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Multi-scale simulation of multi-machine power systems

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ABSTRACT

The proposed method enables the modeling and integration of synchronous machinery models in accurate and efficient simulation of power systems over diverse time scales that cover electromagnetic and electromechanical transients. The underlying models make use of frequency-adaptive simulation of transients (FAST) where analytic signals are used since they lend themselves to the shifting of the Fourier spectra. The shift frequency appears as a simulation parameter in addition to the time step size. When setting the shift to the common carrier frequency of either 50 or 60 Hz, the method emulates phasor-based simulation that is very suitable for extracting envelope information at relatively large time step sizes. At zero shifting, instantaneous values are being tracked. It is shown how this shifting plays a critical role in integrating synchronous machine models that are represented using the Park transformation with the network model. In a further step, it is illustrated how the modeling approach is modified if the Park transformation is not applied. For illustrative purposes, the integration is first validated for a single-machine-infinite-bus system. In a following multi-machine test case involving four machines in two areas, the added value of the proposed methodology becomes clear as both electromagnetic transients and electromechanical transients are emulated accurately and efficiently within one simulation run.

1. Introduction

In the power system community, different methods have been developed for respectively the simulation of electromagnetic and electromechanical transients. The electromagnetic transients program (EMTP) as well as state-space-based methods that simulate electromagnetic transients process instantaneous signals to track the natural waveforms of voltages and currents at time step sizes that are typically in the range of microseconds [1–7]. Simulators for electromechanical transients process phasor signals and track the envelope waveforms of voltages and currents at much larger time step sizes [8–10]. The concept of frequency-adaptive simulation of transients (FAST) [11,12] offers an efficient solution for the representation of both electromagnetic and electromechanical transients within a single tool. Analytic signals bridge the relative merits of instantaneous and dynamic phasor signals and allow for the shifting of the Fourier spectra in the frequency domain. If the shift frequency is set to the carrier frequency of 50 or 60 Hz, then the carrier is eliminated and electromechanical transients are emulated efficiently as it is for dynamic phasor signals. If the shift frequency is set to zero, then the carrier waveform is displayed as it is the case in simulators of the EMTP-type.

In the context of the multi-scale simulation of electromagnetic and electromechanical transients, the contributions made in this paper are fourfold. First, a multi-scale synchronous machine model that makes use of the dq0 transformation, also known as Park transformation, is introduced and discussed. Second, a method of interfacing this synchronous machine model with the remainder of the network model is presented. Third, it is shown how the modeling and interfacing is modified when the dq0 transformation is not applied. Fourth, test cases involving single- and multi-machine power systems have been set up to demonstrate the effectiveness of the developed methodologies.

This paper is organized as follows. The state-of-the-art is reviewed in Section 2. The multi-scale modeling of the machine in the dq0 domain and the related network integration are dealt with in Section 3. The alternate approach of multi-scale modeling of the machine in the phase domain without dq0 transformation is introduced in Section 4. In Section 5, a single machine is connected to an infinite bus to validate the proposed machine model, and a four-machine two-area power system is studied to illustrate the added value through the simulation of a short circuit triggering electromagnetic and electromechanical transients.

2. State of the art

The concept of frequency-adaptive simulation of transients relies on the processing of analytic signals, whose properties are reviewed in Section 2.1. In Section 2.2, the principle of the

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multi-scale modeling of components is reviewed using the inductor modeling as example [11]. The setting of the shift frequency as a new simulation parameter is elaborated upon in Section 2.3.

2.1. Introduction of analytic signal

The analytic signal of a real signal $s(t)$ is obtained as follows:

$$\underline{s}(t) = s(t) + j\mathscr{H}[s(t)], \tag{1}$$

where $\mathscr{H}[s(t)]$ is the Hilbert transform of $s(t)$ and the underscore indicates the signal is complex.

The effect of the creation of the analytic signal from an original signal with bandpass character and carrier frequency f_c, as it typically appears in electromechanical transients, is shown in Fig. 1. While the Fourier spectrum of the real signal $s(t)$ extends to negative frequencies, this is not the case for the Fourier spectrum of the corresponding analytic signal $\underline{s}(t)$.

The analytic signal can be shifted by the frequency f_s, which is hereafter referred to as shift frequency, as follows:

$$\mathscr{S}[\underline{s}(t)] = \underline{s}(t)\mathrm{e}^{-j2\pi f_s t}. \tag{2}$$

Of particular interest is the case where the shift frequency is made equal to the carrier frequency: $f_s = f_c$. In this case, the complex envelope [13] is obtained:

$$\mathscr{E}[\underline{s}(t)] = \underline{s}(t)\mathrm{e}^{-j2\pi f_c t}. \tag{3}$$

The graphical interpretation of this operation is given in Fig. 2. It can be seen that the complex envelope is a lowpass signal, whose maximum frequency is reduced as a result of the shifting. Therefore, compared with the sampling of the original bandpass signal, it is possible to employ a larger time step size for sampling the complex envelope according to Shannon's sampling theorem.

2.2. Basic component model based on analytic signals [11]

With analytic signals, the behavior of an inductance can be described by

$$\frac{\mathrm{d}\underline{i}_L(t)}{\mathrm{d}t} = \frac{\underline{v}_L(t)}{L}. \tag{4}$$

Now, frequency shifting according to (2) is employed. Insertion of the shifted inductance current

$$\mathscr{S}[\underline{i}_L(t)] = \underline{i}_L(t)\mathrm{e}^{-j\omega_s t}, \tag{5}$$

where $\omega_s = 2\pi f_s$, into (4) yields

$$\frac{\mathrm{d}\left(\mathscr{S}[\underline{i}_L(t)]\mathrm{e}^{j\omega_s t}\right)}{\mathrm{d}t} = \frac{\underline{v}_L(t)}{L}. \tag{6}$$

This can be expanded and rearranged as follows:

$$\frac{\mathrm{d}\mathscr{S}[\underline{i}_L(t)]}{\mathrm{d}t} = \mathrm{e}^{-j\omega_s t}\left(-j\omega_s\underline{i}_L(t) + \frac{\underline{v}_L(t)}{L}\right). \tag{7}$$

Differencing (7) by the trapezoidal rule with time step size τ and time step counter k leads to

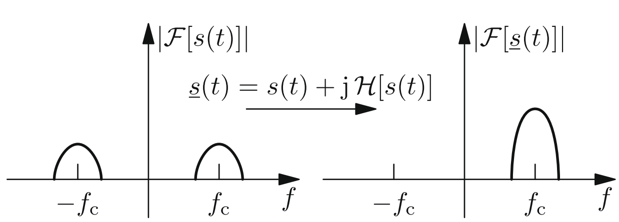

Fig. 1. Application of the Hilbert transform.

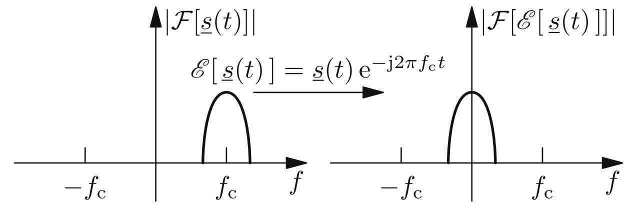

Fig. 2. Shifting by the carrier frequency.

$$\begin{aligned}
&\frac{\mathscr{S}[\underline{i}_L(k)] - \mathscr{S}[\underline{i}_L(k-1)]}{\tau} \\
&= \frac{1}{2}\mathrm{e}^{-j\omega_s k\tau}\left(-j\omega_s\underline{i}_L(k) + \frac{\underline{v}_L(k)}{L}\right) \\
&+ \frac{1}{2}\mathrm{e}^{-j\omega_s(k-1)\tau}\left(-j\omega_s\underline{i}_L(k-1) + \frac{\underline{v}_L(k-1)}{L}\right).
\end{aligned} \tag{8}$$

The difference term on the left of (8) is expressed in terms of the shifted signal. Since, as shown in Fig. 2, frequency shifting is performed to reduce the maximum frequency in the Fourier spectrum, the shifted signal changes at a lower rate compared with the unshifted counterpart. Thus, for $\omega_s = \omega_c$ a larger time step size can be chosen compared with the case where the difference $i_L(k) - i_L(k-1)$ is considered. This in turn reduces the number of time steps and the associated computational effort.

Back substitution of analytic waveforms to (8) yields

$$\begin{aligned}
&\frac{\underline{i}_L(k)\mathrm{e}^{-j\omega_s k\tau} - \underline{i}_L(k-1)\mathrm{e}^{-j\omega_s(k-1)\tau}}{\tau} \\
&= \frac{1}{2}\mathrm{e}^{-j\omega_s k\tau}\left(-j\omega_s\underline{i}_L(k) + \frac{\underline{v}_L(k)}{L}\right) \\
&\quad + \frac{1}{2}\mathrm{e}^{-j\omega_s(k-1)\tau}\left(-j\omega_s\underline{i}_L(k-1) + \frac{\underline{v}_L(k-1)}{L}\right).
\end{aligned} \tag{9}$$

Multiplication by $\mathrm{e}^{j\omega_s k\tau}$ on both sides of (9) leads to

$$\begin{aligned}
\frac{\underline{i}_L(k) - \underline{i}_L(k-1)\mathrm{e}^{j\omega_s\tau}}{\tau} &= \frac{1}{2}\left(-j\omega_s\underline{i}_L(k) + \frac{\underline{v}_L(k)}{L}\right) \\
&\quad + \frac{1}{2}\mathrm{e}^{j\omega_s\tau}\left(-j\omega_s\underline{i}_L(k-1) + \frac{\underline{v}_L(k-1)}{L}\right),
\end{aligned}$$

which can be rearranged as

$$\begin{aligned}
\underline{i}_L(k) = &\frac{\tau}{L(2+j\omega_s\tau)}\underline{v}_L(k) + \mathrm{e}^{j\omega_s\tau}\frac{2-j\omega_s\tau}{2+j\omega_s\tau}\underline{i}_L(k-1) \\
&+ \mathrm{e}^{j\omega_s\tau}\frac{\tau}{L(2+j\omega_s\tau)}\underline{v}_L(k-1).
\end{aligned} \tag{10}$$

The frequency-adaptive companion model of inductance is thus described by [12]

$$\underline{i}_L(k) = \underline{G}_L\underline{v}_L(k) + \underline{\eta}_L(k), \tag{11}$$

with

$$\underline{G}_L = \frac{\tau}{L(2+j\omega_s\tau)}, \tag{12}$$

$$\underline{\eta}_L(k) = \mathrm{e}^{j\omega_s\tau}\left(\frac{2-j\omega_s\tau}{2+j\omega_s\tau}\underline{i}_L(k-1) + \underline{G}_L\underline{v}_L(k-1)\right). \tag{13}$$

The circuit that corresponds to (11), (12) and (13) is referred to as the companion model and is drawn in Fig. 3. It is of the same format as the companion models used in EMTP-type tools. But while in the EMTP-type tools real signals are used, the companion models of FAST process analytic signals.

Other lumped elements are modeled in an analogous manner. The transmission line model involving distributed parameters