Frequency Domain Approach for Statistical Switching Studies: Computational Efficiency and Effect of Network Equivalents

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***Abstract*—In this paper, we explore the use of a frequency domain (FD) modeling and simulation approach to perform statistical studies of switching overvoltages (SSSOV) due to open-ended line energization, as an alternative to the use of time-domain (TD) EMTP-type tools. We analyze the potential advantages of such an approach in terms of accuracy and computational efficiency. We also utilize the FD approach to evaluate the effect of the type of network equivalent used when performing SSSOVs on open-ended lines as part of a network. Our results indicate that applying an FD method for SSSOVs requires substantially lower computer time than an EMTP-type tool to achieve accurate and meaningful statistical results. In addition, the use of constant-lumped-parameter Thevenin equivalents to approximate the rest of the network can result in a considerable deviation from the actual statistical switching behavior of a transmission system. Therefore, equivalents that preserve the rest of the grid's detailed frequency-dependent characteristics are critical for accurate statistical switching overvoltage studies.**

***Keywords*—Frequency domain modeling, network equivalents, Statistical Switching Overvoltages (SSOV).**

I. INTRODUCTION

OPEN-ENDED energization of long high-voltage (HV) transmission lines is one of the most essential transmission system studies given the large transient overvoltages involved. These overvoltages are calculated using simulation tools to estimate their severity for insulation coordination, design/redesign, and protection of transmission systems. There are three essential parts of an effective simulation study of transient overvoltages due to open-ended energization:

1) The use of an accurate and efficient simulation tool: EMTP-type tools are usually preferred given their versatility and easiness of use, although other options are available, such as tools based on state-space analysis [1] or frequency domain modeling [2].
2) The adequate inclusion of network components involved in the event: this includes, of course, the modeling of the transmission line(s) under test, but also the modeling of the rest of the system. Different types of network equivalents are typically considered at the system's sending node when focusing on a transmission line's open-ended energization response.
3) The application of a switch model and switching study that results in the most relevant information for design, protection, and insulation coordination. Regarding this point, statistical studies are the preferred option over worst-case scenarios to obtain enough information to make cost/benefit decisions and avoid over-dimensioning a system.

Statistical studies of switching transients (SSSOVs), essential in all HV transmission systems, consider the 3 points mentioned above. SSSOVs involve the determination of quasi-random values of switch pole closing over a time range (typically half to one cycle of nominal frequency) considering the HV circuit breakers' typical operation. Overvoltages at the receiving node of the line under test are registered for each event, and the resulting data are analyzed statistically. A typical SSSOV involves the simulation of hundreds of events using statistical switch models.

In the present paper, we claim that, even when EMTP-tools are robust and versatile, SSSOVs can be performed more efficiently using a purpose-specific tool based on a frequency domain approach. Frequency domain tools can provide an accuracy-enhanced prediction of transient events with less discrete samples than the time-steps required by time-domain models, given the fact that the solution at each discrete (frequency) sample is independent of the others, which is not the case for time-stepping methods. In addition, frequency-domain modeling allows the rigorous inclusion of frequency-dependent line parameters. Reduced sampling is particularly important when we consider that an SSSOV involves hundreds of simulations, so the computational burden can be very high, especially when studying the open-ended response of a line as part of a grid modeled in detail.

This takes us to the second claim of this paper. According to

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state-of-the-art publications on this topic from the last years, the most common way to model the components connected at the sending node of the line under study is to calculate either a source impedance or a network (Thevenin) equivalent (see for instance [3]-[10]). In both cases, this equivalent is calculated as a constant parameter R-L or L branch in series with the grid source. We argue that the level of detail in the modeling of the grid behind the line under test is crucial to provide accurate and valuable results of an SSSOV, and that the simplification in the network equivalents commonly used for these studies can have a detrimental effect in such results. A frequency-domain approach can also be useful in this regard since the generation of full frequency-dependent network equivalents is very straightforward in this domain. While such equivalents do not involve any loss of accuracy in the frequency domain, they can substantially reduce the computational effort.

With this in mind, the objectives of our paper are twofold: (1) to evaluate the effect (and validity) of the use of network equivalents in the results of SSSOVs from open-ended line energization, and (2) to evaluate and compare the computational effort required by a frequency domain approach for SSSOV compared to that from the use of PSCAD, a well-known and commercially available EMTP-type tool. Both objectives contribute to the state-of-the-art on the use of simulation tools for electromagnetic transients by providing novel results and conclusions that can drive future statistical studies, as well as promoting the use of frequency-domain tools as a feasible alternative to time-domain tools.

II. OVERVIEW OF FREQUENCY-DOMAIN MODELING FOR SWITCHING TRANSIENTS

This section summarizes the models and tools used in this paper to perform statistical studies of switching transients using a frequency domain approach. This description is provided for completeness of the paper and is not intended to be comprehensive since several previous references (such as [11], [12]) provide very detailed explanations. Our paper does not intend to provide new modeling or solution approaches, but rather to evaluate their application to statistical studies and provide results and conclusions that drive the future use of such tools.

The frequency-domain approach used in this paper for system modeling, including models of lines and circuit breakers, as well as the methodology for network construction and reduction, are based on previous work reported in [19], and summarized below.

A. Transmission line model

This is based on frequency-domain, distributed-parameter, two-port (π-circuit) representation, considering full frequency-dependent calculation of line parameter matrices from the concept of complex penetration depth in the conductors and in the ground plane [13]:

$$\begin{bmatrix}\mathbf{I}_S(s)\\ \mathbf{I}_R(s)\end{bmatrix} = \begin{bmatrix}\mathbf{A} & -\mathbf{B}\\ -\mathbf{B} & \mathbf{A}\end{bmatrix}\begin{bmatrix}\mathbf{V}_S(s)\\ \mathbf{V}_R(s)\end{bmatrix}, \qquad (1)$$

where $\mathbf{I}_{S,R}(s)$ and $\mathbf{V}_{S,R}(s)$ are the current and voltage vectors of length n (number of conductors) at the sending and receiving nodes of the line, as shown in Fig. 1, and $\mathbf{A}$ and $\mathbf{B}$ are admittance matrices of size n given by

$$\mathbf{A} = \mathbf{Y}_c \coth(\boldsymbol{\Psi} L), \qquad (2a)$$

$$\mathbf{B} = \mathbf{Y}_c \operatorname{csch}(\boldsymbol{\Psi} L), \qquad (2b)$$

where L is the length of the line, and $\boldsymbol{\Psi}$ and $\mathbf{Y}_c$ are the propagation constant and characteristic admittance matrices of the line, defined by

$$\boldsymbol{\Psi} = \sqrt{\mathbf{ZY}}, \qquad (3a)$$

$$\mathbf{Y}_c = \mathbf{Z}^{-1}\boldsymbol{\Psi}. \qquad (3b)$$

$\mathbf{Z}$ and $\mathbf{Y}$ are the series impedance and shunt admittance matrices of the line. This modeling approach has demonstrated very high accuracy and is commonly used as a base solution to evaluate the accuracy of new line models and solution methods.

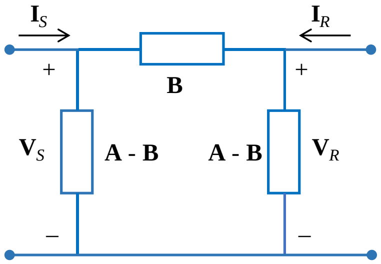


Fig. 1. Two-port admittance model of the transmission line.

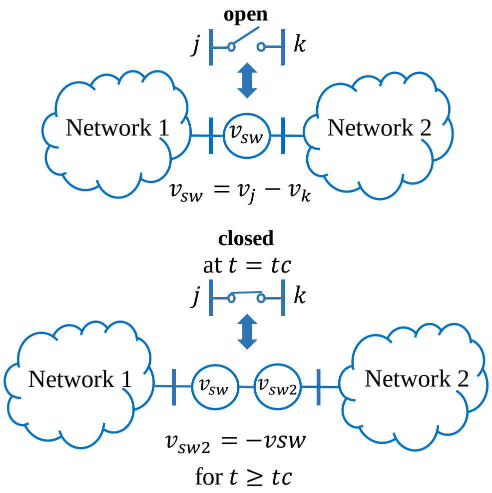


Fig. 2. Basis of superposition principle for simulation of switch closure.

B. Circuit breaker model

Frequency domain analysis is inherently linear. However, several approaches have been developed to enable the simulation of switching operations and inclusion of nonlinear conditions in the frequency domain. A review of those methods discussing their characteristics and limitations can be found in [14]. In this work, we use the superposition principle to simulate line energization because it is very straightforward and efficient, and provides very accurate results [15].

Essentially, the principle of superposition involves solving two linear systems: one before switch operation and another one due only to the switch operation, as illustrated in Fig. 2 [15]. For the simulation of line energization, the initial condition is, of course, with the breaker open. There will be a potential difference between the poles of the switch when simulating this condition. The second condition corresponds to the connection of a voltage source with equal magnitude but opposite polarity than the initial voltage across the circuit breaker. The addition of the response of the system due to these two conditions effectively simulates the switch closure. A delay can be added to the second condition to simulate a switch closure at a certain time $t > 0$. In the general case of sequential pole closure (when each switch pole closes at a different time due to practical operation delay), this procedure is repeated for each pole closure.

C. *Network construction and solution.*

All components, including lines, breakers, source impedances, loads, etc., are defined as two-port admittance models and arranged in a full admittance system of the form

$$\mathbf{I} = \mathbf{Y}\mathbf{V}. \tag{4}$$

The system excitations are defined as Norton equivalents to be included in the vector of injection currents, **I**. This system is solved for the vector of nodal voltages, **V**. Finally, the time-domain solution of the system is obtained using the frequency-time transformation of **V** using the inverse numerical Laplace transform (NLT). Refs. [16] and [17] present complete descriptions and equations for the correct NLT implementation.

III. GENERAL PROCEDURE FOR SSSOVS IN THE FREQUENCY DOMAIN

A. *Statistical switch model*

The procedure followed to perform a statistical study of switching overvoltages, considering the general case of sequential pole closure, starts by calculating each pole's closing time. For simulation purposes, the circuit breaker time is divided into an auxiliary contact for all poles and a main contact for each pole, as shown in Fig. 3 [11], [12], [18]:

- The auxiliary contact determines the start of the closure event, and it follows a uniform probability distribution over the first half a cycle or full cycle of the incident sinusoidal wave (half a cycle is used in this work).
- The main contact determines the actual closing time of each pole, and it follows a Gaussian distribution with a standard deviation given by

  $$\sigma_M = MPS/6, \tag{5}$$

  where MPS stands for maximum pole span and is an operating characteristic of the circuit breaker.

In addition, a time delay can be included between the operation of the auxiliary contact and the main contact for each pole. From Fig. 3, the actual closing time for each pole is calculated as follows:

$$T_\phi = T_{aux} + \tau_\phi + T_{\phi r} \tag{15}$$

where T_{aux} is the closing time of the auxiliary contact (same for all phases), τ_ϕ is the time delay, and $T_{\phi r}$ represents the closing of the main contact. Notice that according to Fig. 3 $T_{\phi r}$ can be positive or negative.

B. *Network equivalent behind the statistical switch*

A common practice when performing SSSOVs related to open-ended energization of transmission lines is to reduce the system behind the switch to a Thevenin equivalent. This equivalent is typically approximated by a lumped constant parameter R-L or L branch calculated from the short circuit current at the system's voltage level. This will of course have a certain effect on the accuracy of the statistical study, but so far, such effect has not been studied in detail.

A more accurate option is to preserve the full detail of the network to which the line is connected while performing the study. However, this can be very computationally expensive when considering the size of the resulting system and the number of simulations performed in a statistical study. An accurate and computationally efficient alternative is to obtain a frequency-dependent network equivalent (FDNE) that completely preserves the grid information while reducing the size of the system to only the nodes of interest. This is a very straightforward procedure in the frequency domain using Kron reduction, which does not imply any loss of accuracy compared to the full system [19]. The combination of reduction and fitting techniques can be applied to approximate an FDNE for utilization in EMTP-type tools. However, this procedure is complex and can introduce numerical errors in highly frequency-dependent systems. Also, since the generation of an FDNE for inclusion in an EMTP-type tool for line switching studies requires initial modeling of the system (or at least part of it) in the frequency domain, at this point, it might be better to solve the system in the frequency domain altogether instead of introducing the FDNE into the time domain simulation. Although we believe that this is the case for SSSOVs; evidently, this would be different for other simulations where EMTP is currently more advantageous since it offers a variety of nonlinear and/or time-dependent models.

Inclusion of nonlinear elements, such as surge arresters, is possible in the frequency domain approach by means of the use of superposition principle and piece-wise approximations [15], but its inclusion is limited and can increase in the simulation time to complete a statistical study.

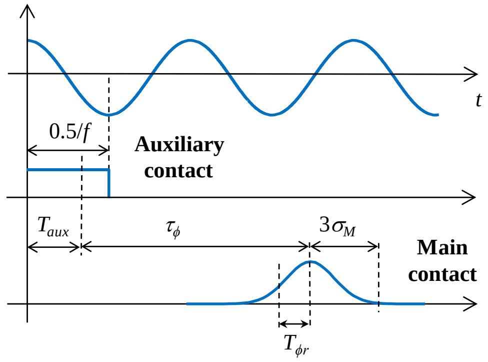


Fig. 3. Generation of the random closing time of one phase of the circuit breaker during sequential energization for SSSOV [11], [12], [18].

C. *Monte-Carlo procedure and postprocessing of results*

The switch model described in III.A is applied to simulate a number of switching events with different closing times. The number of events should be large enough to provide a good estimation of the range of overvoltages generated by the open-ended energization using probability distribution or cumulative probability curves. This is typically obtained with a number of events in the order of hundreds (from 100 to 500 events). After a certain number of events, increasing the amount of simulations does not provide additional statistical information.

The results provided by the study in terms of overvoltages registered include maximum, minimum, mean, standard deviation, as well as 2% and 98% levels (overvoltages at such percentages of the distribution curve). This information is then related to the statistical information of the insulation and protection components of the transmission system to determine the risk of failure of the system and use such information to make cost-benefit decisions in the design or redesign process.

IV. TEST CASE

A. *Description of the test system*

The transmission network under test includes 6 overhead lines with lengths ranging from 100 km to 350 km, all operating at 400 kV and 60 Hz. The lines have varying ground resistivities as shown in Fig. 4. This figure also shows that the system is excited by a 3-phase AC source with an inductance of 10 mH. All lines have the same tower configuration depicted in Fig. 5, which is a typical configuration at the 400 kV level in Mexico. The resistivity of the phase conductors is 40.856 ηΩ·m. The catenary between towers is not considered in this study.

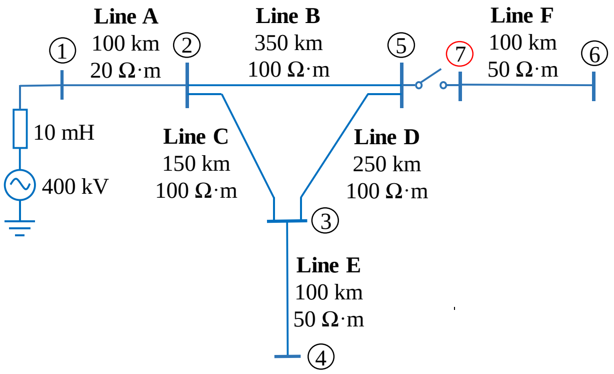


Fig. 4. Network topology for the test case.

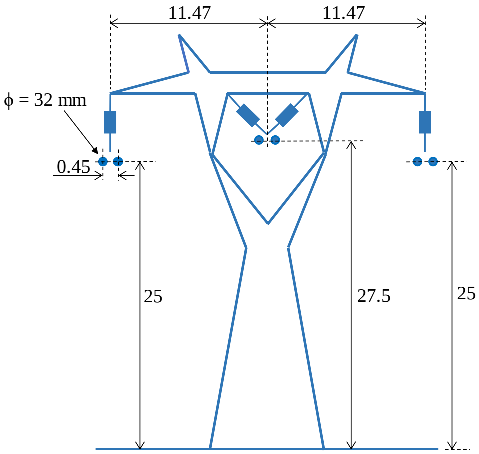


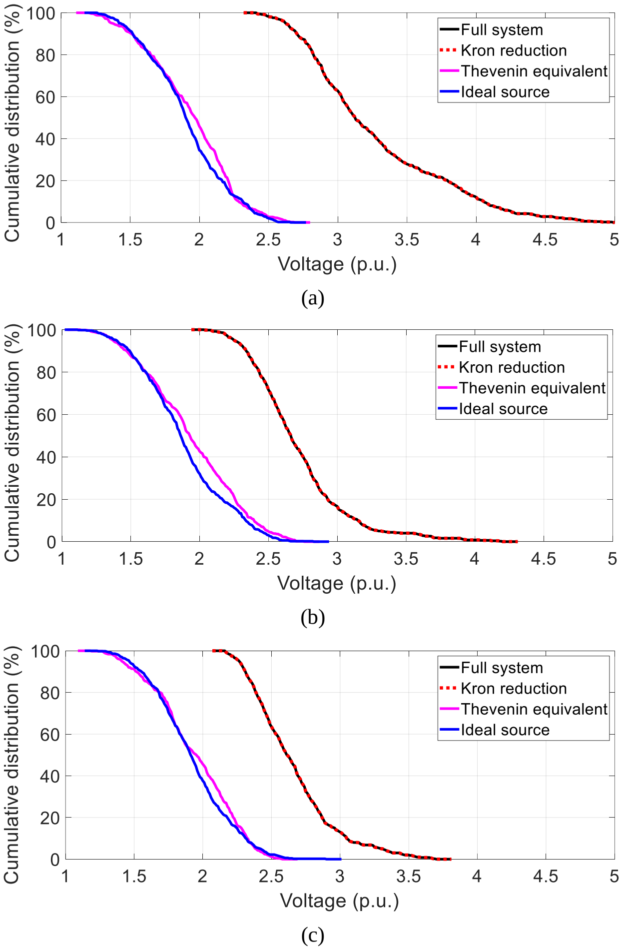
Fig. 5. Tower configuration for the test case (all units in meters).

The system modeling in the frequency domain follows the explanation provided in Section II. On the other hand, the same system is implemented in PSCAD using the phase domain line model, which is the most advanced line model available in this software tool.

B. *Results of SSSOV using frequency-domain approach and effect of network equivalents*

We used the frequency domain modeling and SSSOV approach described in Sections II and III to evaluate the open-ended overvoltages produced by the energization of line F (line E is also open-ended during the study). We simulated 500 events with a number of samples of 4096 for each event. The results are shown in Fig. 6 in terms of cumulative probability distribution, while Table I summarizes the results of this study. Then, the same study was performed applying Kron's technique to reduce the system only to the receiving node of the line under test, as well as the excitation node and the nodes where the switch is located. This eliminates nodes 2, 3 and 4, which results in the system shown in Fig. 7.

It is clear from Fig. 6 and Table I that the reduction of the system does not involve any loss of accuracy in the statistical study, but it does result in a substantial reduction in elapsed time for the complete statistical study using MATLAB (2.3 times faster when considering the reduced system).



(a)

(b)

(c)

Fig. 6. Results of SSOV study for complete system and different types of network equivalents: (a) phase A, (b) phase B, and (c) phase C.

TABLE I
SUMMARY OF SSOV STUDY FOR DIFFERENT TYPES OF NETWORK EQUIVALENTS

	Full network	Kron reduction	Thevenin Equivalent	Ideal source
Vmin: A	2.4222	2.4222	1.2183	1.2700
(p.u.) B	2.0430	2.0430	1.1438	1.1238
C	2.1655	2.1655	1.1999	1.2464
Vmax: A	4.9435	4.9435	2.6977	2.6637
(p.u.) B	4.1644	4.1644	2.7603	2.8392
C	3.5735	3.5735	2.5899	2.9082
Mean: A	3.2682	3.2682	1.9442	1.9159
(p.u.) B	2.7133	2.7133	1.9459	1.8919
C	2.6415	2.6415	1.9478	1.9307
S.D.: A	0.5161	0.5161	0.3107	0.2885
(p.u.) B	0.3453	0.3453	0.3464	0.3154
C	0.2795	0.2795	0.3010	0.286572
CPU time (s)	226	98	97.28	99.62

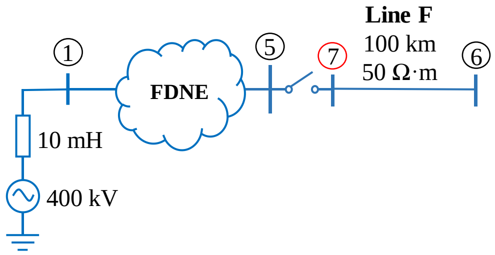


Fig. 7. Frequency-dependent network equivalent (FDNE) using Kron reduction.

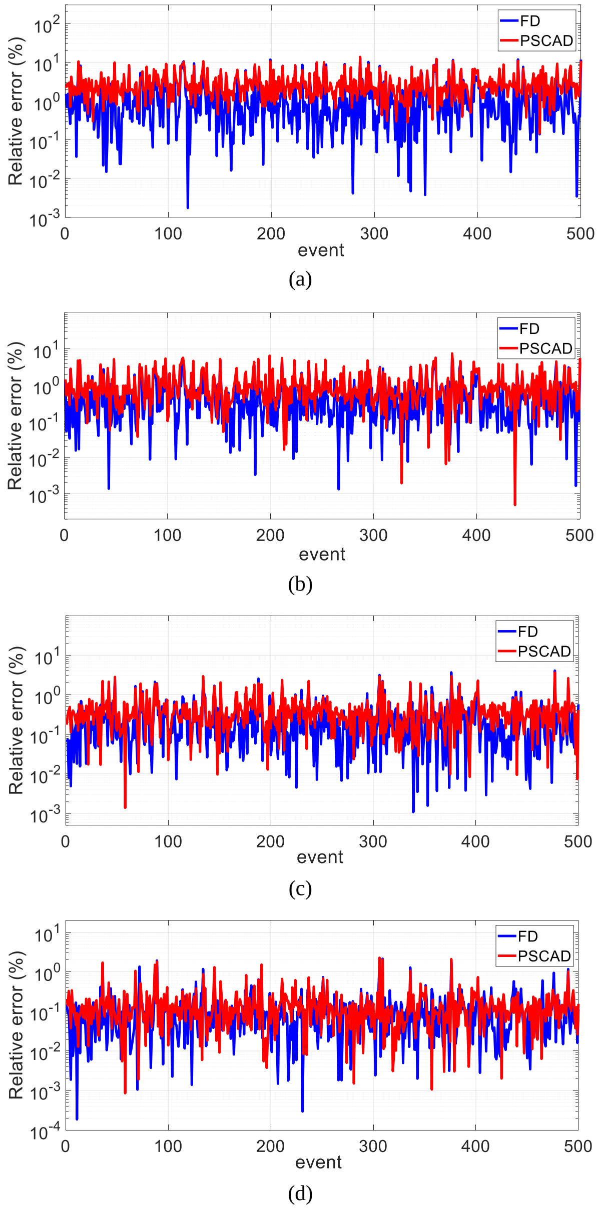
In order to evaluate the effect of typical simplifications of the network behind the switch, an additional study considers the line under test directly connected to the Thevenin source via the statistical switch. In addition, the idealized case of the statistical study when the switch is connected to the voltage source with no inductance is included to show the type of statistical results obtained under such simplification.

Fig. 6 and Table I evidence that neglecting the network behind the switch, either by direct connection to the Thevenin source or considering an ideal source, has a significant effect on the results. It is interesting to notice that, for the system under study, the Thevenin equivalent is actually closer to an infinite bus than to the actual response when considering the line connected to the network.

The superimposition of waves propagating along the grid, especially considering the potential existence of other open-ended lines, generates very high switching overvoltages and, in the case under test, it also produces an unbalance between the statistical overvoltages observed per phase. These features are completely lost when the line is tested as isolated from the grid.

C. Comparison with time-domain simulations

This section evaluates the accuracy and computational burden of the SSOV study performed with the frequency domain approach and with PSCAD. To perform a more in-depth comparison, we take an event-by-event approach rather than only looking at the statistical summary, as seen in Fig. 7. The statistical study is performed in PSCAD using its multiple run feature. The switch closing times for each event are exactly the same for both the frequency domain method and PSCAD. The observation time considered for both tools is 35 ms.



(a)

(b)

(c)

(d)

Fig. 7. Event-by-event relative error vs base solution for the following sampling rates: (a) 2^{10}, (b) 2^{11}, (c) 2^{12}, and (d) 2^{13}

The study starts by obtaining a base solution for each tool, this is, running each tool for a large number of samples for which it is observed than any increase in samples does not result in any noticeable accuracy increase. This number of samples was defined as 2^{15} for both methods (32678 samples). Then, the SSOV study described in the previous subsection was completed for the following number of samples with each tool: 2^{10}, 2^{11}, 2^{12}, and 2^{13}. Each tool was compared against its own base solution using the relative difference of maximum overvoltage per phase. The results of this study provide information about how many samples are required by each tool to achieve results with enough confidence. This is particularly important for statistical studies where a large number of events are simulated.

Fig. 7 shows the event-by-event relative error of each tool against its own base solution for different sampling rates. These results are summarized in Tables II and III by the calculation of mean and median of the relative errors for the complete set of events. The reason for using both mean and median quantities is that the former assumes a completely normal (Gaussian) behavior of the statistical results while the latter does not; therefore, using the median provides additional useful information to have a complete picture of the results and a better comparison between tools.

From Fig. 7 and Tables II and III, it can be noticed that, overall, the frequency domain method provides lower errors for all the sampling rates. This is particularly clear by comparing the median, which indicates that the statistical switching behavior is not completely normal. Such better performance of the frequency domain method is evident in Fig. 7(a), where the plot in blue (FD) reaches substantially lower values of relative error compared with the red line (PSCAD), indicating that the frequency domain method requires a lower sampling rate to achieve results closer to its base solution. A similar conclusion can be reached by looking at Fig. 7(b), except for a small number of outliers where PSCAD presents lower errors.

For samples of 2^{12} and above, both methods show very low relative errors, indicating that such sampling rate is large enough for statistical studies for the time-domain method.

Finally, in Table IV we compare the computer time required by each method to complete a statistical study for the same number of samples. According to this table, the frequency domain approach is between 3.24 to 3.88 times faster than PSCAD considering a complete network, and between 5.77 and 7.9 times faster considering a network equivalent.

For the comparison between PSCAD and the frequency domain approach, two aspects need to be considered: (1) the fact that PSCAD's graphical user interface, data storage, and other features, might produce longer CPU time for each simulation in the SSOV study; (ii) the differences in processing time due to the use of a Fortran compiler in PSCAD versus MATLAB for the frequency domain approach [20].

V. CONCLUSIONS

In this paper we have studied two essential topics for the accurate and effective application of a frequency domain approach in statistical studies of switching transients: (a) sampling rate use for discretization, and (b) effect of network equivalents. Regarding topic (a), the results obtained in this paper show that the frequency domain approach requires substantially less samples than a well-known time-domain tool to achieve similar statistical results. This is reflected in a lower computational burden to perform a complete statistical study. Regarding topic (b) we show, by means of a case study corresponding to a small transmission system, that the results of a statistical study are highly dependent on the network equivalent considered behind the statistical switch model. In general, our results indicate that the use of a full frequency dependent network equivalent (FDNE) is the only way to ensure accurate results in statistical studies of transmission system energization. The combination of a lower sampling rate and straightforward calculation of FDNE makes the frequency domain approach very suitable for statistical switching studies.

TABLE II
SUMMARY OF EVENT-BY-EVENT RELATIVE ERROR (%) OF THE METHODS UNDER COMPARISON (1024 AND 2048 SAMPLES)

Samples	**1024**		**2048**	
Tool	**PSCAD**	**NLT**	**PSCAD**	**NLT**
Mean: A	2.9523	1.7615	1.1815	0.7580
B	4.7180	3.5109	1.6860	0.9092
C	4.3313	2.7444	2.0076	1.2671
Median: A	2.2977	0.8009	0.7554	0.3494
B	3.6160	1.2988	1.2927	0.6177
C	3.0450	1.0470	1.1344	0.4713

TABLE III
SUMMARY OF EVENT-BY-EVENT RELATIVE ERROR (%) OF THE METHODS UNDER COMPARISON (4096 AND 8192 SAMPLES)

Samples	**4096**		**8192**	
Tool	**PSCAD**	**NLT**	**PSCAD**	**NLT**
Mean: A	0.4463	0.3155	0.1696	0.1382
B	0.6564	0.4964	0.2196	0.1933
C	0.5916	0.3555	0.2405	0.1300
Median: A	0.3218	0.1651	0.1102	0.0794
B	0.5296	0.2730	0.1502	0.1259
C	0.4551	0.1785	0.1620	0.0761

TABLE IV
COMPARISON OF COMPUTER TIME REQUIRED BY EACH METHOD

Samples **Method**	**Computer time (s)**		
	1024	**2048**	**4096**
PSCAD (t_{PSCAD})	197	300	775
NLT, complete network ($t_{NLT,1}$)	50.77	92.5	226
NLT, reduced network ($t_{NLT,2}$)	27.00	52	98
	Ratio		
$t_{PSCAD} / t_{NLT,1}$	3.88	3.24	3.42
$t_{PSCAD} / t_{NLT,2}$	7.30	5.77	7.90

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