Synthesis of Transient Equivalents Using Digital Filters for Real Time Simulation of Electromagnetic Transients in Large Electric Power Systems

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***Abstract* – This paper presents a new method to obtain finite impulse response (FIR) digital filters transient equivalents for a complex electric power system. These filters require less computational effort than their analog counterpart, in many cases allowing real time digital simulations of electromagnetic transients. The digital equivalents represent an approximation to the actual driving point and transfer impedances of the sub-network under consideration, and are determined over a prescribed frequency range and propagation mode. The paper presents the technique used to perform the transformation from the frequency domain to the time domain, using the Z plane as an intermediate step. The validation of the method is done comparing simulations that use the new technique and the well-known EMTP program with complete representation of the simulated electric system. The results obtained show the efficiency of the method.**

Keywords – transient equivalents, electromagnetic transients, real time digital simulations, system modeling, digital filters.

I. INTRODUCTION

Electromagnetic transient simulations have been developed for electric power systems based on analog and digital techniques. The transient network analyzer (TNA) is the most popular type of analog simulation equipment, although its use has been restricted due to high cost, large dimensions and the requirement of dedicated infrastructure. Technically the TNA is also restricted to operate on a reduced frequency range and with a limited number of network components. As a consequence of the hardware based TNA procedure, it requires long preparation times between each simulation case, as well as well-trained experts, increasing the cost of simulation process.

The advent of the digital computers has enabled the development of software based digital techniques, and considerable progress has been achieved with the so-called EMTP-type programs. Such programs allow full exploitation of the programmability and flexibility of digital computers, implying a great reduction in the time required to prepare a new simulation. The low cost and portability of personal computers has spread its use by utilities, universities, research centers and even by individuals. However, as in the TNA case, digital techniques have also some limitations, mainly related to its processing time, requiring sometimes very fast and expensive equipment for real time operation.

There are basically two general approaches for digital simulation of electromagnetic transients in electric power systems: frequency and time domain methods. In 1980, Humpage [1] proposed a method in which digital filters are used to model elements of the electric network. This is known as the Z-Transform method, combining the digital filters time-domain implementation to the network frequency domain characteristics. The electric network elements are initially modeled in the analog frequency domain "ω" and then transformed to the digital frequency domain "z". The last step consists on an inverse Z-Transform formulation, resulting in the final time domain operation.

For a large number of transient simulations, time domain methods are preferred, mainly due to their high speed, simplicity and the possibility to represent non-linear and time variant elements, such as circuit breakers, surge arresters and other equipments. Frequency domain approaches would require a tremendous effort to deal with these nonlinear and time varying situations.

However, some problems may arise when it is necessary to model frequency dependencies using time domain methods. A classical example is the frequency dependence of transmission line parameters. An accurate representation of this dependence is essential, because they are very important to the transient response of the whole system, mainly in cases where the representation of ground mode propagation is critical, as is the case of ground faults or sequential switching. Although the representation of such dependences may be complex in time domain methods, the Z-Transform method can easily deal with them, since it is generated from circuit equations in analog domain and aggregate time domain facilities only when the equations are to be transformed to its final time domain implementation. It should be added that this alternative method is also adequate to employ digital signal processor (DSP) architectures, which are low cost and extremely fast, ideal to perform real time simulations. The combined use of modern processors and adequate simulation methods, have made it possible to attain real time electromagnetic transient simulations in electrical networks [2].

This work employs the Z-Transform method and a formulation that is based on Z-plane digital filter rational transfer functions to represent sub-networks. Using a fixed sample time interval and inverse Z-Transform techniques, the Z plane equations are mapped into time domain finite-difference equations, which can be used in specific transient analysis programs such as EMTP, ATP and similar programs.

II. TRANSIENT EQUIVALENTS

For a given frequency band, the most restrictive factor for real time electromagnetic transient simulations is the dimension of the network. TNA simulators are limited by hardware availability, which is closely related to the maximum number of elements that it is able to implement. In the case of digital methods, the impact of network complexity is not concerned with memory, but is fundamentally related to processing time. In order to avoid unnecessary complexity, it is a common practice to fully describe the sub-network close to the disturbance, or which contains non-linear elements affecting the studied phenomena. The remainder of the network is modeled by transient equivalents.

Many studies have dealt with the equivalent problem [2,3,4,5], but the conventional approach is to use 60 Hz short-circuit equivalent impedances, as seen from a connection or external bus. This approach can lead to acceptable results for low frequencies, but is inadequate for transient studies, due to its poor response at high frequencies. A second question concerns how much of the system should be represented by equivalents and how much of it should be detailed. This is a very complex problem with no general solution. The experience and the sensitivity of the electrical engineer are still the only tools available, mainly due to the great diversity of electric power system configurations and associated phenomena.

A compromise is to use more complex equivalents, accurately reproducing, for a certain frequency range, the associated electric network (referred to as external sub-network). As such, only limited parts of the electric system, close to the transient source need to be represented in detail. The major part of the electric power system will be represented by its transient equivalent, and the limits on the detailed representation gets less critical. The classical approach to obtain these equivalents is to model them as RLC circuits, as shown in Figure 1, having approximately the same frequency domain transfer function of the desired external sub-network [4,5].

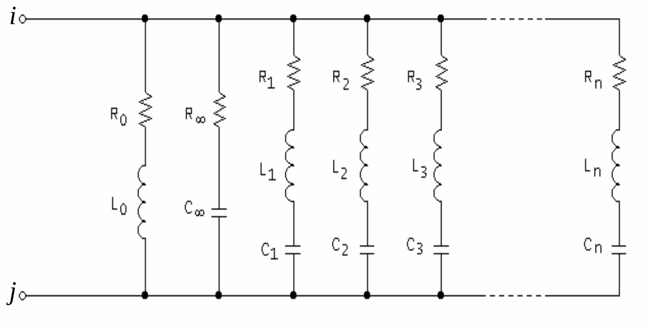

Fig. 1. RLC transient equivalent circuit seen from terminals *i* and *j*.

The most widely used transfer functions are the driving point impedances seen from external terminals *i* and *j* and the transfer impedance from bus *i* to bus *j*. These equivalent circuits present a good performance for the desired frequency range, but usually they also are high order circuits, with corresponding complex implementation. Besides this circumstance, the algorithms to obtain the RLC models are derived from optimization processes that not rarely present ill-conditioned convergence.

Time domain programs use time domain difference equations, derived from these equivalent circuits by means of some numerical technique, such as the trapezoidal integration rule. For instance, it may result for each node *k*, an equation having the form

$$i_k(n) = G_{kk} \, .v_k(n) + i_{kh}(n) \qquad (1)$$

In this equation, G_{kk} is an equivalent conductance, while $i_{kh}(n)$ is a current source, function of the parameters R, L and C of each sub-network branch, and of the voltage and current past values at the external terminals.

This paper introduces an alternative method that leads directly to the digital equations, such as in (1), without requiring the synthesis of RLC circuits. The equivalents are digital filters that approximate the external sub-network for a specific frequency range and propagation mode. These digital filters are Z-plane polynomial functions, used as an intermediate step from the initial analog frequency ω domain to the final time domain.

This type of approach has some advantages when compared to the classical RLC circuits. The first advantage resides in its basic components. They are composed by unitary delays, which are very adequate to represent traveling wave phenomena in transmission lines. A second advantage is related to the technique used to obtain these equivalents, avoiding iterative optimization methods, that may not converge. An extra advantage concerns the digital filter equivalent, representing the entire external network as a single network element. Thus the computational effort concentrates in evaluating past values of this single equivalent element. It will be shown later that the historical terms may be adequately dimensioned, having in mind the objectives of the study, allowing to reducing the computational effort, while increasing the transient simulation speed.

III. METHOD DESCRIPTION

A. Introduction

There are two conditions that must be observed to allow the determination of transient equivalents by the Z-transform method: (a) the external sub-network must be linear and (b) the frequency dependence of all elements must be known. These two conditions should be valid for the entire frequency range, for each propagation mode. It is usually not a problem to consider the external sub-network linear, due to the implicit filtering of high frequency components arising from the physical distance from the disturbance location. The knowledge of the frequency response for all elements is naturally of great importance, and adequate models for most elements are available in the technical literature. The discussion of such models is not included in the scope of the present work. It is important to emphasize that the chosen frequency range is dependent on the studied electromagnetic phenomena and also on the desired transient response resolution.

The proposed method follows three stages: (a) determination of the external sub-network circuit functions in the frequency domain, (b) approximation of these circuit functions in the Z plane, as an intermediate step between the frequency and time domains and (c) use of the Thevenin equivalent circuit in time domain.

This paper only considers one-port networks, that is, there is only one connection bus between the external sub-network and the network where the perturbations occur and are observed. However, the extension of the proposed approach for networks having a larger number of ports is straightforward.

B. One-port Network Transient Equivalent

Consider the network displayed in figure 2, consisting of two sub-networks, A and B, connected at bus *k*. It is desired to represent the external sub-network A by a transient equivalent, in order to reduce the computational effort for transient simulations, such as short-circuits and transmission line energization. Following the classical method, the first step consists in deriving the frequency response of the linear, time invariant, external sub-network A. This frequency response contains all the necessary information to compute its transient response.

The frequency response for the external sub-network A can be obtained from the bus admittance matrix, for each frequency of interest and propagation mode. To achieve this result, it is necessary first to disconnect sub-network B. The second step is to short-circuit all voltage sources and open all current sources in sub-network A. The bus admittance matrix will contain all buses of the sub-network A, including the external bus *k*. Since the only external current injection will be into bus *k*, Kron´s elimination method may be applied, eliminating all internal buses, except bus *k*.

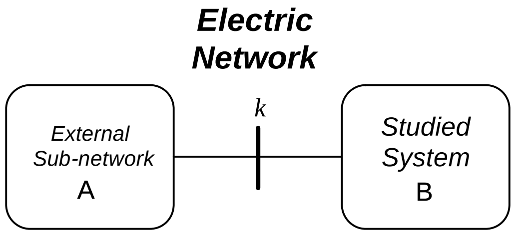

Fig. 2. External sub-network A connected to sub-system B by bus *k*.

When the bus elimination process ends, the bus admittance matrix reduces to the driving point admittance, seen from bus *k* (also called Norton or short-circuit admittance). Repeating the process for all frequencies of interest, the driving point admittance function seen from bus *k* is derived for the entire frequency range. Each function is represented by a sequence of complex values in the analog frequency ω and is valid for a specific propagation mode. Since the sub-network A is assumed linear, it can be represented by a Thevenin equivalent circuit, as indicated in Figure 3.

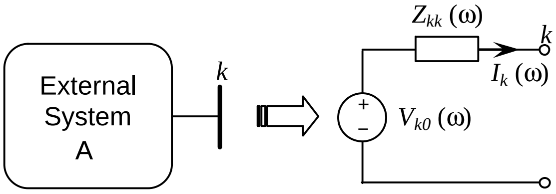

Fig. 3. Sub-network A represented by its Thevenin equivalent circuit in frequency domain.

The circuit equation in the frequency domain for this network is

$$V_k(\omega) = V_{k0}(\omega) - Z_{kk}(\omega).I_k(\omega) \tag{2}$$

where $Z_{kk}(\omega)$ is the Thevenin impedance, or driving point impedance seen from bus *k*, and $V_{k0}(\omega)$ is the Thevenin voltage.

The classical procedure to transform this frequency domain description to the time domain is through convolution integrals, and this demands fairly complex numerical computations. However, using the Z-plane as an intermediate step between the frequency and time domains, the previous equation can be written as

$$V_k(z) = V_{k0}(z) - Z_{kk}(z).I_k(z) \tag{3}$$

In this paper the function Z_{kk}(z) is represented by a Finite Impulse Response (FIR) digital filter of order *r*, which can be described by

$$Z_{kk}(z) = E_0 + E_1 z^{-1} + \ldots + E_r z^{-r} \tag{4}$$

The coefficients E_i above are a temporal sequence of pulses and can be interpreted as the system voltage response for a unitary current pulse injected at bus *k*. The propagation mechanisms that exist in the system itself will cause the response attenuation and will determine a finite number of pulses for this temporal voltage sequence. Substituting equation (4) into equation (3), it follows that:

$$V_k(z) = V_{k0}(z) - E_0 .I_k(z) - \left[E_1 z^{-1} + \ldots + E_r z^{-r}\right].I_k(z) \tag{5}$$

This equation can be transformed to the time domain using the Inverse Z-Transform, resulting in:

$$v_k(n) = v_{k0}(n) - z_{kk} .i_k(n) - v_{kh}(n) \tag{6}$$

where

$$\begin{cases} z_{kk} = E_0 \\ v_{kh}(n) = E_1\, i_k(n-1) + \ldots + E_r\, i_k(n-r) \end{cases} \tag{7}$$

The term z_{kk} in the above equations, can be interpreted as a factor related to the instantaneous response of the system to a current unitary pulse, $v_{k0}(n)$ is the Thevenin voltage in time domain and $v_{kh}(n)$ is a historic voltage term. Figure 4 shows the associate circuit, which can be interpreted as a Thevenin equivalent circuit in time domain.

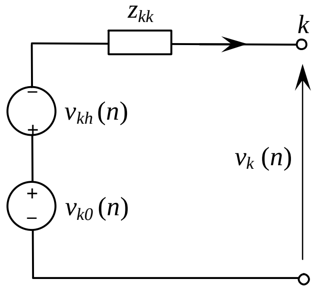

Fig. 4. Thevenin equivalent circuit in time domain.

The computation of Norton equivalent circuits, which are frequently used in time domain transient simulations, can be made applying the Inverse Fourier Transform to the function $Y_{kk}(\omega)$ or, in a similar way, considering that:

$$y_{kk} = {}^{1}\!/_{z_{kk}} = {}^{1}\!/_{E_0} \qquad (8)$$

Multiplying both sides of equation (6) by y_{kk} results in:

$$i_k(n) = i_{k0}(n) - y_{kk}\,.v_k(n) - i_{kh}(n) \qquad (9)$$

where

$$\begin{cases} i_{k0}(n) = y_{kk}\,.v_{k0}(n) \\ i_{kh}(n) = y_{kk}\,.\left[E_1 v_k(n-1) + \ldots + E_r v_k(n-r)\right] \end{cases} \qquad (10)$$

IV. COMPUTING THE EQUIVALENTS

A. Introduction

The network in Figure 5 was adapted from the system in Morched et al [4] and has been used to illustrate the method proposed here. The objective is to model the sub-network to the left of bus 3 by a digital filter transient equivalent, and then to simulate in detail transients in transmission line 3-4. The equivalents were determined by opening the line at bus 3 and computing the driving point admittance and impedance seen from this bus. The syntheses were done initially in frequency domain and then the digital filter equivalents were obtained by approximations on the Z-plane.

The program EQT (EQuivalentes Transitórios, in Portuguese) was developed to compute the desired circuit matrices (bus admittance and bus impedance), in the frequency domain, for each propagation mode. The network was assumed balanced, thus two propagation modes are sufficient. Each matrix is calculated for discrete frequencies within a chosen frequency range. The driving point impedance and admittance seen from bus 3 are obtained for each frequency by performing Kron´s elimination as explained in the previous section. When two or more external buses are to be considered, the reduction process calculates a reduced matrix, in which the diagonal terms are the driving point impedances seen from each external bus, and the off-diagonal elements are the transfer impedances from one bus to another.

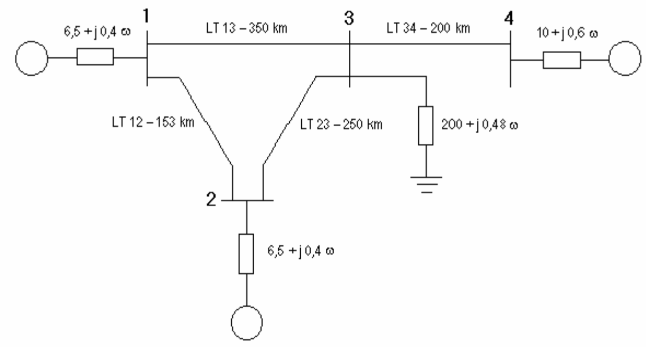

Fig. 5. Test system adopted to illustrate the proposed method .

B. Computation of Circuit Functions for the External Sub-Network

Figure 6 shows the module of the driving point impedance functions for the network in Figure 5, considering bus 3 as the external bus, for ground and aerial modes.

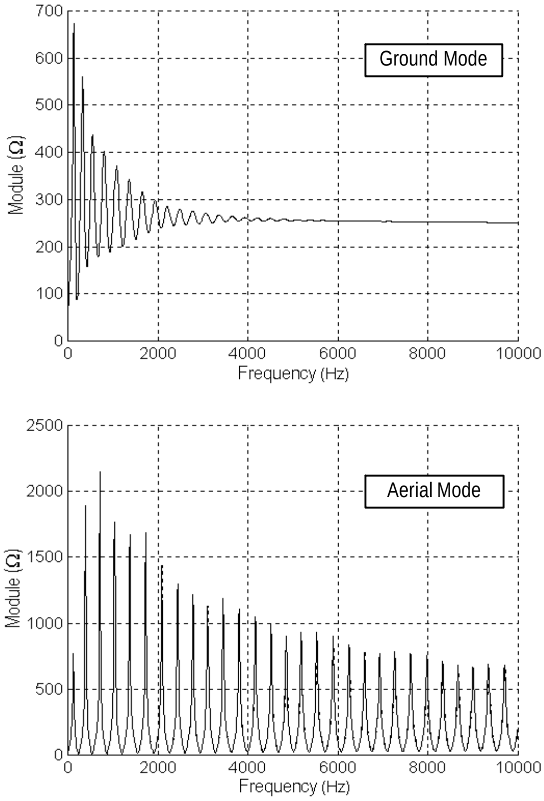

Fig. 6. Module of driving point impedance seen from bus 3 for ground and aerial modes.

It can be seen that these functions have successive parallel and series resonances, for each propagation mode. The resonant points identify the poles (parallel resonance) and zeros (series resonance). When the frequency tends to infinite, the number of poles and zeros tend to infinite too. This happens due to the distributed parameter characteristics of the transmission lines present in the electric network. The approximation of these functions by classical RLC circuits is an arduous task, and specially so for the aerial mode, due to the great number of poles and zeros and the small interval between each pole pair. The computation of the digital filter transient equivalent is, by comparison, quite straightforward.

C. Computation of Digital Filter Transient Equivalents

The computation of digital filter transient equivalents is made by applying the well-known Discrete Inverse Fourier Transform, to the driving point impedance function in the frequency domain. The obtained result consists in a sequence of pulses, which can be interpreted as the response of the electrical system to an unit current impulse, injected at the external bus and is denominated impulse impedance. Each one of the pulses in time corresponds to a coefficient of the desired FIR digital filter, derived as an approximation of the driving point impedance evaluated in the previous item.

Figure 7 displays the driving point impulse impedances for both ground and aerial modes.

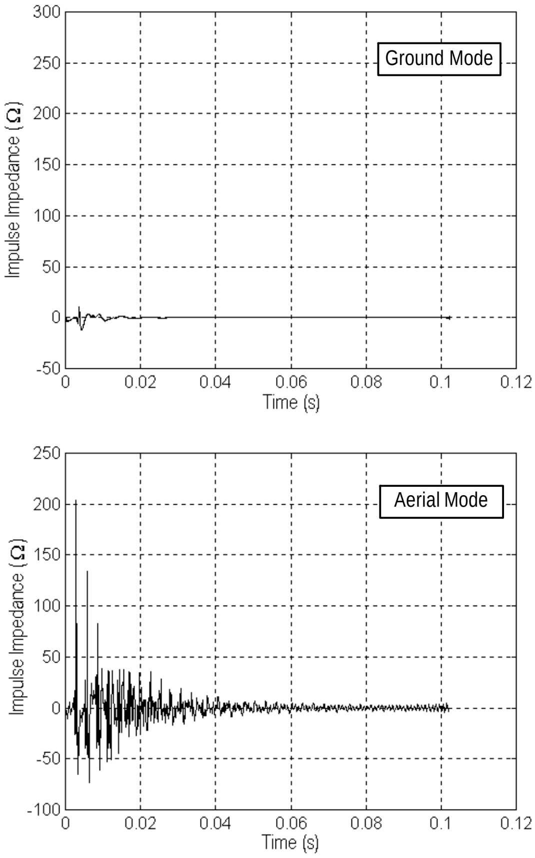

Fig. 7. Impulse impedance for ground and aerial modes

It can be seen that these functions are quickly damped, mainly for the ground mode where, for times greater than 25 ms, the signal energy is negligible. For aerial mode, the signal energy suffers less damping, remaining at significant values for a larger time interval. So, it is convenient to limit the number of filter coefficients for practical applications. This truncation leads to errors, mainly located in the low frequency range, because high frequency components are usually damped due to resistances present in the electric network.

V. TEST CASES RESULTS

A. Transmission Line Energization

In order to validate the proposed method and to assess its efficiency, the digital filter equivalent derived is applied to examine the energization of transmission line 3-4, with the receiving end (bus 4) open.

Figure 8 shows phase A voltage at the receiving end, considering the circuit breaker sequential pole closing. This figure presents a comparison between simulations using the EMTP program, in which the entire network is represented, with the ZTP program, in which the digital filters are either order 256 or 128. The EMTP simulation results are shown by the continuous line, whereas the ZTP results, using equivalent order of 256 are given by the dashed line and order 128 by the dotted line. It can be seen that, as the filter order decreases, the discrepancies increase, showing that low-order equivalents may lead to high errors for longer time intervals.

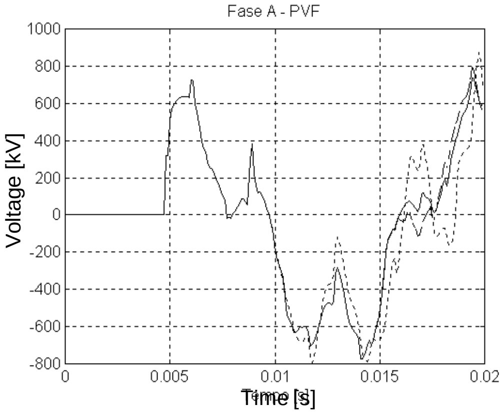

Fig. 8. Transmission Line Energizing.
Comparison between EMTP (solid line) and ZTP
(dashed line: order 256 and dotted line: order 128)

B. Transmission Line Short-Circuits

The digital filter transient equivalent performance for transmission line short-circuits has also been investigated. Figure 9 presents simulation results for a phase A to ground short-circuit applied half-way along transmission line 3-4,. The curves show the phase A voltage and the line current at the sending end (bus 3). The short-circuit was applied at the instant in time when the voltage at the fault point was passing through a maximum. This condition leads to maximum presence of high frequency components and demands a high performance of the digital filter equivalents. The solid line indicates EMTP simulations using the complete model of the network. The dotted line indicates simulations done with the ZTP program and order

200 digital filters. There is again good superposition of the results, confirming the efficiency of the digital filter equivalents.

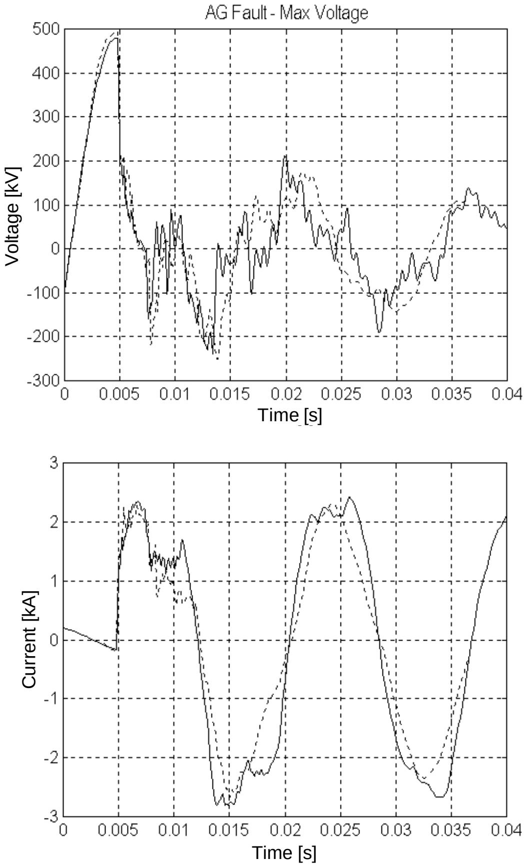

Fig. 9. Transmission Line Short-Circuit. Comparison between EMTP (solid line) and ZTP (dotted line).

VI. CONCLUSIONS

This work has presented a new method to obtain digital filter transient equivalents of electrical networks. Faster and more efficient simulations have been achieved with the proposed method, indicating that it can be used to develop real time simulations of electromagnetic transients in large electric power systems.

A major advantage of this new method is that the impedance approximations are made using the well-known Inverse Discrete Fourier Transform The terms of the transform are directly the coefficients of the digital filter. Thus, the need to resort to iterative methods and to ensure convergence is not an issue with the proposed approach. It is also convenient to emphasize that these new transient equivalents, basically formed by delay lines, also indicate a natural adjustment to the electric power network response, due to the presence of distributed parameter circuits, as is the case of transmission lines. A second advantage is to avoid the evaluation of convolution integrals to convert from the frequency to the time domain, leading to a fairly simple formulation, consisting of correlations between input signals and digital filter coefficients, as seen in equations (6), (7), (9) and (10).

It has also been shown that the digital filter equivalents can adequately represent parts of an electric network in electromagnetic transient simulations. Usually, the use of the proposed method leads to high order FIR digital filters. However, lower orders can be obtained by simply truncating the filters response. The test cases presented have shown acceptable results, with memory savings and fast processing speed. In the test cases, the original digital filter order was 2048, and it was truncated to 256, 200 and 128 coefficients without significant errors in the final simulation results.

Finally, comparisons between EMTP and ZTP simulations of transmission line energization and short-circuit have been presented to validate the method.

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