

FDNE toolbox

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Jesus Morales, 9/28/2022 10:01:00 PM

1 Theoretical background

Frequency-Dependent Network Equivalent (FDNEs) are aimed to reduce the computational burden of transient simulations of large networks. The basic idea consists of dividing the network under study in two zones, namely the study zone and the external zone. Assuming that the external zone has a minor impact for a given transient study occurring within the study zone, a reduced-order model (such as an FDNE) can be used to replace the external zone.

An FDNE model consists of a rational model, its coefficients are calculated to match the frequency response of the subnetwork to replace (external zone) for a finite frequency band. This frequency response can be given as admittance, impedance, scattering-parameters, or transfer function.

Strictly speaking, FDNEs can only be calculated for linear and passive networks [1], however, it is possible to obtain FDNE models for networks containing nonlinear elements. In those cases, the precision of the FDNE model reproducing the transient response of the original network may be poorer.

The FDNE model implemented in this toolbox considers admittance parameters and it has the following mathematical form

$$Y(s) = \sum_{n=1}^N \frac{R_n}{s - a_n} + D \quad (1)$$

where $s = j\omega$, R_n (matrices) and a_n (scalars) are the residues and poles, respectively, D is a constant matrix that determines the asymptotic behavior of the model, and N is the order of the FDNE rational model.

This toolbox applies the Vector Fitting (VF) method [2]-[4] combined with the Loewner-Matrix (LM) method or the Matrix-Pencil-Method (MPM) as described in [5] to calculate FDNE models. The flowchart of the FDNE computation process is shown in Figure 1. As shown in Figure 1, the MPM and LM methods permit to identify the model-order and to obtain an initial set of poles. These initial poles are later iteratively relocated applying the VF method. Finally, the residues are identified via the least-squares method.

A detailed analysis and comparison of the VF, MPM and LM techniques can be found in [6]. More details about model order identification are given in next section.

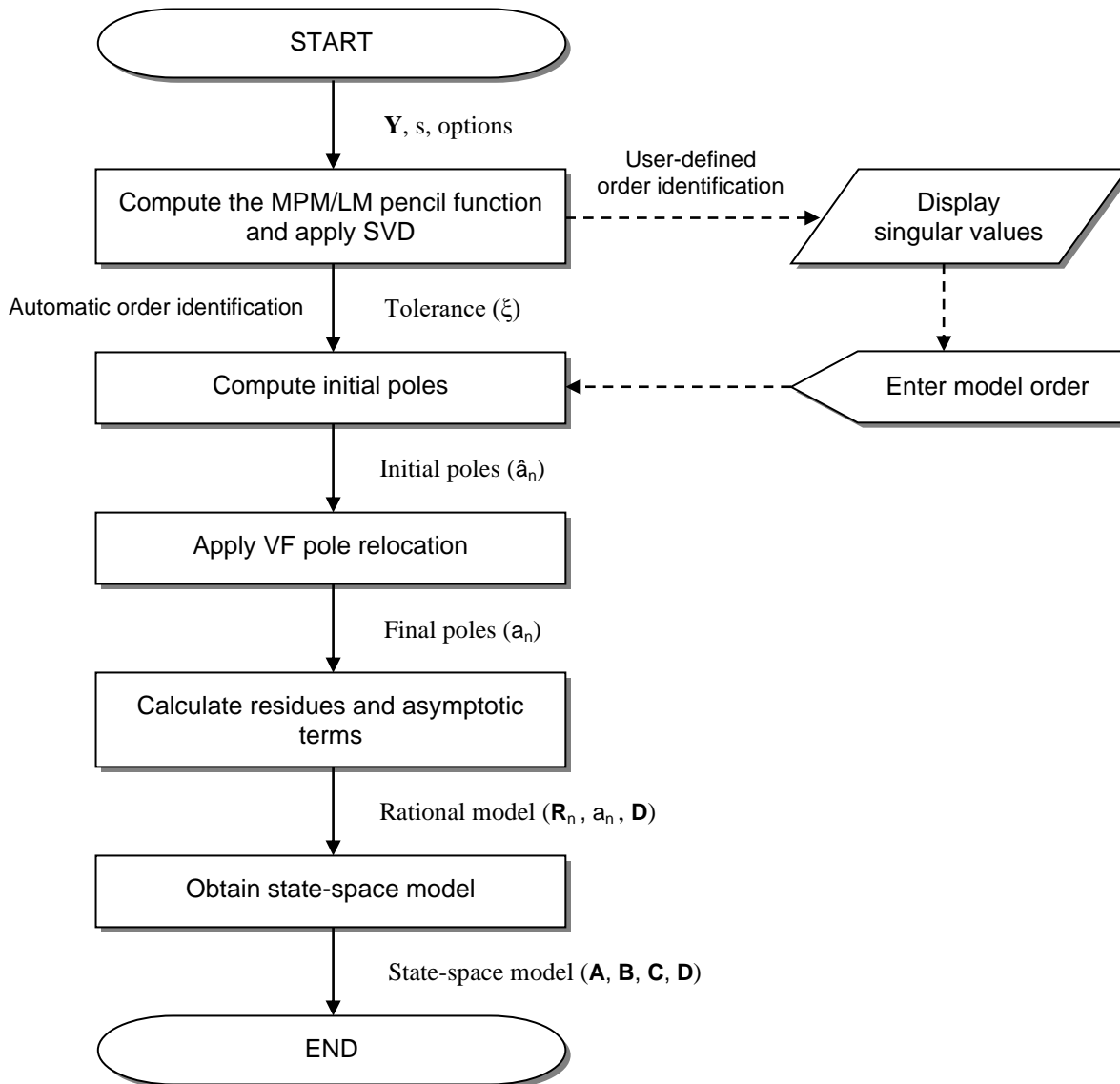


Figure 1. Flow chart of VF - LM/MPM combined fitter.

1.1 Model order identification

According to the theory of MPM and LM methods, the model order of a system is revealed by an abrupt drop in the magnitude of the singular values of the MPM/LM pencil functions [6]. The number of singular values above this drop (named the dominant singular values) denotes the system order. In other words, this indicates the number of poles that shall be used in the fitting.

An example of the singular values for the Loewner pencil function of a transformer frequency response is shown in Figure 2. This figure shows the abovementioned drop at the sixth singular value, suggesting that the model order shall be 6 poles.

Unfortunately, the drop in the singular values is not always observed. For those cases, the first knee in the curve of singular values can be used instead. Also, a tolerance value can be set such that the singular values with magnitude above this threshold can be set as the model order. A tolerance value of 1×10^{-4} is proposed by the fault in this tool. This value has been observed to be appropriate for many cases.

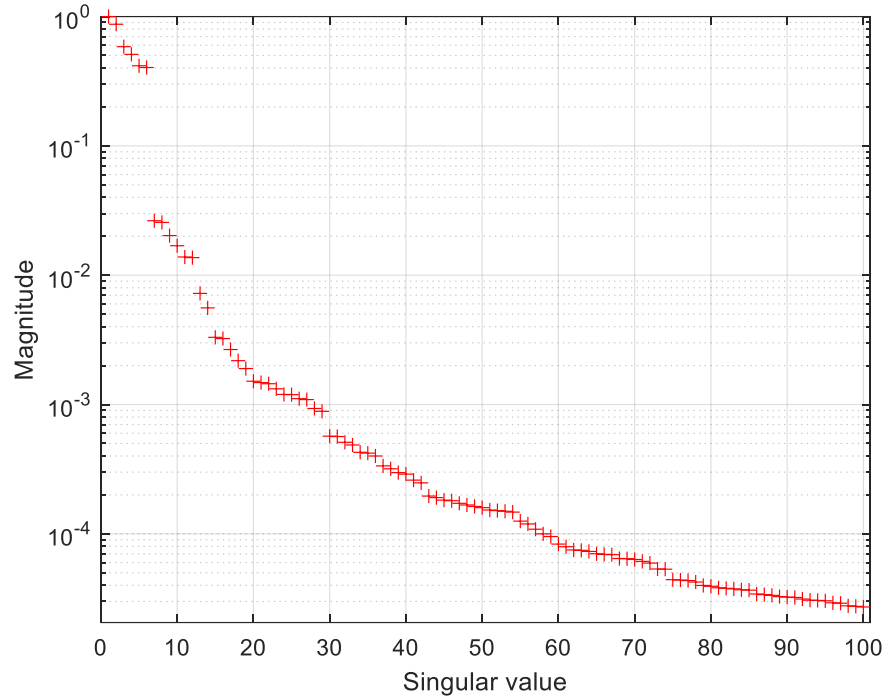


Figure 2. Singular values of the Loewner pencil function of a transformer frequency response.

1.2 State-space model

The FDNE model given in (1), can be alternatively represented as a state-space model of the form

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{v}(t) \\ \mathbf{i}(t) &= \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{v}(t)\end{aligned}\quad (2)$$

where \mathbf{A} and \mathbf{C} contain the FDNE model poles and residues, respectively; \mathbf{B} contains ones and zeroes accordingly; and \mathbf{D} is the same as in (1); the input and output vectors $\mathbf{v}(t)$, $\mathbf{i}(t)$, denote voltages and currents, respectively.

Under this alternative representation, the admittance matrix function in (1) can be equivalently written as

$$\mathbf{Y}(s) = \mathbf{C}(s\mathbf{I} - \mathbf{A})\mathbf{B} + \mathbf{D}\quad (3)$$

1.3 Passivity

Passivity is a requirement for the FDNE model to preserve numerical stability in time-domain simulations. A passive system is defined as a system that can only consume energy but cannot generate it [1]. Mathematically, the requirement for an FDNE model represented as (1) or (3) to be passive is that its Hermitian function must be positive-definite (all its eigenvalues must be positive) for all frequencies, i.e.,

$$\text{eig}[\mathbf{Y}(s) + \mathbf{Y}^H(s)] > 0, \quad \forall s\quad (4)$$

where the superscript H denotes transposed complex-conjugate matrix.

Note that for symmetrical systems and admittance representation, the Hermitian part of the FDNE model is equal to its real part or the conductance matrix \mathbf{G} , such that the passivity requirement (4) can be rewritten as

$$\text{eig}[\mathbf{G}(s)] > 0, \quad \forall s\quad (5)$$

Since passivity cannot be ensured in the fitting process, a passivity assessment stage is necessary once the model has been obtained. If the model results with passivity violations, a passivity enforcement procedure must be applied.

Passivity violations occur mainly due to two reasons: 1. Poor fitting or 2. Out-of-band poles. In the first case, passivity violations may occur at any frequency since the FDNE model eigenvalues poorly match those of the original system, and the solution is to increase the model order. In the second case, passivity violations normally occur at the boundary of the maximum frequency in the frequency range of fitting, this occurs

because some poles with resonant frequency out of the fitting band (out-of-band poles) produce an uncontrolled behavior. For a more detailed study on the causes of passivity violations we refer to [7] and [8].

1.3.1 Passivity assessment and enforcement

Since the eigenvalues of $\mathbf{G}(s)$ in (5) are continuous functions of the frequency, by identifying the frequencies at which at least one eigenvalue of $\mathbf{G}(s)$ crosses the zero, the system can be declared as non-passive. Passivity assessment can be efficiently achieved by computing the eigenvalues of the singularity test matrix, denoted as

$$\mathbf{S} = \mathbf{A}(\mathbf{B}\mathbf{D}^{-1}\mathbf{C} - \mathbf{A}) \quad (6)$$

where matrices \mathbf{A} , \mathbf{B} , \mathbf{C} , \mathbf{D} correspond to the state-space model in (2). The square root of the purely-real eigenvalues of \mathbf{S} in (6) correspond to the zero-crossing frequencies of the eigenvalues of $\mathbf{G}(s)$, i.e., the boundaries of passivity violations. The singularity-test matrix is derived from the Hamiltonian matrix associated to a state-space model. We refer the reader to [1] and [9] for details.

In this toolbox, the singularity test matrix-based passivity assessment is combined with the Pole-Selective Residue Perturbation (PSRP) method presented in [7] for passivity enforcement. The flowchart of the passivity enforcement process implemented in the FDNE toolbox is shown in Figure 3.

Unlike other methods, the PSRP technique consists of only perturbing specific residue matrices (\mathbf{R}_n) of the model. Moreover, the perturbations applied are calculated by simple algebraic steps. These characteristics of the PSRP method permit a very efficient passivity enforcement. It is important to mention that passivity enforcement methods are iterative perturbation processes whose solution cannot be guaranteed.

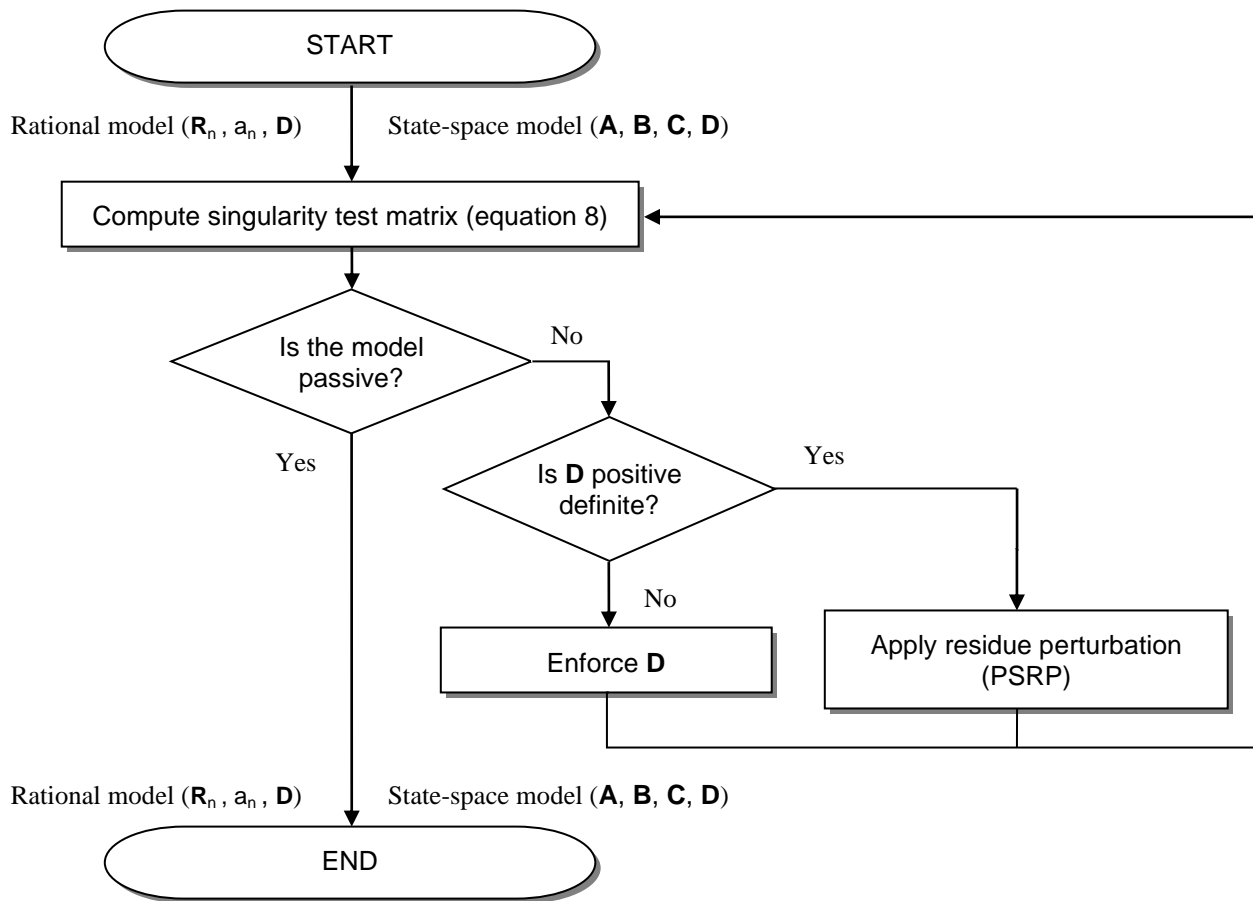


Figure 3. Flow chart of passivity enforcement.

1.4 FDNE calculation steps

The steps for calculating an FDNE are the following:

1. Define the study and external zones.
2. Measure the frequency response of the external zone.
3. Apply the identification/fitting technique to the measured data. Traditionally, the model order is given as an input. Otherwise, it can be searched by trial and error or by a special algorithm.
4. Check passivity of the obtained model.
5. Enforce passivity (if necessary).

The EMTP FDNE toolbox helps the user to achieve the steps listed above with minimal user intervention.

2 Using the FDNE toolbox

Using the FDNE toolbox requires either considering a network already built in EMTP or uploading a file containing the frequency response to synthesize into an FDNE. The former requires applying steps 1 to 5 listed in previous section (section 1.4), whereas the latter only requires steps 3 to 5.

These two techniques are applied with the 'Make FDNE from device' and 'Make FDNE from file' buttons in the FDNE toolbox ribbon as illustrated in Figure 4.

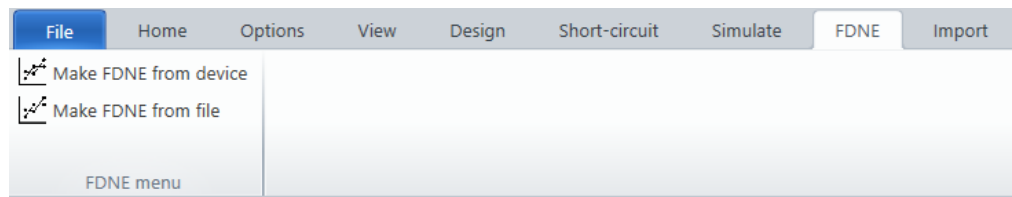


Figure 4. 'Make FDNE from device' and 'Make FDNE from file' buttons.

2.1 Make FDNE from device

As mentioned before, this option requires using a network modeled in EMTP and applying the steps listed in section 1.4. The first step (Define the study and external zones) must be achieved according to the user's criterion. Steps 2 to 5 can be performed automatically or semi-automatically. In the semi-automatic mode, the user is required to select the model order. Additionally, some required fitting/passivity enforcement parameters must be set by the user.

2.1.1 Define study and external zones

Defining the study and external zones must be performed by the user. Then, it is the user responsibility an appropriate selection of the parts of the network to be kept modeled in detail (study-zone) and those to be synthesized within the FDNE model (external zone). Some important points to consider to define the external zone are the following:

- Strictly speaking, the devices to be contained in the external zone must be linear for an appropriate FDNE model identification, however, it is possible to obtain FDNE models that closely match the transient response of a network containing nonlinear devices if those have a low impact on the overall frequency-response network.
- If the external zone contains power sources, the FDNE toolbox will calculate fundamental-frequency equivalent Norton current sources (ideal sources) to match the load-flow or steady-state conditions of the original network.
- If the external zone contains control-based devices, the control responses will be not reproduced.
- In general, there is no restriction about the number of ports to create an FDNE, however, as the number of ports increases the passivity enforcement stage (if required) might become more challenging due to numerical reasons.

2.1.2 Creating a subcircuit

The FDNE toolbox requires the external zone to be enclosed within the subcircuit of a device. To create a new subcircuit for the external zone, the user must follow the steps given below:

- a) Disconnect the external zone from the study zone
- b) Add connector ports to the terminals of the external zone, this option is illustrated in Figure 5.

Select the external zone components and apply the 'Create Subcircuit Block' option as illustrated in

- c) Figure 6. A new device, containing the external zone components will be created.

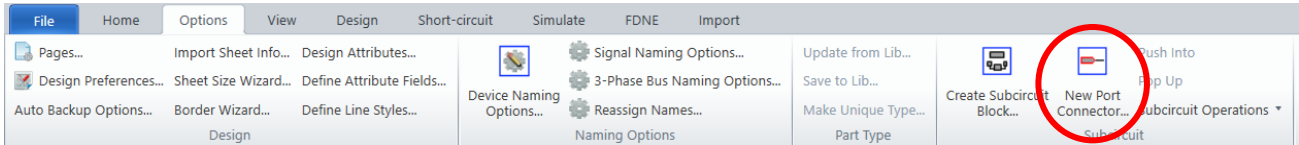


Figure 5. Adding connector ports.

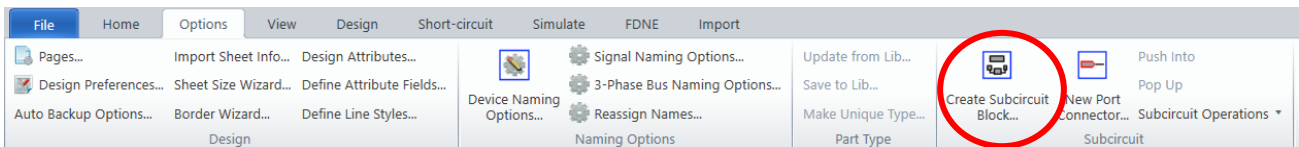


Figure 6. 'Create Subcircuit Block' option.

In order to obtain the FDNE model for the external zone contained in a subcircuit, the user must select the created device and apply the option 'Make FDNE from device' from the FDNE tab in EMTP as illustrated in Figure 7. This option opens a mask to set the FDNE parameters.

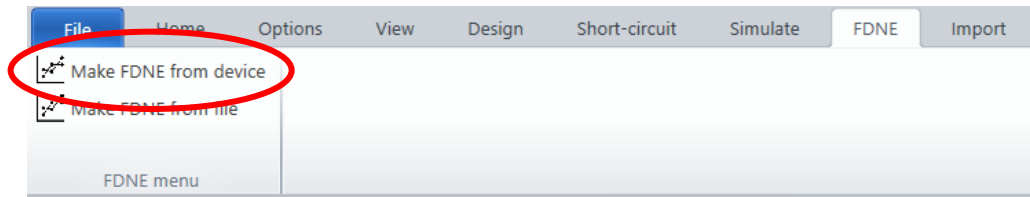


Figure 7. 'Make FDNE from device' option.

Once the FDNE parameters are set, the mask must be closed with OK. Depending on the options selected, the user may require entering some additional inputs or not. If the FDNE model calculations end successfully, the FDNE model will be created and placed automatically as a state-space device inside the subcircuit of the external zone. The EMTP console will display details about the FDNE model calculation.

To illustrate the steps listed above, see the following example.

2.1.3 Example 1.

Let us consider the circuit of Figure 8 where the study and external zones are specified. Note that this circuit is meaningless and is used only for simplicity.

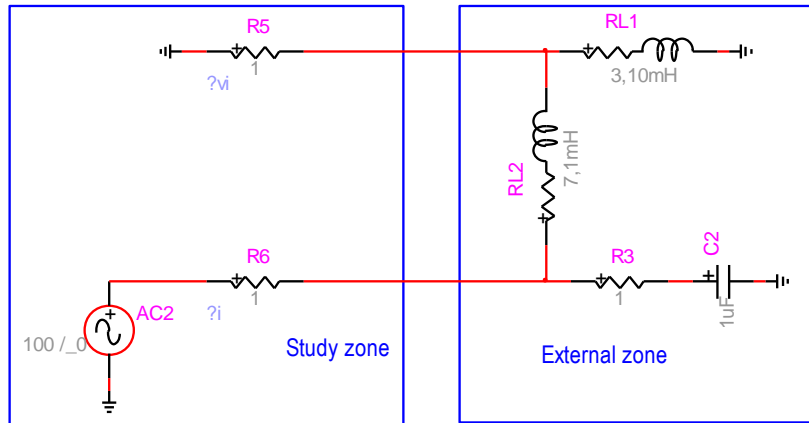


Figure 8. Test circuit 1.

To create a subcircuit for the external zone, the devices of the external zone must be selected as illustrated in Figure 9. Note that this simple example does not require disconnecting the study and external zones.

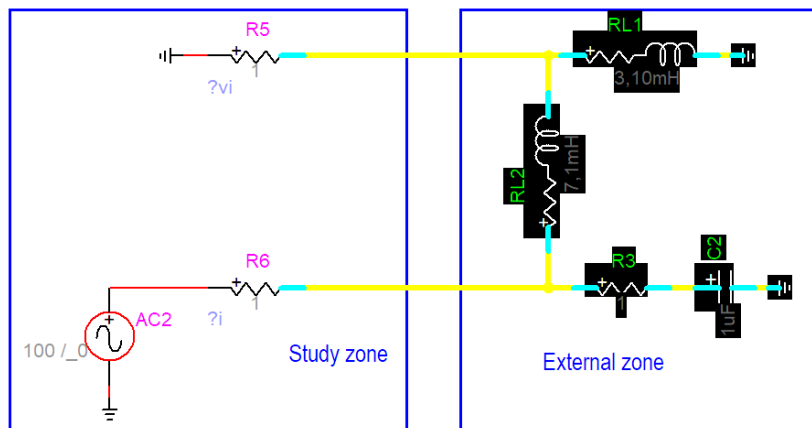


Figure 9. Selecting the devices of the external zone.

Creating a subcircuit of the external zone (see Figure 6), the circuit of Figure 10 is obtained.

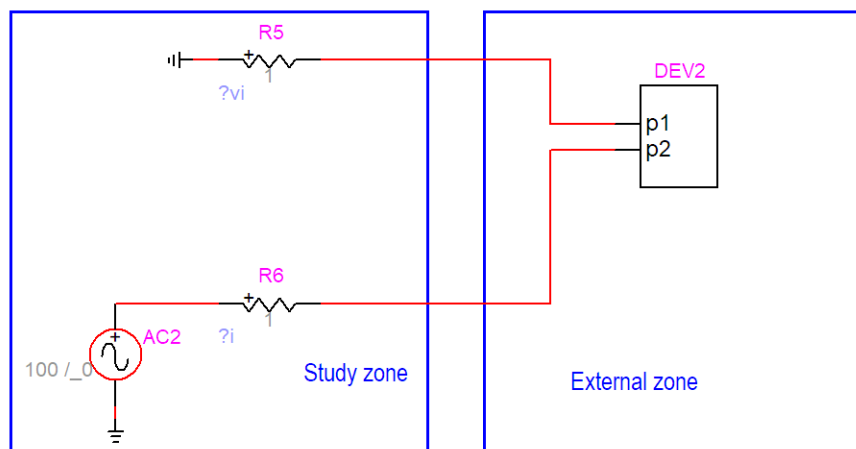


Figure 10. Creating a subcircuit for the external zone.

Selecting the created device (DEV2 in Figure 10) and using the option 'Make FDNE from device,' a mask is open to select the FDNE model settings, this mask is shown in Figure 11 with its default parameters.

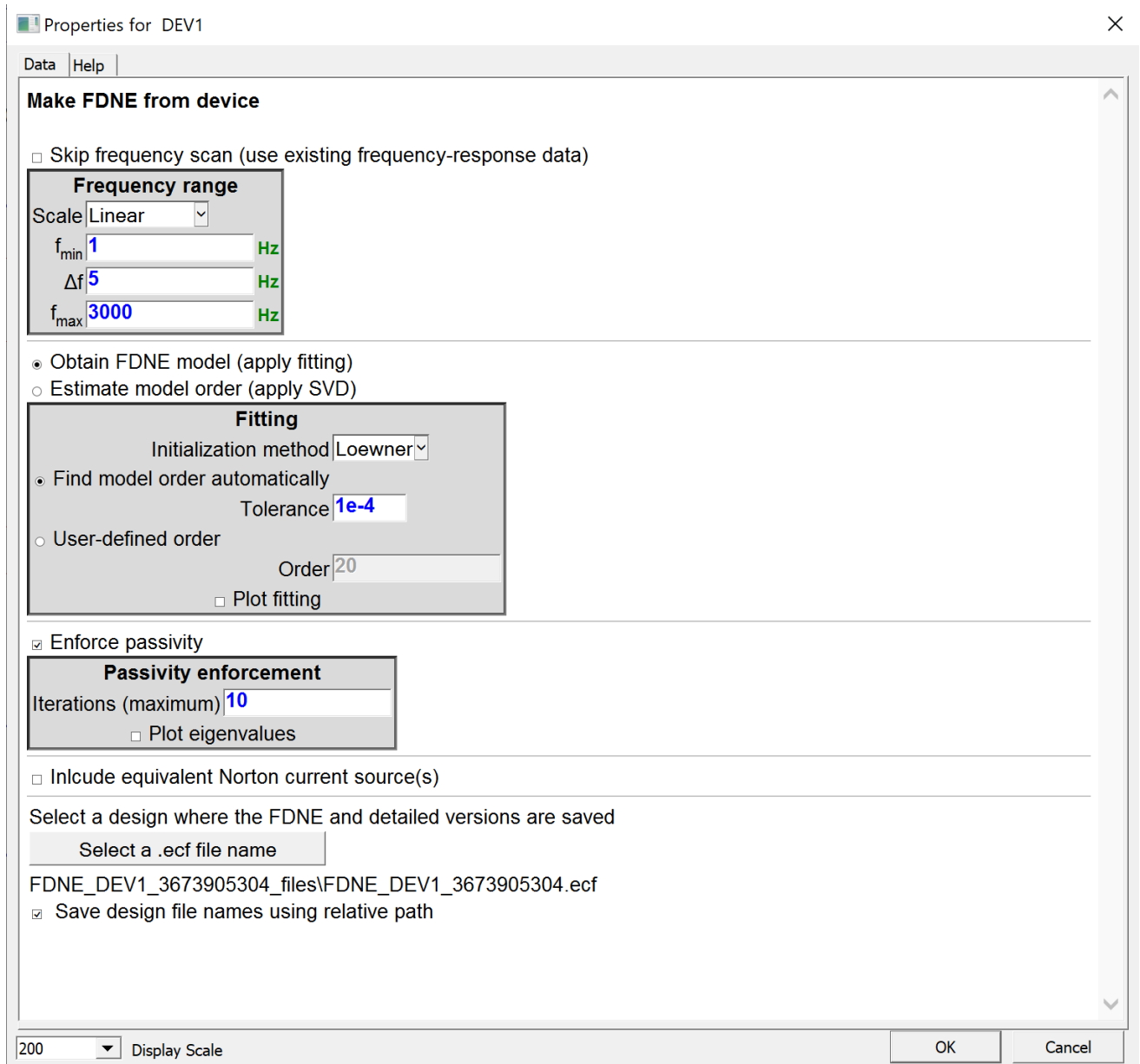


Figure 11. FDNE mask for the 'Make FDNE from device' option.

As it can be observed in Figure 11, the FDNE mask permits the user to define the frequency range for fitting, fitting initialization options, model order identification options and the maximum number of iterations for passivity enforcement (only used if required). Finally, the user must tick the 'Generate FDNE after closing with OK' checkbox to start the FDNE calculations.

Completing the FDNE model calculation for the current example (with the default values in the mask), results in a modification of the subcircuit of device DEV2, see Figure 12. Note that the connections are invisible on the screen but set internally by code.

Some details about the FDNE calculation process and results are displayed in the EMTP console as shown in Figure 13.

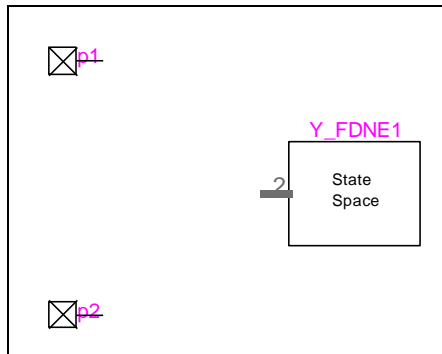


Figure 12. Step 4, subcircuit for the FDNE model obtained.

```

Circuit1.ecf
FDNE computation for device: DEV1

Running frequency scans, please wait ...
  Scanning from port p1 ...
  Scanning from port p1 ...
Frequency scans completed.

FDNE fitter started. Please wait...
Input file: C:\Users\JesusMorales\OneDrive - emtp.com\Documents\FDNE testing 2022\Examples\DummyExample_SinglePhase\FDNE_DEV1_3673905304_fi
Computing FDNE model, wait ...
Fitting succeeded.
  Model order: 4 poles
  RMS error: 2.6753e-15
  relative error: 1.6518e-12 %
  CPU time: 1.4892 seconds
Passivity assessment ...
  The fitted model violates passivity.
  Forcing D matrix to be passive ...
Passivity enforcement succeeded.
  RMS error: 1.1328e-09
  relative error: 6.6661e-07 %
  CPU time: 0.033113 seconds
Model file: C:\Users\JesusMorales\OneDrive - emtp.com\Documents\FDNE testing 2022\Examples\DummyExample_SinglePhase\FDNE_DEV1_3673905304_
FDNE fitter ended successfully.

FDNE circuit built.

FDNE and detailed circuit versions saved in C:\Users\JesusMorales\OneDrive - emtp.com\Documents\FDNE testing 2022\Examples\DummyExample_SinglePI

FDNE interface set.

FDNE module ended.

```

Figure 13. FDNE console details.

2.1.4 Multiport frequency-scan

The user must consider that the accuracy of FDNE models in transient simulations relies on the frequency range selected and on the fitting accuracy.

The FDNE toolbox in EMTP permits the user to measure frequency responses linearly or logarithmically sampled, see Figure 14. The frequency-response of a multiport network is measured applying the Zin tool in EMTP (Input Impedance from the Options library). This process is achieved automatically using the FDNE toolbox. The Zin tool is applied to each port of the selected device (device containing the external zone) neglecting the elements of the study zone. It is recalled that the Zin tool turns-off all the sources in the circuit, such that, only passive elements are considered. For subcircuits containing nonlinear devices, only their linear representation is considered, see the Zin device Help for more details.

Considering that the user might require to repeat the computation of an FDNE (some reasons could be, due to poor fitting observed, passivity enforcement fail, changing parameters or options), the user does not need to

apply the frequency-scan again since the frequency response data is saved each time an FDNE calculation is run. Checking the option 'Skip frequency-scan' (see Figure 14) permits the user to skip this process using the previously saved data, accelerating the new FDNE computation process.

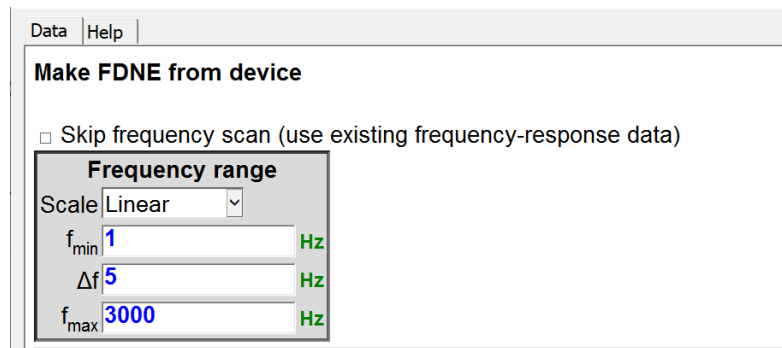


Figure 14. FDNE frequency scan.

2.1.5 FDNE toolbox model order identification

The FDNE toolbox has the option 'Estimate model order (apply SVD)' for model order identification, such as applied in Example 1. When this option is used, the user is required to inspect the singular values of the Loewner/MPM function.

2.1.5.1 Inspecting singular values

The option 'Inspect singular values' allows the user to identify the dominant singular values among the whole set of singular values of the LM- or MPM-pencil function depending on the initialization method selected. As explained in section 1.1, applying singular value decomposition (SVD) to the LM or MPM-pencil functions has the property of revealing the system order by showing abrupt drops between consecutive singular values. For Example 1 given in previous section, the curve of singular values generated using the LM-pencil singular values clearly reveals the system order as dictated by the sudden drop after the fourth singular value, this is shown in Figure 15. Using the 'Inspect singular values' option, the user is required to read the dominant singular values and at the same time to define the FDNE model order. Therefore, the user is required to apply again the option 'Make FDNE from device' to enter the number of poles found in the previous run, this is illustrated in Figure 16.

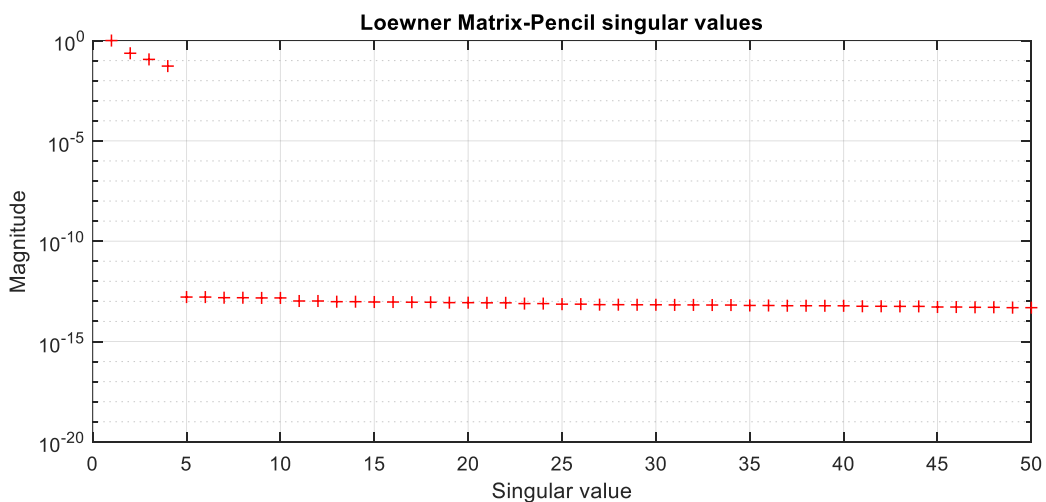


Figure 15. Singular values of the LM-pencil function for Example 1.

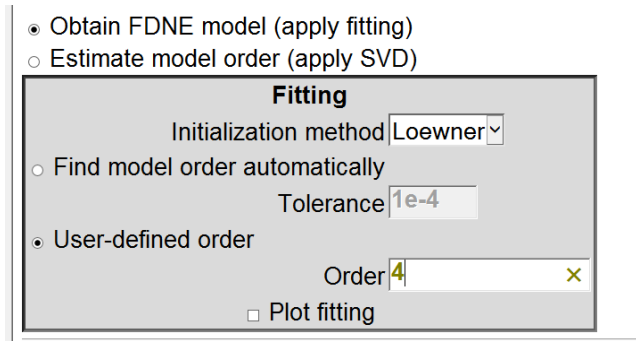


Figure 16. Entering the identified model order after inspection of singular values.

2.1.5.2 Find model order automatically

The option 'Find model order automatically' uses a tolerance value to select the dominant singular values of the LM- or MPM-pencil functions. Using this option, the singular values with magnitude above the tolerance value are selected as dominant. The tolerance value can be modified in the FDNE mask to increase or relax the fitting accuracy as shown in Figure 17. Reducing the tolerance value increases the model order (better fitting accuracy) and vice versa.

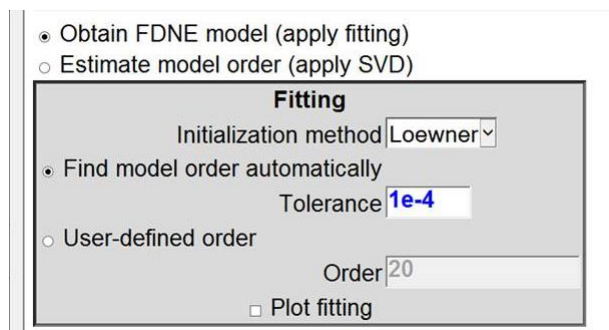


Figure 17. Model order identification options.

For the Example 1 presented above, the default tolerance value used is 1×10^{-4} and the model order results in $N = 4$ poles, this can be verified in Figure 15 since only the magnitudes of the first four singular values are above the tolerance. The result can be further confirmed from Figure 13, in the console results.

2.1.6 Fitting plot

The FDNE toolbox in EMTP gives the user the possibility of verifying the accuracy of the fitting using the checkbox 'Plot fitting' in the FDNE mask, see Figure 17. For Example 1, the resulting fitting plots are shown in Figure 18 (a) and (b). Note that when passivity enforcement is applied, the initial fitting can become corrupted due to the perturbations applied. Therefore, it is important to verify the final fitting accuracy. From Figure 18, the deviation in both, initial and final fittings is in the order of 10^{-15} , confirming a very good accuracy of the fitted FDNE model. It is also observed that passivity is enforced only by perturbing matrix **D** of the model. Further details on the passivity enforcement process are given in next section.

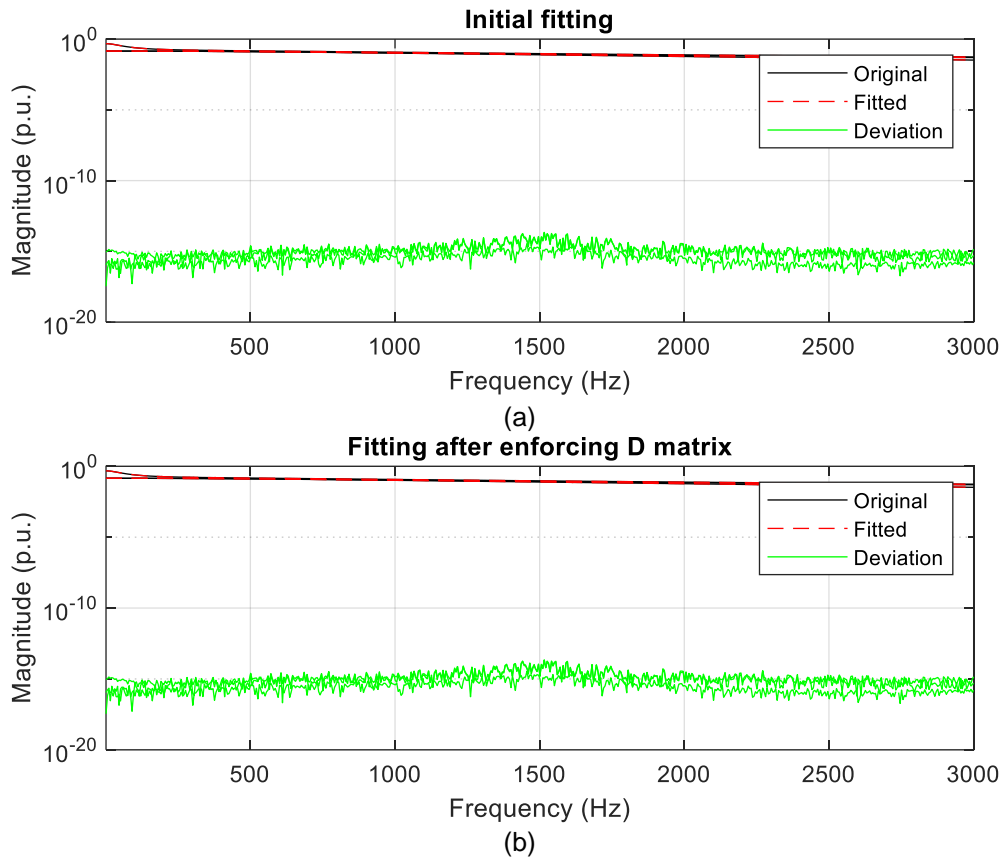


Figure 18. Fitting plot of Example 1, (a) initial fitting, (b) after-passivity enforcement fitting.

2.1.7 Passivity enforcement options

The FDNE toolbox offers the possibility of controlling the maximum number of iterations in the passivity enforcement stage. Also, it offers the possibility of plotting the eigenvalues of the FDNE's conductance matrix $\mathbf{G}(s)$ to monitor the passivity enforcement process, see Figure 19. These options are only used if the obtained FDNE model requires passivity enforcement.

It is important to recall that the passivity enforcement procedure applied in the FDNE toolbox consists of two stages, 1. Passivity enforcement of the constant matrix \mathbf{D} , and 2. Passivity enforcement of the pole/residue part of the model (PSRP method), the flowchart is illustrated in Figure 3. In some cases, enforcing the \mathbf{D} matrix results in an overall passivity enforcement and there is no need of applying the second stage, such as occurred in Example 1 presented above. An example of monitoring the passivity enforcement process is shown next.

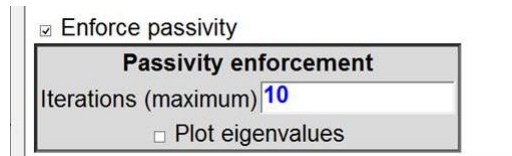


Figure 19. Passivity enforcement options.

2.1.8 Example 2.

As a second example, an FDNE model is calculated for the network of Figure 20. This network EMTP design is available in EMTP application cases. Note that in the circuit of Figure 20, only the study zone is indicated and the rest of the network is considered as the external zone.

For this example, the circuit requires to manually disconnect the internal and external zones and to use pin connectors for creating its subcircuit as explained in section 2.1.2. This is illustrated in Figure 21. After creating the subcircuit for the external zone and connecting again the external and internal zones, the circuit looks as shown in Figure 22.

Before calculating the FDNE, the circuit of Figure 22 must be run again for load-flow solution with the new network configuration. The load-flow solution is required for computing equivalent Norton-type current sources for the FDNE.

To continue calculating the FDNE model, the External_Zone device in Figure 22 is selected and the 'Make FDNE from device' option is applied. Using the default settings and selecting the 'Plot eigenvalues' option, the computation process for the FDNE is launched. The user will see on the screen the passivity enforcement evolution as shown in Figure 23 (a) and (b). Note that for this case, the passivity violation is small and it is removed after the first iteration as indicated in Figure 23 (b). For a better visualization, a zoom-out is applied and shown in Figure 23 (c).

As a complement for this example, the resulting fitting plots are shown in Figure 24 before and after passivity enforcement. More details about FDNE equivalent sources are given in next section.

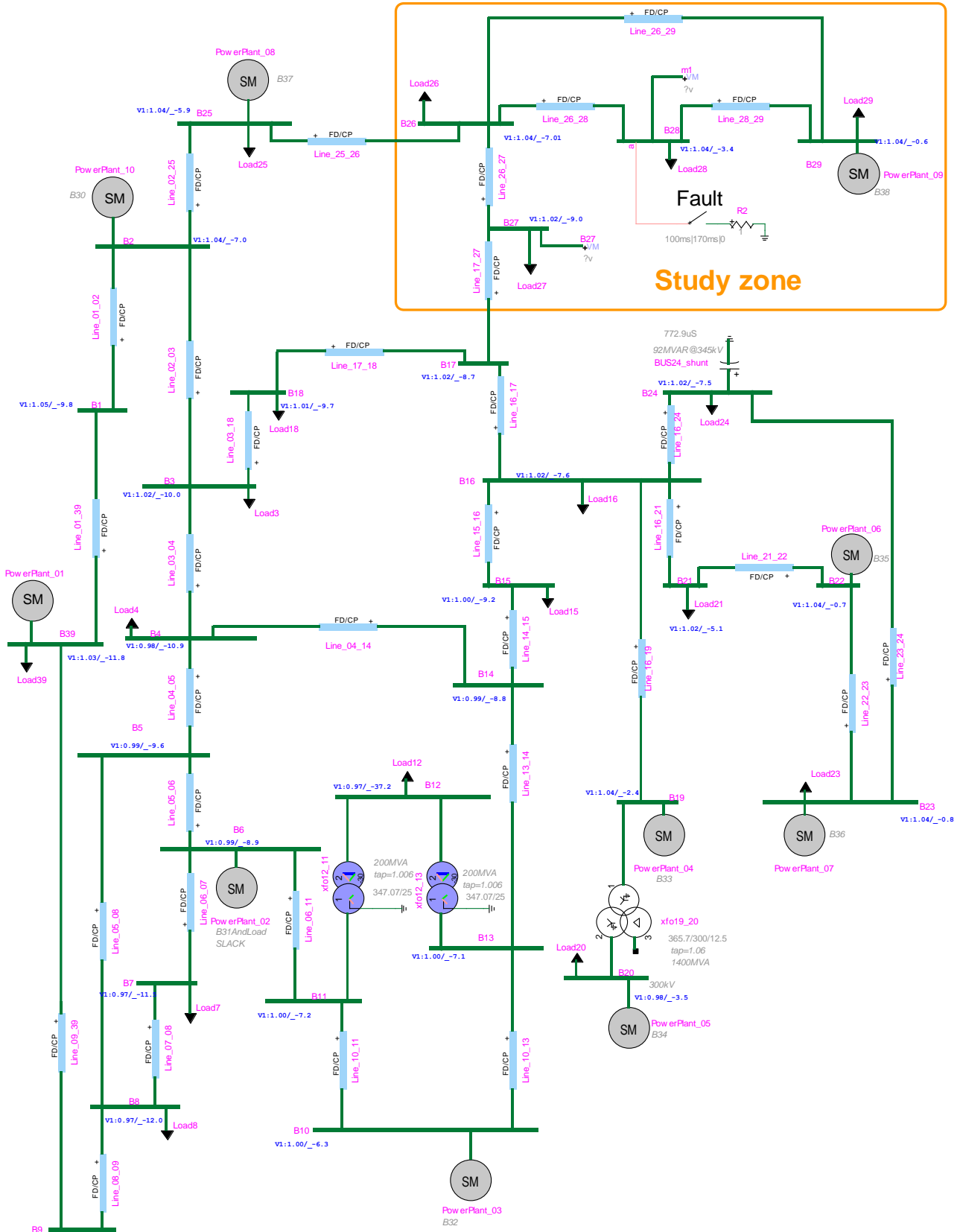


Figure 20. Test case 2, IEEE 39-bus benchmark.

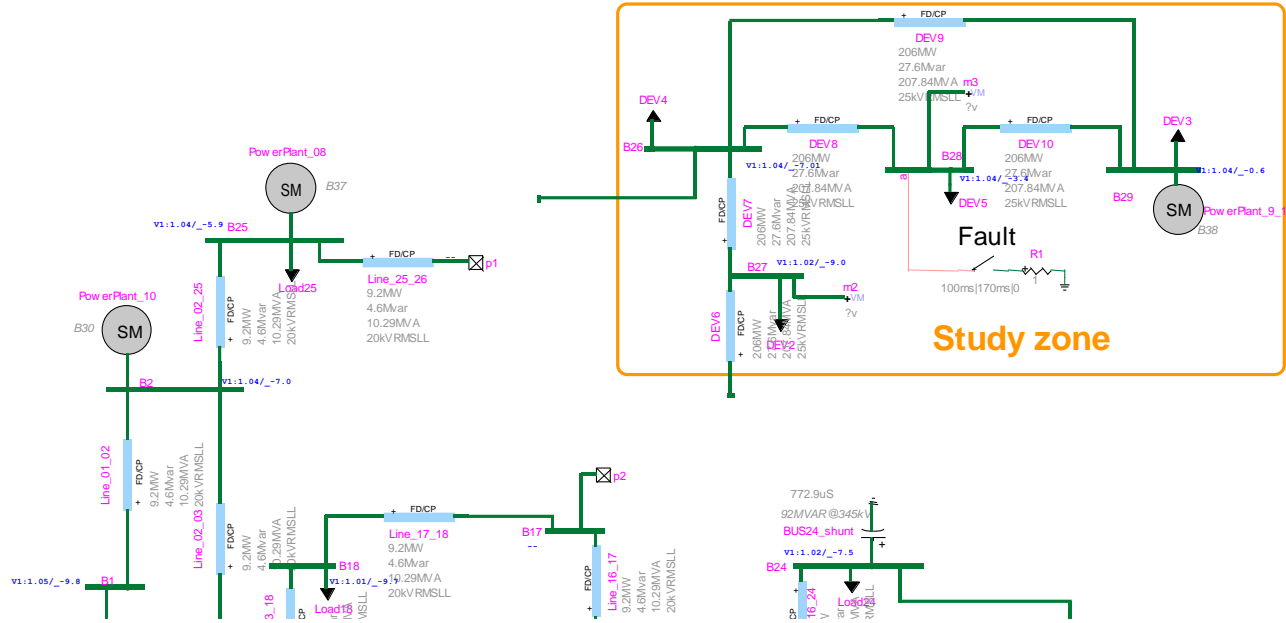


Figure 21. Preparing the external zone for creating a subcircuit.

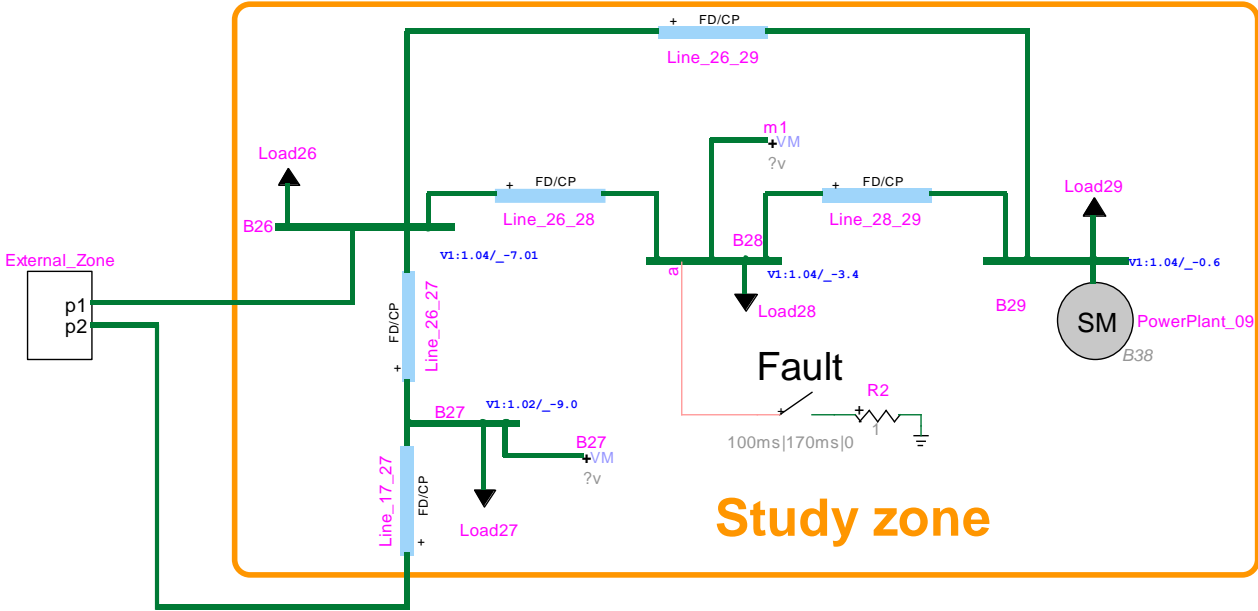


Figure 22. Test case 2 with external zone embedded in a device.

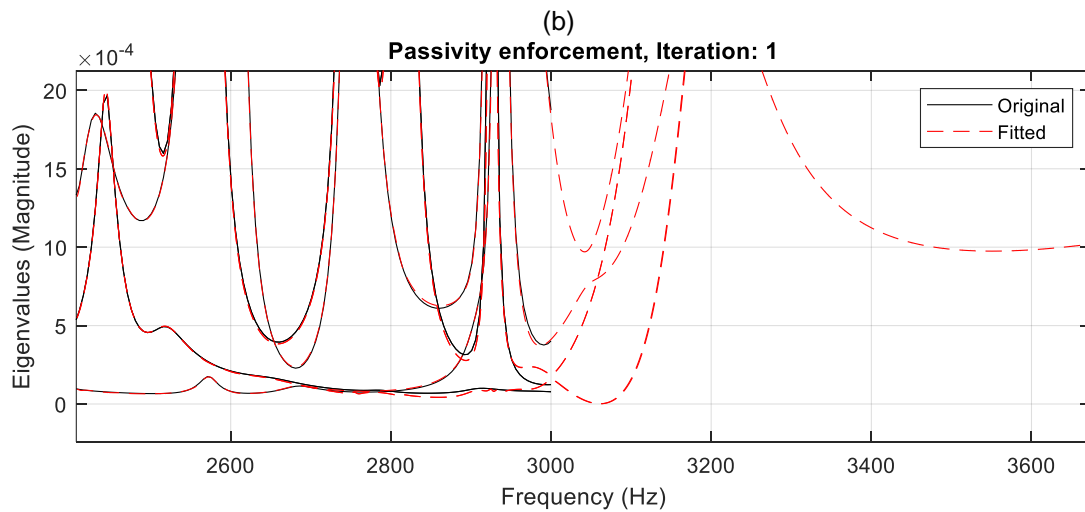
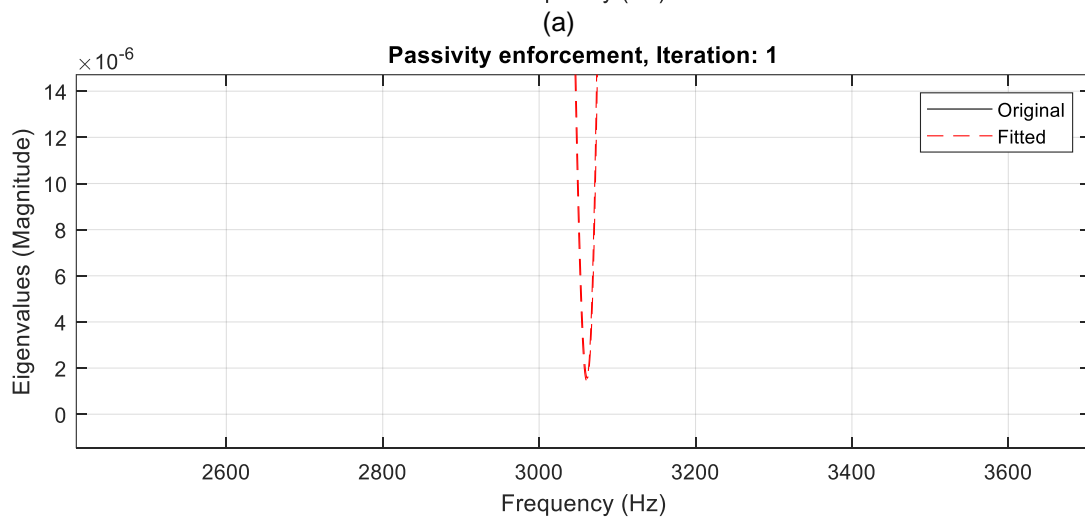
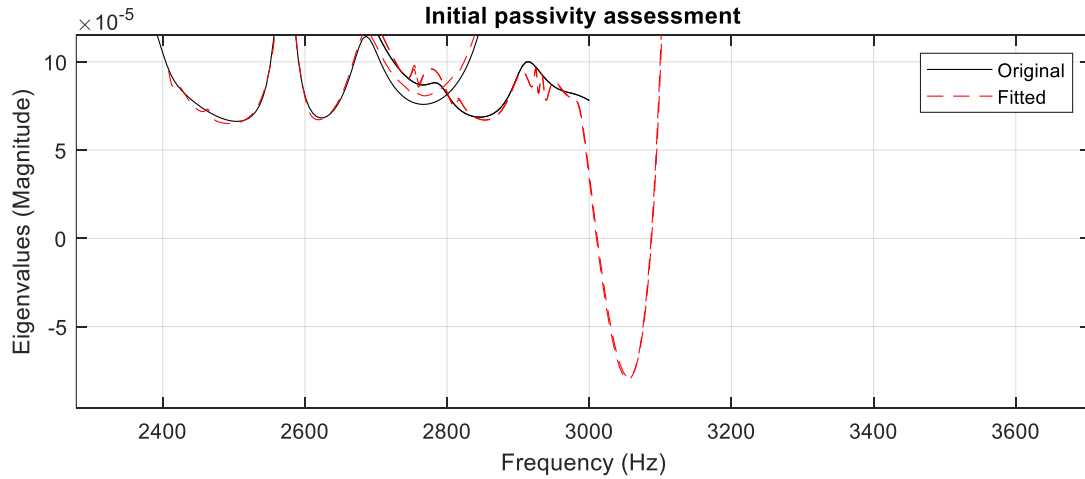


Figure 23. Passivity enforcement monitoring (a) Initial passivity violations, (b) passivity assessment after iteration 1 of passivity enforcement (c) zoom-out of (b).

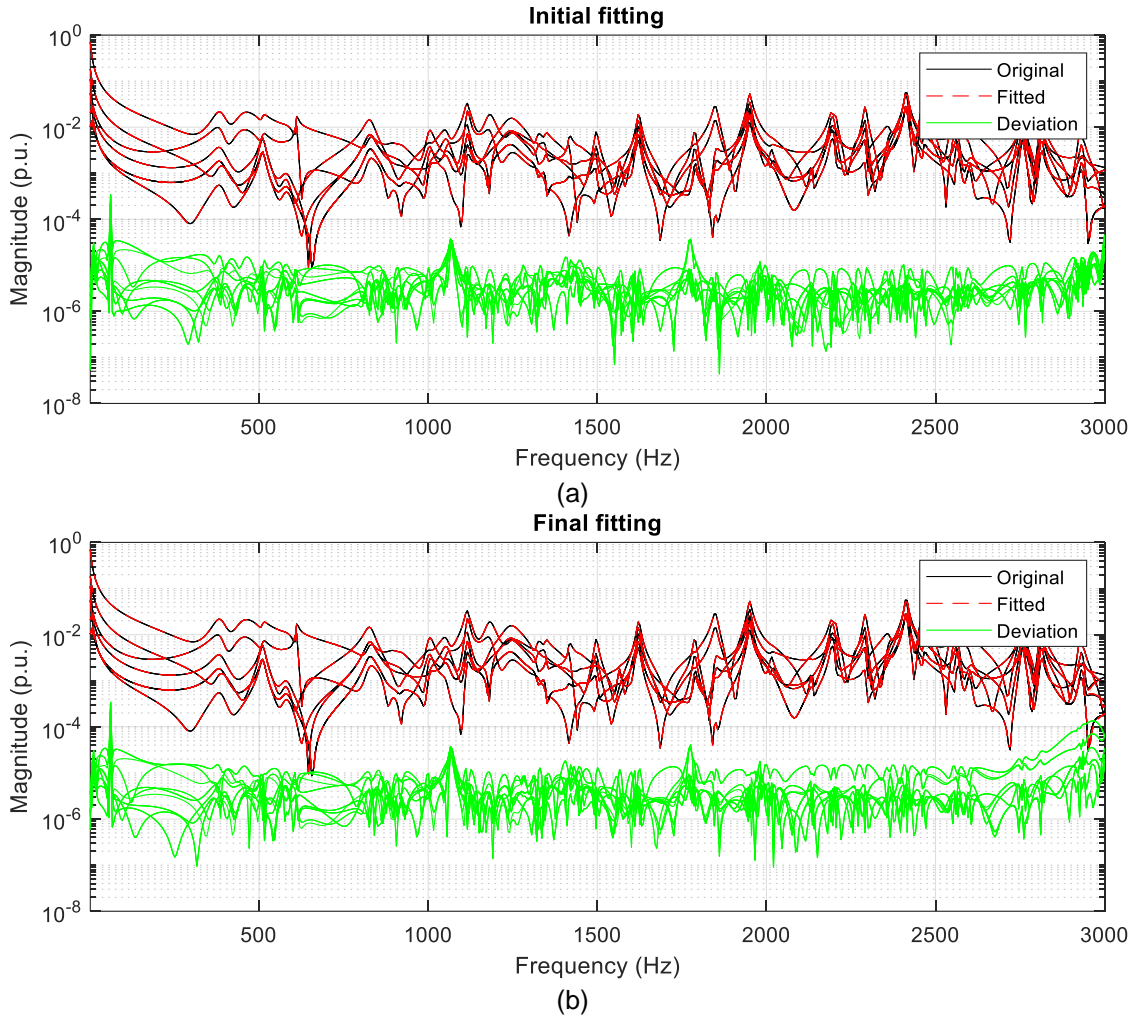


Figure 24. Fitting plots for example 2, (a) initial fitting (b) fitting after passivity enforcement.

2.1.9 FDNE model with equivalent sources

The calculation of FDNEs for subnetworks containing power sources requires the representation of those power sources to match the original circuit steady-state conditions. This toolbox offers two options for calculating fundamental-frequency equivalent current sources (ideal sources) to match those steady-state conditions as illustrated in the flow chart of Figure 25.

Note that in any case, if the external zone contains power sources with control-devices, those control devices responses cannot be reproduced by the FDNE. Also, note that no user intervention is required for setting these equivalent sources.

Regarding Option 2, Load-Flow Slack constraints are added to the FDNE model with the voltages found at the boundaries of the FDNE using the original circuit.

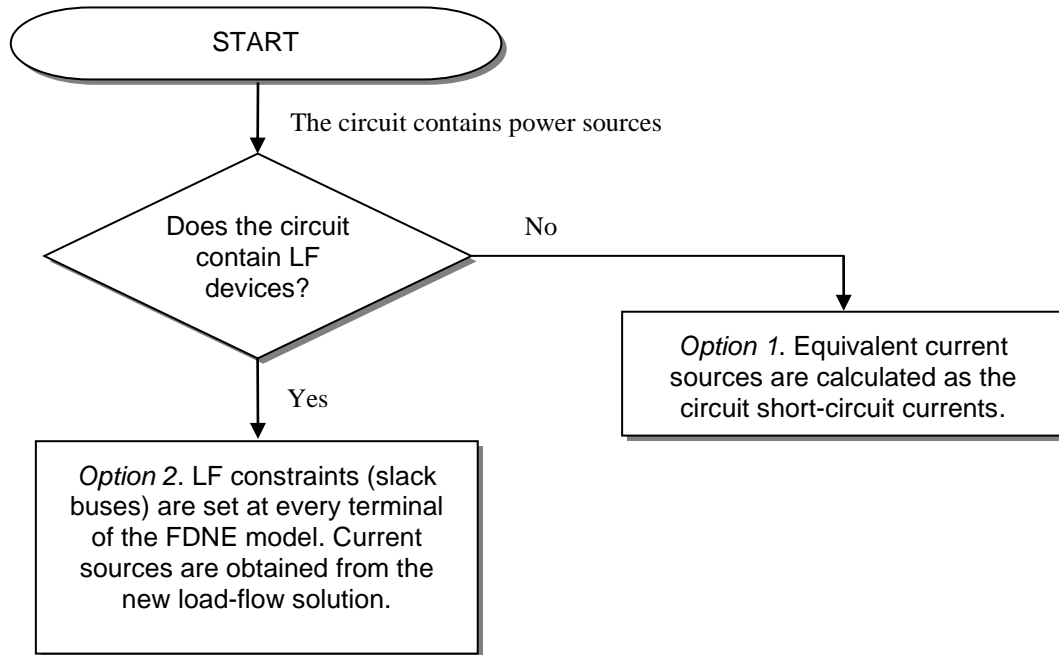


Figure 25. Flow chart for calculating equivalent FDNE power sources.

For the example 2 introduced above, the resulting FDNE circuit model is illustrated in Figure 26. Note that a state-space model with 6 inputs/outputs and two three-phase ideal current sources are given forming a Norton-type model where the equivalent admittance is frequency-dependent. Also, note that the state-space model does not show connections on the screen, however, connections are represented internally in the EMTP design. For this case, Option 2 in Figure 25 has been set.

Each FDNE equivalent current source in Figure 26 has the subcircuit shown in Figure 27. Note that the FDNE current source devices are black-box scripted devices where the values are assigned internally in EMTP. The performance of the FDNE model of Example 2 is tested in time simulations in next section.

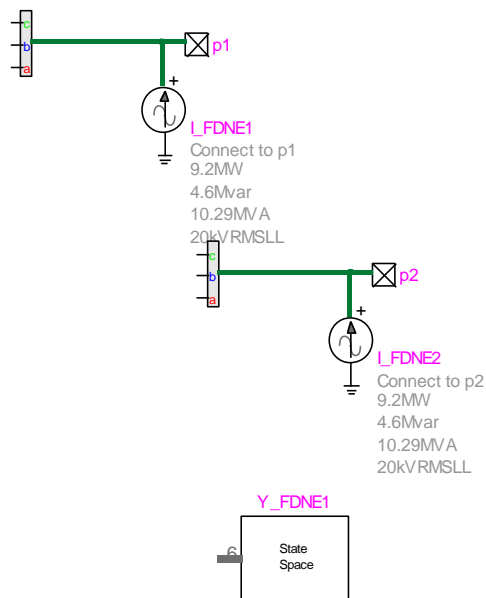


Figure 26. Resulting FDNE model for example 2.

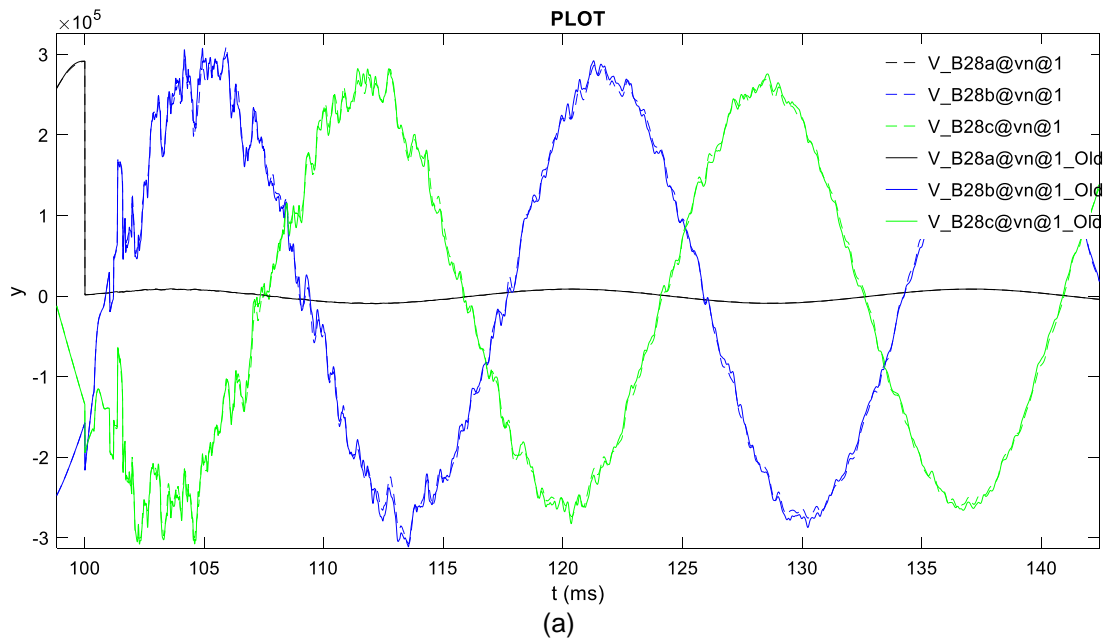


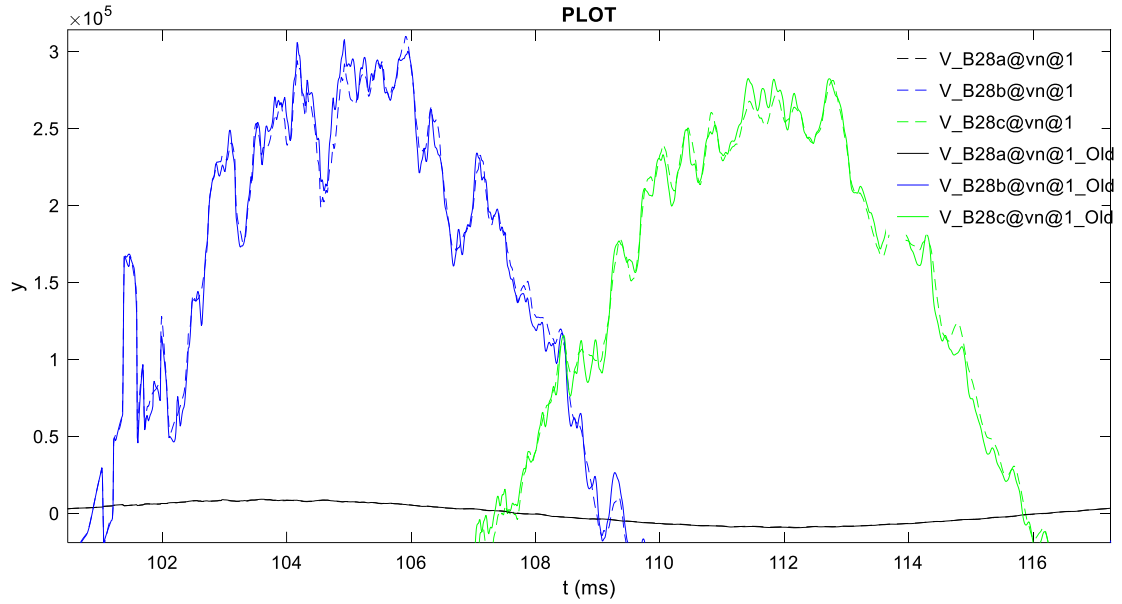
Figure 27. Subcircuit of FDNE current sources.

2.1.10 Time domain simulations

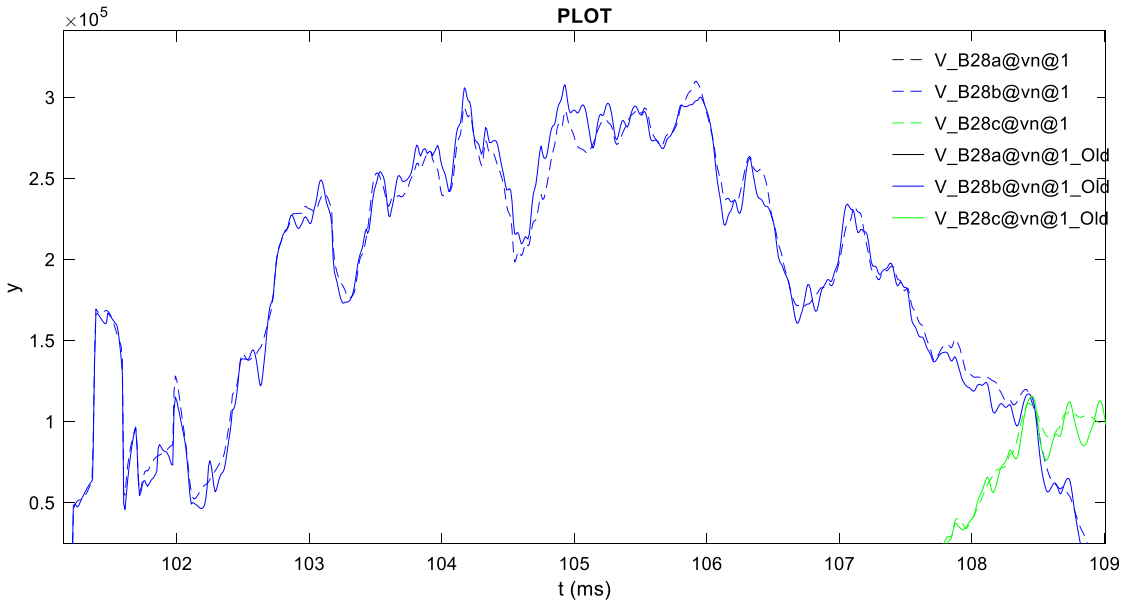
In this section, the FDNE model calculated in Example 2 is tested in time-domain simulation using a time step of $5\mu\text{s}$ and a simulation time of 0.5s. The resulting transient waveforms for the voltage at bus B28 after applying a temporary single-phase fault are shown in Figure 24 (a)-(c). In these figures, the FDNE model curves are represented by dashed lines whereas the detailed model curves are represented by solid lines and with the legend `_Old`. These figures show a very close match between the FDNE model and the detailed representation.

The CPU simulation times for Example 2 are given in Table I for different simulation time-steps. In all cases in Table I, the simulation time is 0.5s. These CPU simulation times demonstrate the FDNE capabilities.





(b)



(c)

Figure 28. Transient voltages at bus B28 of the network of Example 2, detailed and FDNE models responses.

Table I. Comparison of CPU simulation time between detailed model and FDNE.

Simulation time-step (μ s)	CPU time (s)		Acceleration factor
	Detailed model	FDNE	
20	20.6	3.3	6.2
15	22.1	4.8	4.6
10	25.8	7.2	3.6
5	54	14.8	3.7
2	129	34	3.8

2.2 Make FDNE from file

The FDNE toolbox offers the possibility of calculating FDNEs from frequency-responses obtained out of EMTP. To use this option, the frequency-response must be loaded from a text file containing the frequency response with an specific format.

Consider a generic network with n-ports to be synthesized by an FDNE. The frequency response measured from its n-ports corresponds to the $n \times n$ size admittance matrix

$$\mathbf{Y}(s) = \begin{bmatrix} y_{11}(s) & y_{12}(s) & \cdots & y_{1n}(s) \\ y_{21}(s) & y_{22}(s) & \cdots & y_{2n}(s) \\ \vdots & \vdots & \ddots & \vdots \\ y_{n1}(s) & y_{n2}(s) & \cdots & y_{nn}(s) \end{bmatrix} \quad (7)$$

Since the FDNE toolbox considers symmetrical systems, only the upper-triangular matrix elements are required. The format of the required text file must respect the following rules:

1. The first line of the text file must indicate if the phase of the frequency response is given in degrees or radians explicitly with the string 'radians' or 'degrees', the number of ports, and the number of frequency samples measured. These data must be separated by a comma in the same line.
2. From the second line of the text file, the frequency samples as well as the magnitude and phase of the upper triangular entries of $\mathbf{Y}(s)$ must be given in the order shown in Table II. In this table, the θ_{ij} elements denote the phase angle of the $y_{ij}(s)$ matrix entries.

Table II. Frequency-response format for text files.

f_1$	|y_{11}(s_1)|$	$\theta_{11}(s_1)$	...	$|y_{1n}(s_1)|$	$\theta_{1n}(s_1)$	$|y_{22}(s_1)|$	$\theta_{22}(s_1)$	...	$|y_{2n}(s_1)|$	$\theta_{2n}(s_1)$	...	$|y_{nn}(s_1)|$	$\theta_{nn}(s_1)$
f_2$	|y_{11}(s_2)|$	$\theta_{11}(s_2)$	...	$|y_{1n}(s_2)|$	$\theta_{1n}(s_2)$	$|y_{22}(s_2)|$	$\theta_{22}(s_2)$	...	$|y_{2n}(s_2)|$	$\theta_{2n}(s_2)$	...	$|y_{nn}(s_2)|$	$\theta_{nn}(s_2)$
\vdots	\vdots	\vdots		\vdots	\vdots	\vdots	\vdots		\vdots	\vdots		\vdots	\vdots
f_k$	|y_{11}(s_k)|$	$\theta_{11}(s_k)$	...	$|y_{1n}(s_k)|$	$\theta_{1n}(s_k)$	$|y_{22}(s_k)|$	$\theta_{22}(s_k)$	...	$|y_{2n}(s_k)|$	$\theta_{2n}(s_k)$	...	$|y_{nn}(s_k)|$	$\theta_{nn}(s_k)$

First row of $\mathbf{Y}(s)$
Second row of $\mathbf{Y}(s)$
 n^{th} row of $\mathbf{Y}(s)$

An alternative format to load the frequency response into the FDNE calculator is to import a Matlab (.mat) file containing a structure-type variable named FDNEdata. This structure must contain the fields 'Y' and 's' being matrices with dimensions $n \times n \times k$ and $1 \times k$, respectively, according to the generic admittance matrix in (7). Using the option 'Make FDNE from file' opens the mask illustrated in Figure 29.

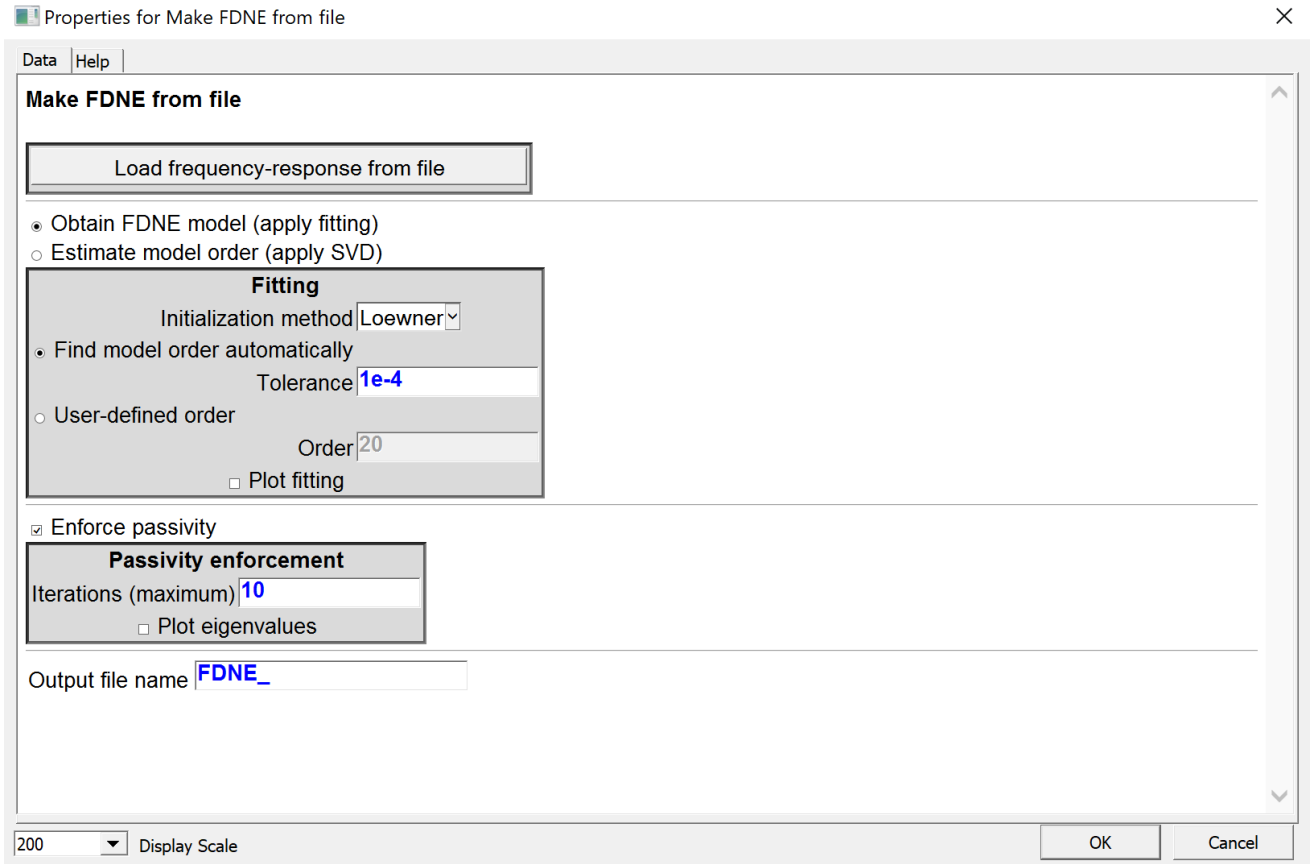


Figure 29. Mask for the 'Making FDNE from file' option.

2.2.1 Example 3

In this section an FDNE is calculated from the frequency response of a transformer from a file. This frequency response file is included with the FDNE toolbox and it has been obtained from [10]. The frequency response (admittance) function is shown in Figure 30. The FDNE data is a Matlab file containing the following fields (as displayed in Matlab Command Window):

FDNEdata =

struct with fields:

Y: [1×160 double]
s: [1×160 double]

The FDNE model obtained from fitting the frequency response in Figure 30 is given as a state-space device in EMTP as shown in Figure 31.

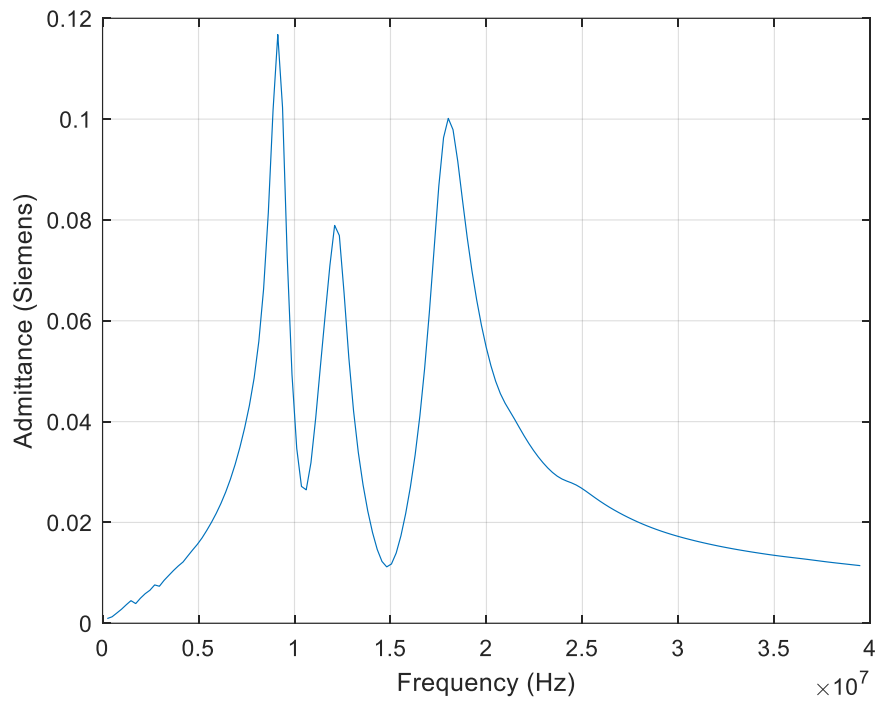


Figure 30. Transformer frequency-response.

```

FDNE computation for input file: C:\Users\JesusMorales\OneDrive - emtp.com\Docu
FDNE fitter started. Please wait...
Input frequency-response file: C:\Users\JesusMorales\OneDrive - emtp.com\Docur
Fitting succeeded.
  Model order: 57 poles
  RMS error: 2.638e-05
  relative error: 0.13947 %
  CPU time: 1.1886 seconds

Model file: C:\Users\JesusMorales\OneDrive - emtp.com\Documents\FDNE testing
FDNE fitter ended successfully.

Find the FDNE model in "Y_FDNE2" device

```

Figure 31. Model obtained from fitting the frequency response in Figure 30.

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