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A frequency-domain equivalent-based approach to compute periodic steady-state of electrical networks

Mauricio Caixba*, Abner Ramirez

Center for Research and Advanced Studies of Mexico (CINVESTAV), 1145 Av. del Bosque, Col. El Bajio, Zapopan 45019, Jalisco, Mexico

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ABSTRACT

An alternative hybrid time/frequency domain approach to compute the periodic steady-state of an electrical network is presented. The network under analysis can include a variety of linear and nonlinear components, e.g., *PV*-buses, nonlinear reactors, and electronic devices. In the proposed approach, the linear part of the network is modeled in the frequency-domain (FD) via an equivalent input-admittance and all nonlinear components but *PV*-buses are resolved in the time-domain (TD). The FD equivalent is interfaced to the nonlinear components via discrete Fourier transform (DFT) operations, accounting for harmonic and interharmonic frequencies. The interfacing voltage/current variables are solved through a global Gauss–Seidel procedure; *PV*-buses are solved via a local Newton-type iterative procedure. It is shown that the proposed approach achieves faster computations than traditional hybrid methods due to (i) the compact FD equivalent representation of the linear part of the network and (ii) the Gauss–Seidel iterative scheme that avoids calculation and inversions of Jacobians. A sample network is used to compare the proposed method with a Newton-type solution scheme; the resulting waveforms are also compared with those given by the PSCAD™/EMTDC™ simulation software.

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1. Introduction

Frequency content analysis of electrical systems directly impacts their design and protection. Furthermore, that analysis is one of the fundaments for characterization and assessment of resonance conditions. Former steady-state analysis of electrical networks was based on fundamental power flow algorithms [1–9] which mainly used Newton-type solution methods [6]. The increasing installation of nonlinear components in electrical networks has further required to include a wide range of frequencies, e.g., harmonic and/or interharmonic components, and to use alternative numerical solution schemes [10–40]. The existent periodic steady-state computation techniques, that can be used for harmonic analysis, can be classified into three general groups: (i) FD, (ii) TD, and (iii) hybrid FD/TD methods [19,25,39,34].

Traditional FD techniques represent nonlinear components, e.g., reactors and electronic devices, as equivalent harmonic current sources. Among these methods are: (a) the current source method [26], (b) the direct current injection [33], and (c) the iterative harmonic analysis (IHA) which is based on a Gauss–Seidel solution scheme [13–15,20]. The IHA method can be readily applied to unbalanced systems. However, its extension to include interharmonics involve some difficulties [24]. In addition, the IHA must perform a TD estimation of nonlinear loads currents at each iteration step and its convergence has to be addressed by means of appropriate numerical techniques [20,24,33]. An alternate FD approach is the multi-frequency power flow (MFPF) [15–17,21–24], which accounts simultaneously for all harmonics in a matrix-vector formulation. The MFPF utilizes a Newton–Raphson solution scheme and readily incorporates interharmonic components by setting the base frequency as the highest common denominator of all involved frequencies. However, the traditional implementation of the MFPF involves large computational resources due to the inversion of large matrices and the computation of a Jacobian at each iterative step [24].

Pure TD methods readily include nonlinear elements and switching devices in the electrical system under analysis. However, TD methods involve large processing times to obtain the steady-state for lightly damped circuits. In this tenor, substantial improvements have been achieved by using acceleration methods, e.g., the limit cycle [25,27,41–43]. The fundamental idea in acceleration methods is to use the intercepts with a Poincaré plane to extrapolate the limit cycle by using Newton's method [27]. To locate the set of state variables at the limit cycle, the identification of the transition matrix is performed by mainly two approaches: via direct

* Corresponding author. Tel.: +52 2949432630.
E-mail addresses: mcaixba@gdl.cinvestav.mx (M. Caixba), abner.ramirez@ctsdesign.com (A. Ramirez).

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integration and via numerical differentiation using sequential perturbations [25,42,43]. Since these two computational approaches can involve meaningful computational times for large systems, they can be implemented in a hybrid scheme, as proposed in [25]. Among the several applications of acceleration techniques are the solution of unified power flow controller [41] and custom power parks simulations [43].

Hybrid FD/TD techniques, which solve the linear part of a network in FD and handle nonlinear components in TD, achieve faster computational times, especially for frequency-dependent systems. Hybrid methods have traditionally been focused on harmonic analysis [25,24]. The forward/backward sweeping technique has recently been adapted as a hybrid FD/TD technique for simultaneous harmonic and interharmonic analysis [40]. The sweeping technique avoids calculation of large transfer matrices and inversion of Jacobians; however, quadratic convergence cannot be achieved as in Newton-based methods [28,38,40]. Alternatively, the hybrid approach proposed in [25] utilizes a global iterative solution scheme between the linear part, represented in the FD, and the nonlinear part of the network. A local iterative procedure, based on TD acceleration techniques, is performed to solve the nonlinear part. Decoupling of harmonics is also assumed in [25] when calculating the current mismatch at the interface between linear and nonlinear parts, requiring additional structural considerations. However, the harmonic decoupling becomes attractive only for the solution of networks with low or moderate frequency distortion [25].

This paper proposes an alternative hybrid FD/TD approach based on the concept of FD equivalents [35,44,45]. In the proposed approach the external (linear) subsystem, modeled as FD equivalent, is interfaced to nonlinear components and generator buses (*PV*-buses, constant active power $|P|$ and voltage magnitude $|V|$) via a two-stage solution scheme. The solution involves (i) a Newton-type local iterative process at nodes considered as *PV*-buses and (ii) a fixed-point global iteration to update node voltages interfacing the linear and the nonlinear sub-networks. Nonlinear components are computed in the TD; the interfacing between the corresponding TD and FD variables is performed by a fast Fourier transform (FFT/IFFT) algorithm. The method considers full frequency coupling, regardless the degree of nonlinearity, and readily handles unbalanced conditions. It is shown in this paper that the use of FD equivalents for the linear part of the network substantially reduces processing times compared to traditional methods. As major characteristics, the proposed approach is able to handle large frequency-dependent networks efficiently and accounts for a wide range of frequencies, including harmonics and interharmonics.

Using a sample network, the proposed method is validated and compared with a traditional Newton-type solution scheme, where the *PV*-buses are modeled as in [31].

In this paper, unless otherwise specified, uppercase-type variables denote FD vector/matrix quantities (generally complex) and lowercase-type variables stand for TD instantaneous quantities.

2. Review of the MHD

The modified harmonic domain (MHD) [36] is utilized to model the linear part of the network in the FD. The MHD permits to readily include a wide range of frequencies, i.e., harmonics and interharmonics [33]. Also, the MHD permits to transform, in a similar way to the traditional harmonic domain (HD), the scalar ordinary differential equation (ODE):

$$\dot{x}(t) = a(t)x(t) + b(t)v(t), \tag{1}$$

into the algebraic system of equations:

$$DX = AX + BV, \tag{2}$$

where the new (generally complex) variables are defined as (T_r denotes transpose):

$$X = [X_o \quad X_1 \cdots X_{N-1}]^{T_r}, \tag{3a}$$

$$D = \mathrm{diag}[0 j\Delta\omega j2\Delta\omega \cdots j(N-1)\Delta\omega], \tag{3b}$$

where $\Delta\omega$ and N are the sampling step and number of samples, respectively. Additionally, A and B correspond to Toeplitz-type matrices. Expression (2) is obtained first by replacing all variables in (1) by their corresponding DFT expressions. A subsequent step cancels out the DFT exponentials of both sides of the obtained DFT-based equation, resulting in (2) with the terms in the diagonal matrix D given by the derivation with respect to time of the DFT representation of $x(t)$. Further details of the MHD can be seen in [36]. In the proposed method, the electrical network relations, usually represented by ODEs, as in (1), are expressed in the MHD, as in (2), for periodic steady-state computations.

3. FD/TD hybrid approach

Based on the network equivalent concept [46–48,44,45], the external subsystem consists of all linear elements and the study zone involves both nonlinear components and *PV*-buses, as illustrated in Fig. 1. The general solution of the illustrative network of Fig. 1 consists of (i) a global Gauss–Seidel iterative scheme at the interface between the FD equivalent and nonlinear components and (ii) a local Newton–Raphson procedure for *PV*-buses. The following steps are applied.

Step 1. The nodal formulation of the network of Fig. 1 is expressed in the MHD as:

$$\begin{bmatrix} I_S \\ -I_{NL} \\ I_{PV} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} V_S \\ V_{NL} \\ V_{PV} \end{bmatrix}, \tag{4}$$

where I_S and V_S represent internal current sources and nodal voltages, respectively, of the external subsystem; I_{NL} corresponds to the current flowing into nonlinear elements; V_{NL} is the voltage at the terminals of the nonlinear elements; I_{PV} is the current by the *PV*-buses and V_{PV} the corresponding terminal voltage vector.The admittance elements in (4) correspond to MHD admittance matrices involving combinations of linear elements such as linear loads and frequency dependent transmission lines [36,40]; the lines represented in this paper via frequency dependent line models.

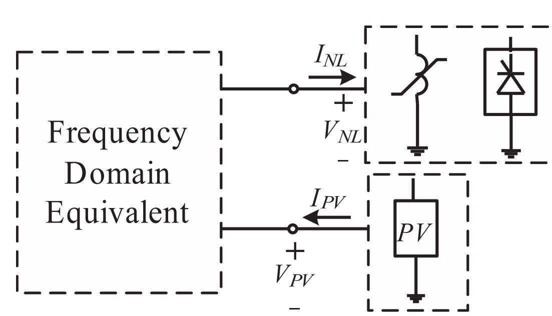

Fig. 1. Network representation with nonlinear components and *PV*-buses.

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