Application of Frequency-Dependent Network Equivalents for EMTP Simulation of Transformer Inrush Current in Large Networks

Y. Vernay, B. Gustavsen

***Abstract*-- In the near future, RTE will install long cable systems and power electronics converters to reinforce its grid. This situation requires RTE to perform extensive EMTP studies to analyze the interaction between the new network components and those of the existing network. To do so, large scale modeling of the network is often required for a good representation in the case of low-frequency transients. However this "detailed network modeling" can lead to several problems; the main one being lengthy computation times.**

This paper describes the utilization of Frequency Dependent Network Equivalents (FDNE) to represent a substantial part of the network as a way of mitigating the lengthy computation times. Comparisons are made between FDNE and a detailed network model in time domain for the energization of transformers on the French 400 kV and 225 kV network. This paper shows that large savings in CPU time is achieved with the FDNE model for transformer energization studies, without significant loss of accuracy.

***Keywords*: EMTP, Electromagnetic transient studies, Frequency dependent network equivalent, large scale network simulation.**

I. Introduction

THE French TSO RTE (Réseau de Transport d'Electricité) is in charge of the largest transmission grid in Europe. Large investments are being made to the French network to reinforce it, to augment the capacity of exchange with the border networks, and to integrate new industrial loads or renewable resources such as offshore wind farms. In 2012 the global investment of RTE was of 1368 M€, which is 200 M€ more than in 2011. A large part of this investment concerns the new construction of HVDC interconnections and long HVAC cable systems. These new components in the French grid may give rise to unusual electromagnetic transients and therefore require EMTP studies.

For the insertion of many long HVAC cables, RTE has performed frequency scan studies to detect potential adverse resonances between the cable and the network which can generate harmonic temporary overvoltages during no-load transformer energization. As we will see in Section II, the study of this low frequency phenomenon is very sensitive to the size of the network modeling which has to be large enough to correctly represent the harmonic impedance of the network. The joint CIGRE/CIRED WG CC02 [2] recommends to model accurately at least the entire primary transmission network for a proper evaluation of the harmonic impedances.

Large scale network modeling can be problematic for time domain studies, especially for assessment of temporary overvoltages which are the point of interest of this paper. Indeed, temporary overvoltages during no-load transformer energization have to be observed during several seconds with a small time step. Variation of initial parameters has to be simulated, in particular the time instant of closing of transformer circuit breaker poles and the residual fluxes of the transformer. A complete transformer energization study can lead to several thousands of simulations [3]. The computation time of these simulations can be a critical issue for the study.

In 2010, RTE modeled the complete 400 kV French grid in EMTP-RV [4]. This work has not been achieved for the purpose of one single study but in order to have a built, validated and up-to-date network model available for each new study. Since that time, part of the French 225 kV, 90 kV and 63 kV network have been added to this EMTP file for the purpose of other EMTP studies.

After completing this modeling work, RTE has faced several problems which are typical of large scale network modeling:

- How to keep the network data up-to-date?
- Can the model be used in time domain simulations with acceptable computation time?
- Is there a way to exchange EMTP files without revealing confidential information about the network?

The first question has already been treated in a previous IPST paper: [4]. The current paper suggests a solution for the two last questions by replacing a substantial part of the network by a compact, low-order model that reproduces the essential behavior of the network within a prescribed frequency range, the so-called Frequency-Dependent Network Equivalent (FDNE), see [5] and references therein. This type of modeling can be used whenever the non-linear effects of

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the subnetwork represented by the FDNE are negligible.

Comparisons are made in Section III between simulations using FDNE and the full network model in terms of computation time and accuracy for node voltages. It is found that large savings in CPU time is achieved with the FDNE model for the transformer energization studies, without significant loss of accuracy.

Another advantage of this solution is to facilitate the exchange of data between different companies as the information given by frequency responses of a sub network are less commercially sensitive than the underlying structure or components of the network.

II. Large Network Modeling Impact on the Frequency Response Calculation

As one in many simulation studies cannot afford very long computation times, a common solution is to represent only the study part of the network with a detailed model and represent the adjacent network using a short-circuit equivalent at the borders that is calculated at the operating frequency (50/60 Hz). For studies of low-frequency phenomena, this solution is inadequate as the frequency response of network varies with the size of the network. Figures 1 and 2 illustrate this point for a French 400 kV substation called Sub A. This work has already been presented by the first author in the Cigre Brochure Transformer Energization [1].

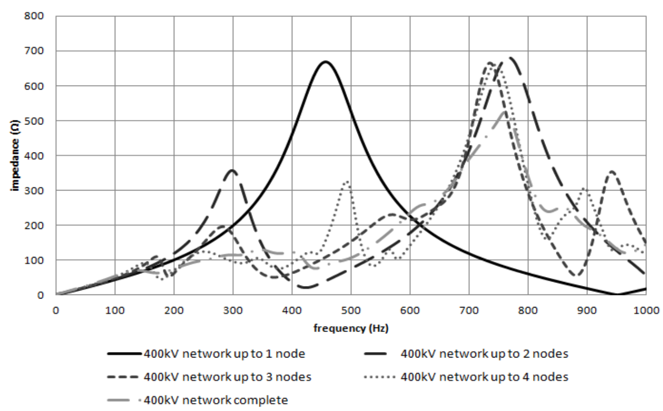

Fig. 1. Frequency responses of the network at Sub A for different sizes of 400 kV network modeling.

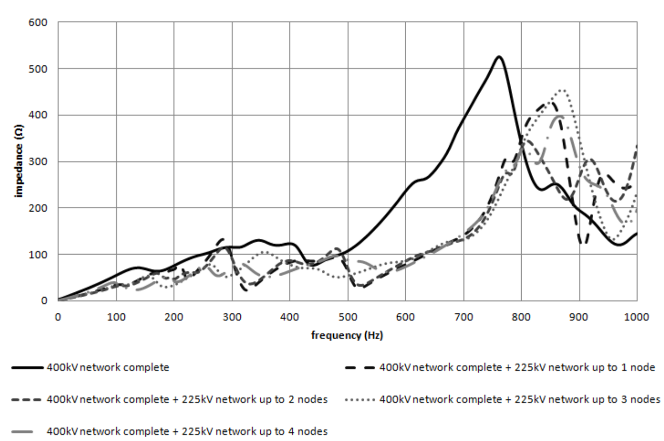

Fig. 2. Frequency responses of the network at Sub A for different sizes of 225 kV network modeling.

As we can see, the impact of the network modeling on the frequency response is very significant. At least for this specific case, a good representation of the frequency response at Sub A implies the modeling of the complete 400 kV network and of the 225 kV up to one node which represents a total of 375 three-phase nodes.

III. FDNE Generation

A. Overview

This paper applies FDNE modeling for the application of transformer energization studies in the French 400kV and 225 kV network. Since the dominating frequencies of the transient waveforms in the considered study are generally below a few kHz, the required bandwidth of the model is limited and so a low-order model will suffice. The starting point is the existing large network. From the network we generate frequency domain responses (admittances) with respect to the bus of interest via the frequency scan option of EMTP-RV (Section III-B). The frequency domain responses are subjected to model extraction by fitting them with a rational function-based model (Sections III-C, III.D). This step involves Vector Fitting (VF) [6] and passivity enforcement by residue perturbation [7]. The model, which is on pole-residue form, is converted into a state-space model that can be included in EMTP-RV using its state-space block model (Section III-F). Compensating current sources are introduced to represent the contribution from generators in the system (Section III-E).

B. Harmonic Impedance Calculation (input data)

The frequency domain behavior of the network, including its phase asymmetry, is fully characterized by the impedance matrix at the point of network reduction:

$$\mathbf{Z}(s) = \begin{bmatrix} Z_{aa}(s) & Z_{ab}(s) & Z_{ac}(s) \\ Z_{ba}(s) & Z_{bb(s)}(s) & Z_{bc}(s) \\ Z_{ca}(s) & Z_{cb}(s) & Z_{cc}(s) \end{bmatrix} \tag{1}$$

This matrix can easily be obtained with 3 frequency response calculations using the "Frequency scan" feature in EMTP-RV. Injecting a 1 A current source in the *i*th node gives directly the *i*th column of the Z-matrix as the voltage on each phase of the bus. The impedance matrix is next inverted to give the admittance matrix, $\mathbf{Y}=\mathbf{Z}^{-1}$.

C. Fitting

The admittance data $\mathbf{Y}(s)$ are next subjected to modeling by the pole residue model (2). The modeling is done using Vector Fitting [6] with relaxation [8] and fast implementation [9]. The obtained model satisfies the physicality constraints of symmetry for $\mathbf{Z}$, stable poles and complex conjugacy for poles and residues.

$$\mathbf{Y}(s) \cong \sum_{i=1}^{n} \frac{\mathbf{R}_i}{s - a_i} + \mathbf{D} \tag{2}$$

D. Passivity enforcement

The model is next subjected to passivity enforcement by adding a perturbation $\Delta\mathbf{R}_i$ to the residue matrices while minimizing the change to the admittance matrix $\Delta\mathbf{Y}$ (3a) such that the passivity criterion (3b) is satisfied at all frequencies [7].

$$\Delta\mathbf{Y}(\omega) = \sum_{i=1}^{n} \frac{\Delta\mathbf{R}_i}{j\omega - a_i} + \Delta\mathbf{D} \approx \mathbf{0} \tag{3a}$$

$$\mathrm{eig}(\mathrm{Re}\{\mathbf{Y} + \Delta\mathbf{Y}\}) > \mathbf{0} \tag{3b}$$

Finally, the pole-residue model is rewritten in the form of a state-space model (4). This conversion leads to a diagonal **A** with repeated poles and a **C** that holds the elements of the residue matrices $\mathbf{R}_i$. **B** is a matrix of ones and zeros.

$$\mathbf{Y}(s) \cong \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D} \tag{4}$$

E. Internal Sources

It is desirable that a simulation can be started from steady state conditions. When making the usual assumption that the generator voltages remain constant during a transient event, we can easily achieve this by first calculating the phasor solution at 50 Hz. This calculation gives the three voltages at the considered bus,

$$\mathbf{v}_{bus} = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^T \tag{5}$$

From the rational model, the admittance matrix at 50 Hz, $\mathbf{Y}_{50}$, is calculated and then we calculate matching current sources as follows:

$$\mathbf{i}_{bus} = \mathbf{Y}_{50}\mathbf{v}_{bus} \tag{5}$$

These three (stationary) 50 Hz current sources are connected to phases *a*, *b*, and *c* of the bus and maintained stationary in the simulation.

F. Implementation in EMTP-RV

EMTP-RV has a built in state-space block component which we use for interfacing the model (4). The state-space equations are converted by this component into nodal equations that are integrated in the full modified augmented nodal matrix [10]. The only thing required is to convert the model into a real-only model. In addition we manually connect the three stationary current sources that are needed for achieving the correct initial condition.

G. Alternative Modeling Using Modes

It is sometimes possible to obtain an acceptable accuracy also when basing the modeling on modes and a constant transformation matrix. In this case, we consider that the network is perfectly symmetric (balanced **Z**). To see this, the frequency scan was used to extract the zero sequence and positive sequence components of the impedance. These two scalar components are inverted and are independently subjected to rational modeling using VF and passivity enforcement,

$$y_0(s) \cong \sum_{i=1}^{n_0} \frac{r_{i,0}}{s - a_{i,0}} + d_{i,0} \tag{6a}$$

$$y_+(s) = y_-(s) \cong \sum_{i=1}^{n_+} \frac{r_{i,+}}{s - a_{i,+}} + d_{i,+} \tag{6b}$$

The rational models may now be interfaced with EMTP using these three state-space models in combination with the (constant) transformation matrix. To achieve this, the modal-domain models are transformed back into the phase domain using (7) with **T** being the Fortescue transformation matrix. This results in a phase domain model on the form (2) which is cast in the form of a state-space model (4), and matching current sources can again be calculated using (5).

$$\mathbf{Y}(s) = \mathbf{T}diag(\begin{bmatrix} \sum_{i=1}^{n_0} \frac{r_{i,0}}{s - a_{i,0}} + d_{i,0} \\ \sum_{i=1}^{n_+} \frac{r_{i,+}}{s - a_{i,+}} + d_{i,+} \\ \sum_{i=1}^{n_+} \frac{r_{i,+}}{s - a_{i,+}} + d_{i,+} \end{bmatrix})\mathbf{T}^{-1} \tag{7}$$

IV. Results

A comparison of the result between the complete network modeling and FDNE is made for two substations:

- Sub A:
  - 400 kV substation in a meshed, loaded network.
  - Modeling in the phase domain.
  - Event: Three-phase fault and clearing.

- Sub F:
  - 225 kV substation connected to the system via a single, long cable.
  - Modeling using modes.
  - Event: Transformer energization.

The network components included in the complete network model are listed in Table I.

TABLE I
OVERVIEW OF NETWORK COMPONENTS

Devices	Number of elements	Number of phases
Electrical nodes	1428	4284
Input impedance	1	1
Voltage source with impedance	157	471
Transformer, ideal unit	249	747
RLC components	828	2484
PI circuit	150	450
Frequency dependent parameters line model	13	81

Frequency dependent parameters cable model	73	393
Distributed parameter line model (No frequency dependent parameters)	854	2565
PQ load	876	2628
Nonlinear inductance	86	258

A. Sub A, Three-Phase Fault and Clearing Close to a Transformer

Sub A is a 400 kV French substation where a three-phase fault and clearing is applied on the bus bar with a 600 MVA auto-transformer connected, see Fig. 3.

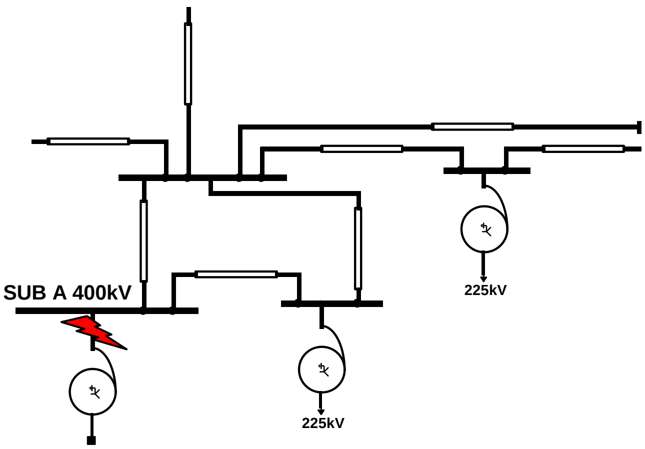

Fig. 3. Substation A

The frequency scan is run at Substation A to generate a phase domain FDNE valid up to 10 kHz to represent the network. For the frequency scan, we used a combination of 1001 linearly spaced and 1001 logarithmically spaced frequency samples, between 1 Hz and 10 kHz. This choice of samples gave a good resolution of the frequency responses both at high and low frequencies. For the rational modeling we used 150 pole-residue terms and inverse magnitude weighting in the steps of rational fitting and passivity enforcement. Fig. 4 compares the frequency responses of the admittance matrix with that of the extracted model, showing a good model accuracy.

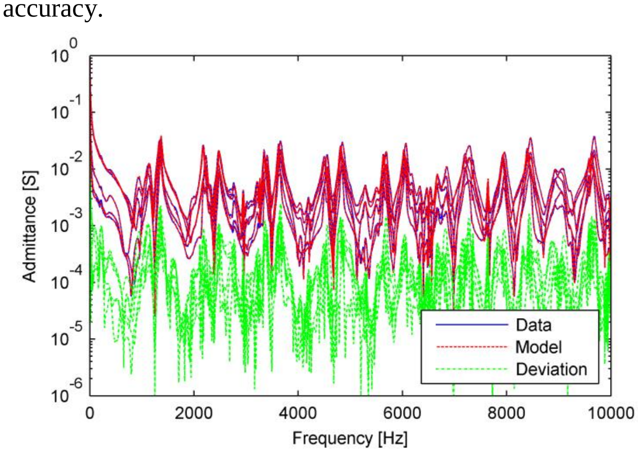

Fig. 4. Comparison between original frequency scan and FDNE at Sub A.

A three-phase fault situation is simulated using either the complete network model or the FDNE, at substation A (200 ms duration, time step of 10 µs: 20,000 time steps). As we can observe in Fig. 5, the results by the two types of modeling approaches are very close in the time domain.

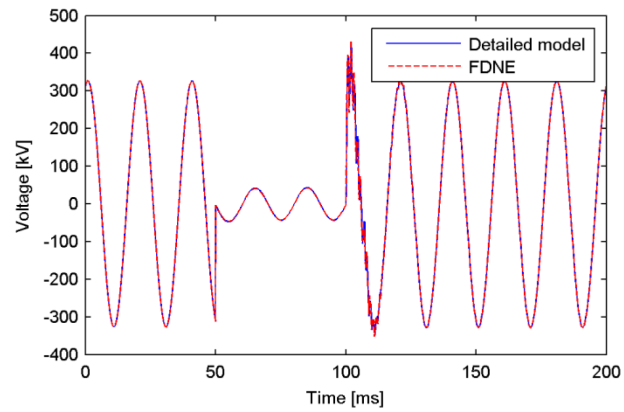

Fig. 5. Three-phase fault and clearing at the busbar of substation A, voltage in phase A with complete network modeling and with FDNE

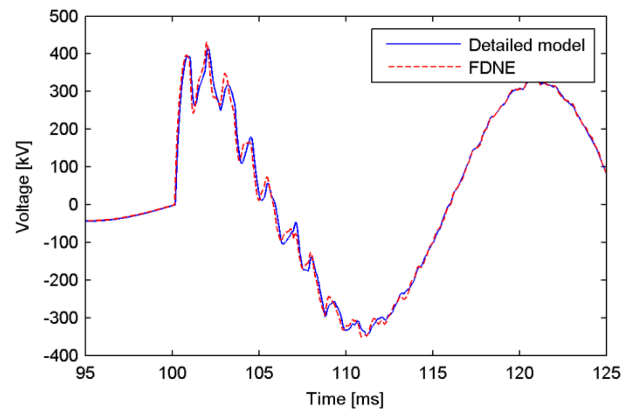

Fig. 6. Same as Fig. 5, with zoom on the high-frequency transient part.

Table II gives an indication about the CPU times required to run the time domain simulation. If we include the "preparation and reading time" necessary for the large network modeling, the total CPU time is reduced by a factor 18 at each time domain simulation. CPU times have been evaluated with EMTP-RV version 2.4 for an Intel Core i7-3720QM 2.60GHz processor.

TABLE II
CPU TIME COMPARISON

Type of simulation	CPU time: Complete network	CPU time: FDNE
Prepare and read data	39.0 s	0.05 s
Steady-State initialization	0.3 s	1.0 s
Time Domain simulation	63.9 s	4.7 s

There is also some time required for extracting the rational model, the frequency scan of the 2002 points needed 21 s and the subsequent model extraction step using 20 VF iterations required 13.8 s, including the subsequent passivity enforcement step. But these specific calculations are only performed once to build the FDNE model.

B. Sub F, No-Load Transformer Energization With 5^{th} Harmonic Network Resonance.

In this configuration a 170 MVA unloaded transformer is energized from the 225 kV substations F (sub F). The transformer is connected to the rest of the 225 kV by a long radial HVAC cable, see Fig. 6. The network topology implies a 5^{th} harmonic high resonance. This situation is typically studied in the time domain with parametric variation of initial parameter (residual fluxes and breaker closing time) during long HVAC cable insertion project.

The FDNE modeling from sub F was made based on a frequency scan of the positive and zero sequence parameters between 1 Hz and 10 kHz, using a combination of logarithmically and linearly spaced frequency samples, 2002 samples in total. Fig. 7 shows the fitted responses for y_0 and $y+$. We used 50 poles for y_0 and 100 poles for y_+, and the diagonal model was transformed back into the phase domain by (7).

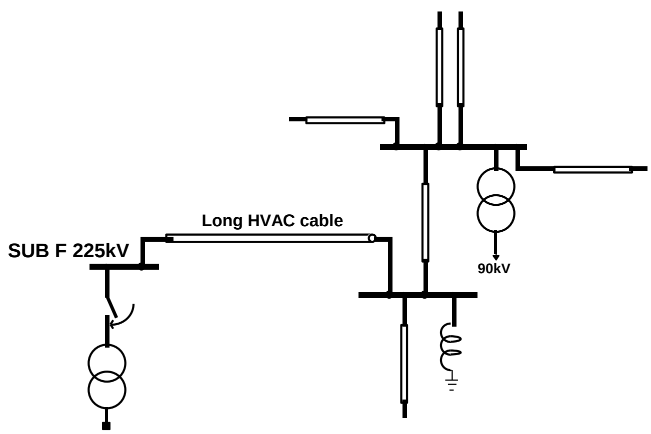

Fig. 6. Substation F

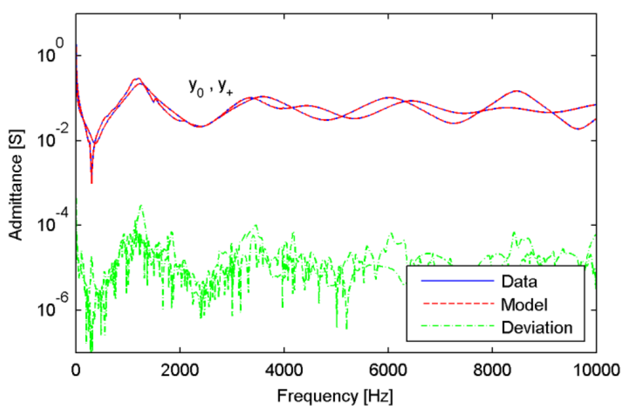

Fig. 7. Comparison between original frequency scan and FDNE at Sub F.

Two time domain simulations of this situation were run (3 s duration, Δt=10µs: 300,000 samples); one with the complete network modeling and one with the FDNE. Fig. 8 shows the resulting voltage waveform in Phase A using the complete network model.

Figs. 9 and 10 zoom respectively in the first 100 ms and last 100 ms of the voltage waveform, when simulated using either the complete network or the FDNE. The waveforms are seen to be practically identical.

A high gain of CPU time is achieved with the use of FDNE as we can see in Table III below, by a factor of 56.

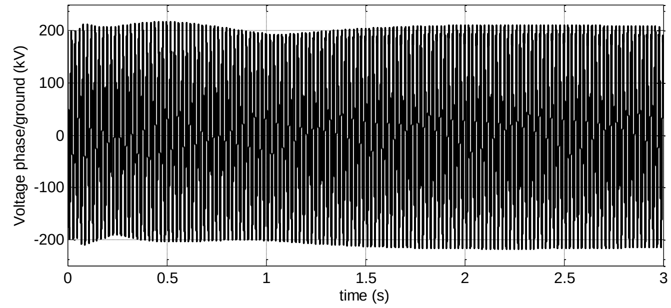

Fig. 7. Transformer energization at substation A. Voltage in phase A with complete network modeling

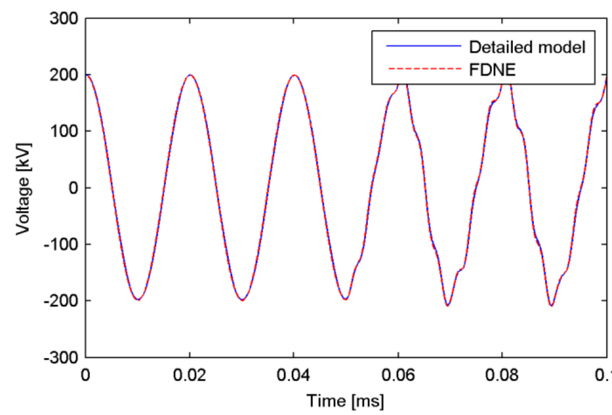

Fig. 8. Transformer energization at substation A, voltage phase A with complete network modeling and with FDNE, zoom on the first 100ms.

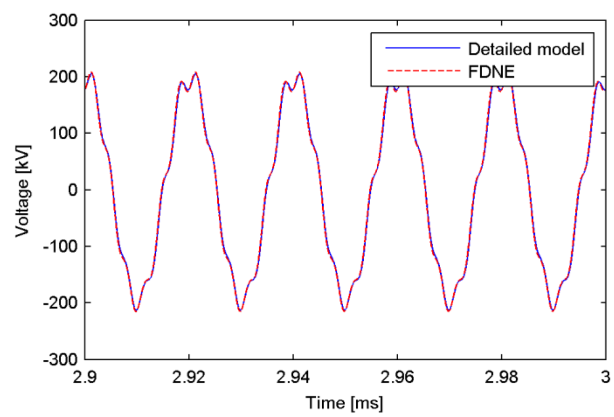

Fig. 9. Transformer energization at substation A, voltage phase A with complete network modeling and with FDNE, zoom on the last 100 ms.

TABLE III
CPU TIME COMPARISON

Type of simulation	CPU time Complete network	CPU time FDNE
Prepare and reading data	39.0 s	0.02 s
Steady-State	0.3 s	0.08 s
Time Domain	1220.1 s	22.3 s

V. DISCUSSION

In this work we used two alternative ways of calculating an FDNE model: full phase domain modeling and modal domain modeling with a constant transformation matrix. We generally recommend to use the phase domain approach since small imbalances in the system will be included. On the other hand, the use of modes allows faster simulations when the modal formulation is retained in the phase domain.

The simulation timing results shows that the use of FDNE gave a reduction in CPU time by factors 18 and 56 for the two case studies (bus A, bus F). It is remarked that these two approaches are here to illustrate the modeling of FDNE and not from specific studies. Still, we conclude that for the type of study used in this work, the FDNE approach achieves great savings in CPU time with negligible loss of accuracy.

The actual version of the state space equation device in EMTP-RV 2.4 does not take into account the sparsity of the *A*-matrix which is purely diagonal in the technique proposed here. Improvements to the model interface can therefore be expected to give further large savings in CPU time.

In the two examples, the transformers were directly connected to FDNE component. A more complete study may involve a part of classical (detailed) modeling in addition to the FDNE. In such approach, multi-terminal FDNE modeling may be necessary. This aspect has not been studied here but is seen as a potential future improvement. Such multi-terminal modeling is in particular relevant when non-linear or propagation effects cannot be ignored.

VI. Conclusion

This paper has focused on systematic transformer energization studies with the aim of calculating the transformer inrush current and terminal voltages.

- The inrush current is dependent on the low-frequency harmonic impedance seen into the system. Since the low-frequency transients penetrate deep into the system, it is necessary to include a very large part of the system in the network model. Using a smaller-size network is possible by placing 50 Hz Thevenin equivalents at the network borders, but such procedure can easily compromise the simulation accuracy.
- Usage of a frequency-dependent network equivalent (FDNE) allows to fully include the frequency-dependency of the border network. In this work, it was possible to use a single FDNE that was connected directly to the transformer's terminals. The FDNE includes the effect of embedded generators in the system, allowing the simulation to be started from 50 Hz initial conditions.
- The FDNE approach was applied to transformers at two different substations. Compared to a full simulation using a detailed network model, the CPU time was reduced by a factor of 18 and 56 for the two respective cases. As the present version of the model interface in EMTP-RV cannot utilize the sparsity of the state-space model, there is scope for substantial improvements to the CPU time.
- FDNE modeling can also be used as a way to exchange model of network between companies without revealing confidential information regarding the network topology and its parameters.

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