$

$$[X] = [\,[X_1] \quad [X_2] \quad \cdots \quad [X_n]\,]^t \quad (6)$$

vector [X] has $n(m+2)$ elements, while $[X_k]$ has $(m+2)$. A generic vector $[X_k]$ in $[X]$, as described in Eq. (6), is described as follows:

$$[X_k]^t = [\,I_{k0} \quad I_{k1} \quad I_{k2} \quad \cdots \quad I_{km} \quad V_k\,] \quad (7)$$

where $[X_k]^t$ is the transposed vector of $[X_k]$, emphasizing that the voltage and current values in $[X_k]$ are related to the k-th element of the cascade.

The state matrix [A] has dimensions of $n(m+2)$ and is composed of submatrices with dimensions of $(m+2)$. The generic submatrix $[A_{kk}]$ in the main diagonal of the matrix [A] is described as a function of the electric lumped elements of the k-th π circuit [5]:

$$[A_{kk}] = \begin{bmatrix} -\frac{\sum_{j=0}^{j=m} R_j}{L_0} & -\frac{R_1}{L_0} & -\frac{R_2}{L_0} & \cdots & -\frac{R_m}{L_0} & -\frac{1}{L_0} \\ \frac{R_1}{L_1} & -\frac{R_1}{L_1} & 0 & \cdots & 0 & 0 \\ \frac{R_2}{L_2} & 0 & -\frac{R_2}{L_2} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{R_m}{L_m} & 0 & 0 & \cdots & -\frac{R_m}{L_m} & 0 \\ \frac{1}{C} & 0 & 0 & \cdots & 0 & -\frac{G}{C} \end{bmatrix} \quad (8)$$

Vector [B] has dimensions of $n(m+2)$ and is expressed as follows:

$$[B] = \left[\frac{1}{L_0} \quad 0 \quad \cdots \quad 0\right]^t \quad (9)$$

This state-space model is well described by Refs. [5,6], in which a step-by-step description is presented showing the three-phase representation of this well-established model using modal analysis techniques [8]. This line model is considered to be a reference for the proposed correction procedure. In the following sections, the mathematical modeling of the FIR digital filter and its insertion in the state-space line model is described in detail. Thereafter, time-domain simulations are performed and properly compared with results obtained from other established line models.

3. The zero-phase FIR filtering

Causal filters are usually applied to real-time processes in which the system output $y(a)$ is a function solely of the previous inputs $y(a–b)$, for $b = 0, 1, 2$, etc. However, an intrinsic characteristic of the causal filters is the introduction of a phase shift. The usual method for dealing with this negative feature is to model the causal filter for a linear phase shift or a linear frequency passband, resulting in the same time delay for each frequency component [9].

For post processing applications in which causal filters are not commonly used, the phase shift can be easily avoided [10]. Furthermore, even for real-time applications, the signals can be processed in samples with length N in the cases in which causal filtering is not required [11].

Concerning the procedures in which postprocessing is feasible, the implementation of a null phase-shift filter is straightforward. The frequency response of a filter $H(z)$ is given as $H(e^{j\omega})$, and the phase shift is given as $\varphi_H(\omega) = \arg(H(e^{j\omega}))$. This approach means that the frequency component ω_1 is shifted by an angle of