Robust Sparse Network Equivalent for Large Systems: Part II—Performance Evaluation

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Abstract—This paper deals with the calculation of a sparse network equivalent (SNE) for the analysis of electromagnetic transients in large systems. The methodology and the mathematical details are presented in the companion paper [1]. This sequel presents application examples to demonstrate the accuracy and computational efficiency of the SNE. Equivalents for networks composed of 12, 50, and 100 transmission lines are derived and the results are discussed.

Index Terms—Discrete time, electromagnetic transients, network equivalent, quadratic programming, time-domain fitting.

I. INTRODUCTION

OUR paper [1] described a methodology for deriving a sparse network equivalent (SNE) based on time-domain fitting procedures. The issue of the robustness of the equivalent, which implies both its stability and passivity, is solved by adding a set of constraints to the fitting equations for calculating the equivalent. Quadratic programming [2] is used to calculate the solution for the set of linear equations resulting from the combined fitting and constraint equations.

This paper presents the results of derivation of SNEs and also their use in transient calculations. In such calculations, the network is divided into a study zone and an external system, to be respectively represented in full detail and by an equivalent. SNEs for external systems composed of up to 100 transmission lines are derived. The accuracy and computational efficiency of the SNEs in transient calculations are compared with those of the whole network with full representation. The computational efficiencies of the SNEs are also compared with the estimated performances of nonsparse equivalents.

The remainder of this paper is organized as follows. Section II presents a discussion of the motivation for developing the sparse time-domain fitting technique. The networks used for the transient calculations and SNE derivation are presented in Section III. The deduced SNEs and comparisons with respect to accuracy and computational efficiency are provided in Sec-

tion IV along with the discussion of the results. The conclusions are given in Section V.

II. MOTIVATION FOR THE SPARSE TIME-DOMAIN FITTING TECHNIQUE

Both frequency-domain and time-domain fitting techniques have been used to derive network equivalents [3], [4]. Issues of sparsity and robustness in deriving time-domain based equivalents have been reported in [1]. The motivation for sparse time-domain fitting comes from the analysis of a network composed of lossless transmission lines. In this case, the SNE methodology provides an exact model at a fraction of the computational cost of a nonsparse equivalent and, as it is derived in time-domain, it can be interfaced with the study zone directly in time domain. This is possible because the external system is modeled by a constant-coefficient difference equation (of order p)

$$i(n) = b_0 v(n) + \sum_{k=1}^p (b_k v(n-k) - a_k i(n-k)), n=0, \dots, N-1. \quad (1)$$

Equation (1) is in the proper form to be integrated into a transient calculation program [1]. It relates the input voltage sequence $v(n)$ to the output current $i(n)$ by means of coefficients sets a_k and b_k which describe the admittance of the external system. If the external system is composed of lossless transmission lines, the sparsity comes from the fact that some of the coefficients of the sets a_k and b_k are actually zero. This effectively reduces the computational burden.

SNEs present clear advantage over frequency-domain fitting techniques in the case of lossless systems. For a frequency-domain model of such systems to be computationally as efficient as the SNE, the errors in the time-domain transient calculation would be unacceptable. As an example, we discuss the case of the 12 transmission line external system presented in Fig. 1 when it is modeled using lossless transmission lines with a time step of 20 μ s.

An SNE with $p = 545$ and only 84 nonzero coefficients is an exact model for the system. If a reduced order frequency-domain model is obtained, for instance using only 84 partial fractions, the error both in time and frequency domain is large. This is caused by the large number of peaks that the admittance of the system presents in the frequency domain, as shown in Fig. 2. In this case, only 42 out of about 270 peaks are accurately modeled and the smaller peaks are neglected causing a final, not small, error. Only high-order models in the frequency domain can represent the network accurately. Networks composed of transmission lines naturally possess high order due to the time

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Fig. 1. Single line diagram of the 12 transmission lines external system.

delays imposed by the lines. SNEs provide a suitable solution for modeling these systems as they have a high dynamic order at a reduced computational burden permitted by sparsity.

A lossless transmission system approximates the line-mode behavior of a realistic system; however, it cannot accurately represent the ground-mode behavior. When frequency dependent models are adopted for the transmission lines, the results presented in Section IV show that SNE provides considerable savings in the computational burden with only a small degree of inaccuracy. The comparison of the SNEs and reduced-order frequency-domain equivalents obtained using vector fitting [5], for the case of frequency dependent models, is favorable to SNEs. For the same degree of accuracy, the computational cost is comparable in the case of a ground-mode and fairly favorable to the SNEs in the case of a line-mode. The fact that in transient calculations for a three-phase system the line-mode accounts for about two-thirds of the total computational burden, justifies our attempt for developing the sparse time-domain fitting technique used to derive the SNEs.

III. STUDY SYSTEMS

Four different external systems are used for derivation and comparison of the SNEs. They are composed of *i*) 12 transmission lines, *ii*) 12 transmission lines and loads, *iii*) 50 transmission lines, and *iv*) 100 transmission lines. These systems are chosen to demonstrate the feasibility of the SNE calculation for a broad range of systems sizes. All systems are composed of eight different transmission lines with lengths equal to 90, 120, 150, 180, 210, 240, 270, and 300 km. The lines are assumed to be fully transposed and frequency dependent models are used. The characteristic impedances and propagation functions of the transmission lines are represented by ten partial fractions for both line and ground modes. The partial fractions are obtained using vector fitting [5]. The study zone for all cases consists of a 210-km transmission line represented by a frequency dependent model (also ten partial fractions). A single line diagram of the 12-line external system, with and without load, is presented in Fig. 1. The loads are series RL branches at 0.8 power factor. The apparent power and location of each load is included in Fig. 1. Both the 50-line and 100-line external systems are represented by the single line diagram shown in Fig. 3. The 50-line system is restricted up to bus III, while the 100-line system comprises the whole external system presented in Fig. 3.

Fig. 2. Absolute value of Y_{ω} for the 12-line external system of Fig. 1 (lossless lines). The is restricted in both axes to enhance readability (the maximum frequency is 25 kHz).

IV. CALCULATION AND COMPARISON OF THE SNEs

SNEs are to be calculated for an external system separately for the line and the ground modes via modal decomposition. The use of such decomposition limits the application of the methodology to the case of fully transposed transmission lines if highly accurate results are desired. However, for a large system, consisting mainly but not exclusively of transposed lines, no significant errors are expected by treating it as a transposed network. The routines for *i*) transient computations using either full representation or the SNE (integrated into a transient calculation routine) and *ii*) calculation of the SNE were developed in Matlab [2]. Transient calculations for all of the external systems, when excited by unit step voltages, are performed to generate the sequences $v(n)$ and $i(n)$ of (1) to be used for the SNE's calculation. For the two 12-line systems, a 20- μ s time step is used. A 50- μ s time step is used for the 50-line and 100-line systems. These values limit the frequency range of the transient studies to 25 and 10 kHz, respectively. From the current sequence $i(n)$ for each system, the singular value decomposition (SVD) of the lower partition of the corresponding current matrix [1] is calculated as a guide to determine the order p for each system. The singular values for the 12-line systems are shown in Fig. 4(a) and for the 50-line and 100-line systems in Fig. 4(b) for both line and ground modes. The difference between the modes is easily noticed in Fig. 4. While for the line-mode case the singular values are significant up to the index related to the network length [1], the singular values for the ground-mode, due to the high losses, vanish at a much earlier index. Since the reflected travelling waves take longer to reach the sending bus for the ground mode when compared to the line mode, the order p for the former is correspondingly larger [1]. Thus, p for each ground-mode SNE is chosen based on the corresponding value determined for the line-mode SNE. A multiplying factor of 1.25 is a good initial value, while a suitable range is 1.1 to 1.5. The guiding values of p obtained from the SVD analysis (singular values $> 10^{-11}$) are 570, 672, 916, and 1262, respectively, for the 12-line system, without load, 12-line system with load, 50-line system, and 100-line system. The parameters for the SVD calculations are $N = 4000$ and $p = 1800$. The limits for p taken from the lengths of the networks [1] are 115, 280,

Fig. 3. Single-line diagram of the 50-line and the 100-line external systems.

Fig. 4. Singular value decomposition of the 12-line (a), 50-line (b), and 100-line (b) external systems.

424 (minimum) and 680, 2900, 5800 (maximum), for the 12-, 50-, and 100-line systems, respectively. The maximum length is not meaningful for the 50-line and 100-line systems due to the effect of the losses [1]. In the following sections, the SNEs of the external systems are detailed and compared.

A. Twelve-Line External System

The purpose is to demonstrate the feasibility of obtaining SNEs when a small time step is used. The calculated SNE is compared for accuracy and computational efficiency with the simulation results obtained based on full network representation. For accuracy,

Fig. 5. Currents for the line mode obtained using full representation and SNE for the 12 transmission lines external system: (a) line-mode, (b) ground-mode.

the overall fitting error F_{err} is calculated (using currents as an example) as

$$F_{err} = \frac{\|I_{fn} - I_{SNE}\|}{\|I_{fn}\|} \quad (2)$$

where the subscripts “SNE” and “fn” refer to the results from the SNE and full network representations, respectively. For each SNE, the F_{err} resulting from the fitting procedure is presented. This value is obtained using the sequence $v(n)$ as input to the SNE and the resulting current is compared to $i(n)$ producing the corresponding F_{err} . The errors for the admittance values at 0 and 60 Hz are presented as percent deviations. The number of floating point operations (flops) required to compute a transient calculation is the main criterion for computational efficiency comparisons.

Starting with the values of p from the SVD analysis and using $N = 2500$, the SNEs for the line and the ground modes are calculated. For the line mode, the parameters are $p = 590$ and N_S , the number of nonzero coefficients for each set a_k and b_k , is equal to 160. Before the constrained solution of the fitting equations, the SNE is both unstable, $F_{err} = 9.95 \times 10^4$, and non-passive, with errors of -0.49% and -0.09% (real part), 0.18% (imaginary part) for the admittance values at 0 and 60 Hz, respectively. The constrained solution makes the SNE stable, passive, and with errors less than 0.25% for the admittance values at the specific frequencies. The final value for F_{err} is 0.0271. The basic parameters for the ground-mode SNE are $p = 850$ and $N_S = 50$. The initial solution leads to a stable but non-passive equivalent while final solution gives an error less than 0.20% for the admittance values and a $F_{err} = 0.0060$. The current sequences used to compute these values of F_{err} for both modes are presented in Fig. 5(a) and Fig. 5(b), respectively, for the line-mode and ground-mode SNEs.

To demonstrate the importance of choosing a proper value for p , SNEs for both line and ground modes of the 12-line external system are calculated using lower values for p . Naturally, the fitting procedure makes the SNEs both stable and passive. However, the resulting fitting errors are larger for the same computational burden: N_S is the same for each case. The line-mode SNE based on $p = 400$ produces a fitting error of $F_{err} = 0.0516$, which is by 90% larger than the previous value. For the ground-mode SNE, two values of p are used. Using $p = 560$ leads to $F_{err} = 0.0111$, which is in excess of 86% compared

TABLE I
 F_{err} -12-LINE EXTERNAL SYSTEM SNE

Phase:	A	b	c
$V_{send.}$	0.0017	0.0071	0.0010
$V_{rec.}$	0.0085	0.0336	0.0053
I_{send}	0.0226	0.0370	0.0159

with the previous one. The SVD analysis indicates $p = 200$ for the ground-mode SNE. Using this value, we obtain $F_{err} = 0.1126$. Thus, we choose for the ground-mode SNE a value of p larger than the corresponding line-mode SNE.

To further assess the accuracy provided by the SNE, we compare the transient response of the network (study zone and external system) presented in Fig. 1 using full representation and the SNE. A frequency dependent (FD) line model is used for the study zone. The transient response is due to the energization at bus I by three step function voltage sources with appropriate amplitudes to excite both line and ground modes. The step voltage source is chosen because it excites the equivalent in a broad range of frequencies, thus permitting a better assessment of its accuracy. Table I shows F_{err} corresponding to 2000 data points. Sending and receiving buses correspond to buses I and II of Fig. 1.

These transients calculations are also used to compare the computational efficiency of the SNEs. In addition to the results for the FD model of the study zone, we also present those obtained when a constant parameter (CP) line model is used for the study zone. This concentrates the computational burden on the external system allowing a better evaluation of the computational efficiency of the SNE. Table II presents the time and flops required to perform the transient calculation using (i) full representation; ii) nonsparse equivalents; and iii) SNEs. The performance of the nonsparse equivalents is estimated based on the weighted ratio p/N_S for both line and ground mode SNE's. The discrepancies between time and flops comparisons are due to the inefficient way Matlab script-files handle “for” loops. Thus, we rely more on the flops comparisons.

From Tables I and II, we conclude that the SNEs provide high computational efficiency at the cost of a minor loss in accuracy in transient calculations, when a small time step is needed. To the contrary, the nonsparse equivalent does not present any advantage in flops comparisons.

TABLE II
TIME AND FLOPS COMPARISONS 12-LINE SYSTEM SNE

FD MODEL (study zone)	Time (s) (absolute)	Time (relative)	Mflops (absolute)	Mflops (relative)
Full representation	728.66	1.0	42.078	1.0
Non-sparse equiv.	153.56	0.2104	62.847	1.4934
SNE	18.90	0.0259	7.735	0.1838
CP MODEL (study zone)	Time (s) (absolute)	Time (s) (relative)	Mflops (absolute)	Mflops (relative)
Full representation	683.02	1.0	39.487	1.0
Non-sparse equiv.	40.056	0.0585	41.665	1.0554
SNE	4.93	0.0072	5.128	0.1299

Fig. 6. Voltages at bus II (phase *a*) due to monopolar energization of the 13-line network of Fig. 1. (without loads).

To evaluate the SNE using 60-Hz voltage sources, the transient calculations due to a monopolar switching operation (at bus I of Fig. 1) are compared for the cases of full network representation and SNE. Frequency dependent model is used for the study zone. The energization is performed on phase *a*, while the sending end of phase *b* is left open and the sending end of phase *c* is short-circuited. Voltages at bus II (receiving end) are presented in Fig. 6. F_{err} for these curves is 0.0376. From the results, one concludes that the SNE also performs well for 60-Hz voltage energization in highly asymmetrical conditions.

B. Twelve-Line External System With Loads

In this case, we analyze the effect of loads on deriving SNEs. The procedure for deriving and testing the SNEs for this case is the same as the previous one. The basic parameters for the line-mode SNE are $N = 2500$, $p = 690$, and $N_S = 100$. The initial solution is both unstable ($F_{err} = 0.8536$) and nonpassive, while the final solution is stable and passive and the error is $F_{err} = 0.0087$. For the ground-mode SNE, the parameters are $N = 2500$, $p = 900$, and $N_S = 60$, with the initial solution both stable and passive. The final value of F_{err} is 0.0008. The errors of the admittance values at 0 and 60 Hz are forced to be less than 1% for the line-mode SNE and 0.1% for the ground-mode SNE.

As in the previous case, the accuracy is also checked comparing the transients calculations for the full network (study zone and external system) presented in Fig. 1. The corresponding F_{err} values (2000 data points) are shown in

TABLE III
 F_{err} -12-LINE EXTERNAL SYSTEM (WITH LOADS) SNE

Phase:	<i>a</i>	<i>b</i>	<i>c</i>
V_{send}	0.0032	0.0179	0.0018
V_{rec}	0.0210	0.0866	0.0126
I_{send}	0.0084	0.0213	0.0054

TABLE IV
TIME AND FLOPS 12-LINE SYSTEM SNE (WITH LOADS)

FD MODEL (study zone)	Time (s) (absolute)	Time (relative)	Mflops (absolute)	Mflops (relative)
Full representation	728.81	1.0	50.772	1.0
Non-sparse equiv.	178.27	0.2448	61.968	1.2202
SNE	18.57	0.0255	6.455	0.1271
CP MODEL (study zone)	Time (s) (absolute)	Time (s) (relative)	Mflops (absolute)	Mflops (relative)
Full representation	678.56	1.0	48.180	1.0
Non-sparse equiv.	44.06	0.0653	36.941	0.7670
SNE	4.59	0.0068	3.848	0.0799

Fig. 7. Voltages at bus II (phase *a*) due to monopolar energization of the 13-line network of Fig. 1 (with loads).

Table III. The computational efficiency is evaluated using FD and CP line models for the study zone. The results for time and flops requirements are presented in Table IV. The transient voltage responses of phase *a* at bus II due to a monopolar switching operation, with conditions similar to the previous case, are presented in Fig. 7. The curves in this figure exhibit an error of $F_{err} = 0.0463$.

We see from the results that the presence of loads in the network poses no difficulty in deriving SNEs. Compared to the case without loads, the calculated SNEs have similar accuracy and require less computational effort: 8% against 13% of the flops required by the full representation when a CP line model is adopted for the study zone.

C. Fifty-Line and 100-Line External Systems

The objective of these two cases is to evaluate the performance of the SNEs for large and very large systems. These results demonstrate that losses in the network result in the reflected traveling waves from the farthest nodes to be barely no-

Fig. 8. Currents for the line mode obtained using full representation and SNE: (a) 50-line and (b) 100-line external systems.

TABLE V
 F_{err} -50-LINE EXTERNAL SYSTEM SNE

Phase:	<i>A</i>	<i>b</i>	<i>c</i>
$V_{send.}$	0.0001	0.0043	0.000067
$V_{rec.}$	0.0055	0.0227	0.0037
$I_{send.}$	0.0079	0.0182	0.0056

TABLE VI
 F_{err} -100-LINE EXTERNAL SYSTEM SNE

Phase:	<i>a</i>	<i>b</i>	<i>c</i>
$V_{send.}$	0.0016	0.0007	0.000097
$V_{rec.}$	0.0085	0.0362	0.0052
$I_{send.}$	0.0077	0.0201	0.0051

TABLE VII
TIME AND FLOPS COMPARISONS 50-LINE SNE

FD MODEL (study zone)	Time (s) (absolute)	Time (relative)	Mflops (absolute)	Mflops (relative)
Full representation	2911.80	1.0	210.948	1.0
Non-sparse equiv.	102.83	0.0352	60.548	0.2869
SNE	20.75	0.0071	12.218	0.0579
CP MODEL (study zone)	Time (s) (absolute)	Time (s) (relative)	Mflops (absolute)	Mflops (relative)
Full representation	2853.90	1.0	208.355	1.0
Non-sparse equiv.	28.69	0.0099	47.613	0.2285
SNE	5.79	0.0020	9.608	0.0461

ticeable at the sending end. This permits obtaining SNEs for virtually any network size. The same procedure as used for the performance evaluation of the 12-line external systems SNEs is used for these cases.

For the 50-line external system, the basic parameters are as follows. The line-mode SNE has parameters $N = 3000$, $p = 980$ and $N_S = 300$; and for the ground-mode SNE $N = 3000$, $p = 1000$, and $N_S = 120$. The initial solution leads to SNEs to be (i) unstable and nonpassive for the line-mode and (ii) unstable and passive for the ground-mode. The errors are $F_{err} = 0.0105$ and $F_{err} = 0.0104$, respectively, for the line and ground modes

SNEs. The admittance values at 0 and 60 Hz are forced to have errors less than 1% for both SNEs.

The corresponding basic parameters for the 100-line external system are i) line-mode SNE: $N = 3000$, $p = 1260$, $N_S = 300$, and $F_{err} = 0.0157$, ii) ground-mode SNE: $N = 3000$, $p = 1300$, $N_S = 100$, and $F_{err} = 0.0060$. Both equivalents are unstable at the first solution, while the line-mode is nonpassive and the ground-mode is passive. The errors for the admittance values at 0 and 60 Hz are enforced to be within 1%. The current sequences for the line mode obtained using full representation and the SNEs are presented in Fig. 8(a) and Fig. 8(b) for the 50-line and 100-line external systems, respectively.

Regarding accuracy, the comparisons are made for the transient calculations of the complete network (study zone and external system) obtained using both SNEs and full representation. These calculations lead to F_{err} values presented in Tables V and VI for the 51-line and 101-line networks, respectively. These networks are presented in Fig. 3. As in the previous cases, CP and FD models are used for the study zone for the sake of computational efficiency comparisons. The corresponding results are shown in Tables VII and VIII for the 51-line and 101-line networks, respectively.

From the results presented in Tables V to VIII, we conclude that the size of the network does not pose difficulty in deriving SNEs. Also, the computational efficiency of the SNEs becomes impressive: it takes only 4.61% and 1.72% of the computational burden required to perform calculations with full network representation. This is achieved at an acceptable loss in accuracy.

Finally, the comparisons regarding the monopolar switching operation performed at bus I of the 51-line and 101-line networks are shown in Figs. 9 and 10, respectively, for the phase *a* (bus II). The corresponding F_{err} for these curves are 0.0230 and 0.0373. These figures demonstrate that the SNEs for large and very large systems have good performance in simulating energizations in highly asymmetrical conditions.

V. CONCLUSIONS

The paper presents a performance analysis of sparse network equivalents (SNEs) for a broad range of cases. The SNEs are obtained using the methodology presented in [1] for external

TABLE VIII
TIME AND FLOPS COMPARISONS 100-LINE SNE

FD MODEL (study zone)	Time (s) (absolute)	Time (relative)	Mflops (absolute)	Mflops (relative)
Full representation	5987.60	1.0	539.461	1.0
Non-sparse equiv.	145.95	0.0243	84.872	0.1576
SNE	20.46	0.0034	11.898	0.0221
CP MODEL (study zone)	Time (s) (absolute)	Time (s) (relative)	Mflops (absolute)	Mflops (relative)
Full representation	5913.20	1.0	536.866	1.0
Non-sparse equiv.	40.80	0.0071	66.254	0.1227
SNE	5.72	0.0010	9.288	0.0172

Fig. 9. Voltages at bus II (phase *a*) due to monopolar energization of the 51-line network (up to bus III) of Fig. 3.

Fig. 10. Voltages at bus II (phase *a*) due to monopolar energization of the 101-line network of Fig. 3.

systems composed of 12 transmission lines (with and without loads), 50 and 100 transmission lines. All line-mode and ground-mode SNEs are made passive and stable with fitting errors around 2% or better. The admittance values at 0 Hz and 60 Hz are enforced to have errors within 0.1% to 1%, depending on the case.

Transient simulations using full and SNE network representations (the latter integrated into a transient calculation routine)

are compared for accuracy and computational efficiency. The SNEs presented an acceptable loss in accuracy in simulations done using both step function and 60-Hz voltage sources. The computational efficiency provided by the SNEs is significant, taking only 13% (for a 12-line external system), or just 1.72% (for a 100-line external system) of the flops counting required by the full representation. Compared to the nonsparse equivalent, the SNEs are between 5 to 9.6 and times more efficient.

The authors are working on the extension of the SNE methodology to multiport and active networks and expect to report their results in the near future.

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