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Dynamic modeling and analysis of generalized unified power flow controller

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ABSTRACT

This paper presents a unified solution to compute power quality indices in the generalized unified power flow controller (GUPFC) during steady and transient conditions using a dynamic harmonic domain technique. This technique allows the user to analyze harmonics generated in the GUPFC more precisely than using time domain techniques. The derivation of a model is presented and then simulated in the presence of voltage disturbances to demonstrate its use in power quality assessment. The results of the proposed model are validated against time domain simulations.

1. Introduction

Over the last few decades, the use of semiconductor devices in large-scale power systems has spread around the world due to the increased ratings of these devices, and resulting in an area of academic study we now call high-power electronics [1,2]. These devices are used to improve the electrical and economic performance of power transmission systems, which the electric utilities companies use to deliver electricity to their customers [3]. But since they are nonlinear devices, they produce undesirable distortions in the voltage and current waveforms in the circuits to which they are connected. These distortions also result in the presence of undesirable harmonics [4].

The study of the harmonic content of distorted, but periodic, waveforms via the simulation of time-domain (TD) models require long simulation run times. This is a consequence of the need to let the transients die out and to allow sufficient time, under steady-state conditions, for the accurate calculation of the harmonics via the fast Fourier transform (FFT) [5–9]. Electromagnetic transients' simulations tools such as PSCAD/EMTDC can be used to calculate transients as a function of time. To compute the harmonic content during the corresponding period of interest, a post-processing routine can then be used. Fox example, windowed fast Fourier Transform (WFFT) method has been used for the calculation of harmonic information of a signal. However, this method has some drawbacks such as leakage picket-fence, aliasing, and edge effect [10]. Additionally, this method is dependent on the size of the window to achieve accuracy in results. However, adjusting the size of this window is not a small procedure. Hence, keeping in mind these drawbacks, it is difficult to accurately assess power quality. The time-domain methods with WFFT achieve harmonic behavior of the system under stationary conditions. However, these methods lose their accuracy during time-varying conditions [10]. Therefore, it is not possible to capture the accurate harmonic response of the system using these methods with WFFT during fast disturbances.

An alternative methodology has been proposed, which models the systems in the harmonic-domain (HD) rather than in the time domain, thus producing models for the steady-state simulation [7]. This has been demonstrated by its application to high-voltage DC (HVDC) transmission systems [11–14], and in flexible AC transmission systems (FACTS) such as fixed capacitor-thyristor controlled reactor (FC-TCR) [15,16], thyristor-controlled reactor (TCR) [17], thyristor-controlled switched capacitors (TCSC) [15], static compensators (STATCOM) [18,19], static synchronous series compensators (SSSC) [20], and unified power flow controllers (UPFC) [14,21,22].

The procedure in [39] referred to as phasor dynamics, for the first time, is to give prominence to the time-varying nature of the signals in phasor description. Dynamic phasor models incorporate the relatively large Fourier coefficients [39] which in most cases is the DC

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component. This technique is based on the generalized averaging method and it has been applied to obtain FACTS controller models [40]. In [39] the paper was focused on the representation of the DC and fundamental frequency components. However, additional harmonic terms can significantly improve the efficacy of models. It was recommended that effects of important harmonics should be included in the models [40].

Recently, a new methodology, the dynamic harmonic domain (DHD) technique, which is an extension of the theory of dynamic phasors to provide a dynamic, harmonic frame of reference, has been proposed [23]. This allows for the determination of the harmonic content of distorted waveforms, not only in the steady state, but also during transients. The proposed DHD methodology has been demonstrated by its application to the study of the dynamic behavior of harmonics in HVDC [14], STATCOM [23], TCR [24], SVC [25,26], SSSC [25,26] and UPFC [25,26] systems, and has shown that DHD models have none of the disadvantages associated with WFFT and therefore it is a possible method to be used for the accurate assessment of power quality [23]. Recently, the DHD modeling has been successfully applied for several applications in transmission and distribution systems [27–32]. The DHD modeling approach can also be applied to multi-phase, multi-machine systems. This is explained as follows: In [9,18] the multi-pulse STATCOM was modeled using HD and was simulated using multi-phase switching functions in order to understand the reaction of these controllers to various switching functions and study their influence on power quality indices under steady and disturbance conditions. DHD methodology is applicable for all the power electronics controller HD models developed in the open literature [9].

This paper presents the DHD modeling of a much more complex controller, the generalized unified power flow controller (GUPFC) [33], which is a multi-line voltage-source controller and one of the newest additions to the set of FACTS controllers. A simulation of the proposed model allows for the assessment of power quality by the calculation of power quality indices.

The paper is organized as follows: in Section 2, the basic theory of the dynamic harmonic-domain methodology is presented. Section 3, the main contribution of this study, presents the DHD modeling of the GUPFC. Numerical results are presented and discussed in Section 4. It also includes a validation of the model results by a comparison to time domain results.

2. Dynamic harmonic domain

The following development of the dynamic harmonic domain method is adapted from [23,34,35]. A continuous, periodic function $x(t)$ with $t \in (-\infty, \infty)$ and period T may be represented to any degree of accuracy by the time-dependent complex Fourier series given by [36].

$$x(t) = \sum_{n=-\infty}^{\infty} X_n(t) e^{jn\omega_0 t} \tag{1}$$

where $\omega_0 = 2\pi/T$. Note that the complex Fourier coefficients $X_n(t)$ depend on time in the following manner. At any time t, consider a time window of length T just prior to t, namely the interval $[t-T, t]$ Then the Fourier coefficients that are assigned to t are taken to be

$$X_n(t) = \frac{1}{T} \int_{t-T}^{t} x(\tau) e^{-jn\omega_0 \tau} d\tau \tag{2}$$

The complex coefficients in (2) are referred to as *dynamic phasors* [34]. This representation of the signal $x(t)$ is the fundamental concept which underlies the DHD method. Eq. (2) gives the time-evolution of the complex Fourier coefficients as a window of length T is translated along the waveform $x(t)$.

For numerical calculations the infinite sum in (1) can be limited to a finite number of harmonics, say $n \in [-h, h]$. Then $x(t)$ may be approximated by

$$x(t) \approx \sum_{n=-h}^{h} X_n(t) e^{jn\omega_0 t} \tag{3}$$

In this case, (3) may be represented in matrix notation by

$$x(t) = \mathbf{G}^{\mathrm{T}}(t)\mathbf{X}(t) \tag{4}$$

where

$$\begin{aligned} \mathbf{G}(t) &= \begin{bmatrix} e^{-jh\omega_0 t} & \cdots & e^{-j\omega_0 t} & 1 & e^{j\omega_0 t} & \cdots & e^{jh\omega_0 t} \end{bmatrix}^T \text{and} \\ \mathbf{X}(t) &= \begin{bmatrix} X_{-h}(t) & \cdots & X_{-1}(t) & X_0(t) & X_1(t) & \cdots & X_h(t) \end{bmatrix}^T \end{aligned} \tag{5}$$

The vector $\mathbf{G}(t)$ is made up of the first $2h+1$ orthogonal basis elements in the complex Fourier series representation of $x(t)$ and $\mathbf{X}(t)$ is the vector whose components are the harmonic coefficients of $x(t)$

State-space models can be expressed in the DHD as follows. Consider the linear time-periodic (LTP) system

$$\begin{aligned} \dot{x}(t) &= a(t)x(t) + b(t)u(t) \\ y(t) &= c(t)x(t) + e(t)u(t) \end{aligned} \tag{6}$$

where all functions are assumed to have period T.

In order to transform (6) into the harmonic domain, some preliminary results are needed. Differentiating (4) gives

$$\dot{x}(t) = \mathbf{G}^T(t)\dot{\mathbf{X}}(t) + \dot{\mathbf{G}}^T(t)\mathbf{X}(t) \tag{7}$$

The derivative of the basis vector $\mathbf{G}(t)$ can be expressed as

$$\dot{\mathbf{G}}(t) = \mathbf{D}(jh\omega_0)\mathbf{G}(t) \tag{8}$$