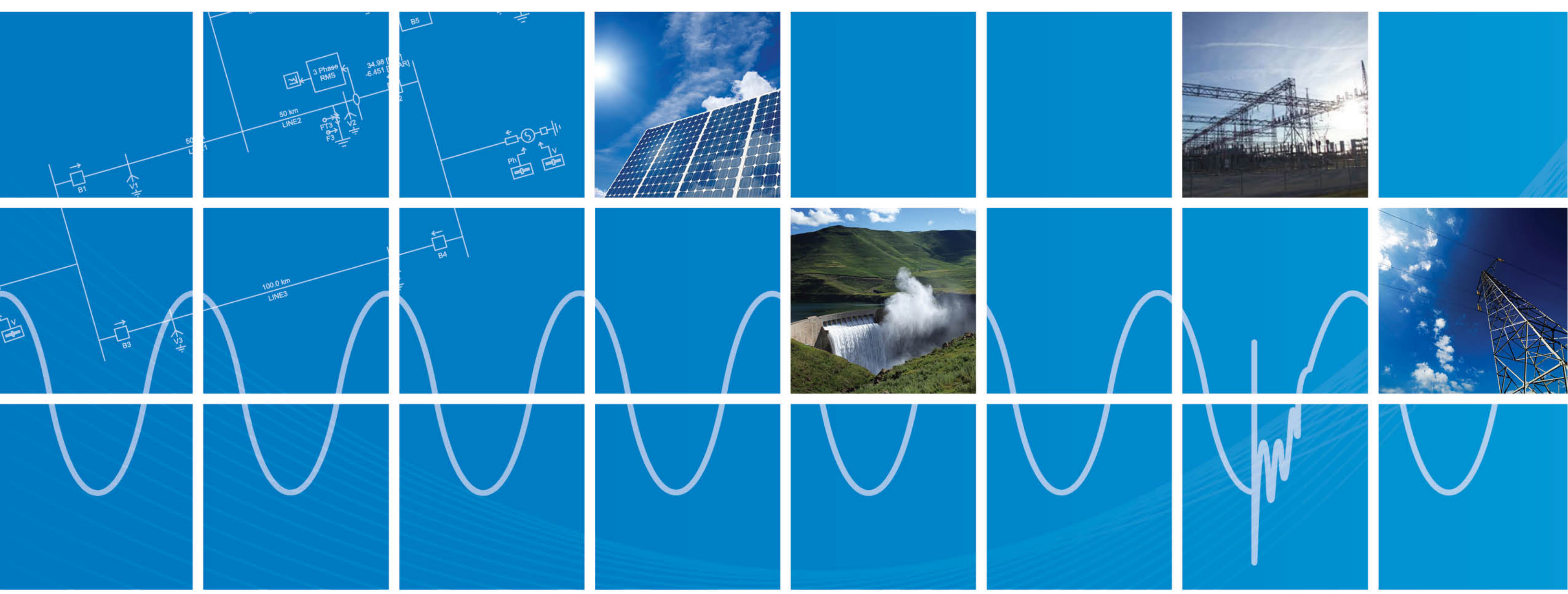
PSCAD™

Frequency-Dependent Network Equivalent (FDNE)

Written for PSCAD (All Versions)

October 9, 2021
Initial



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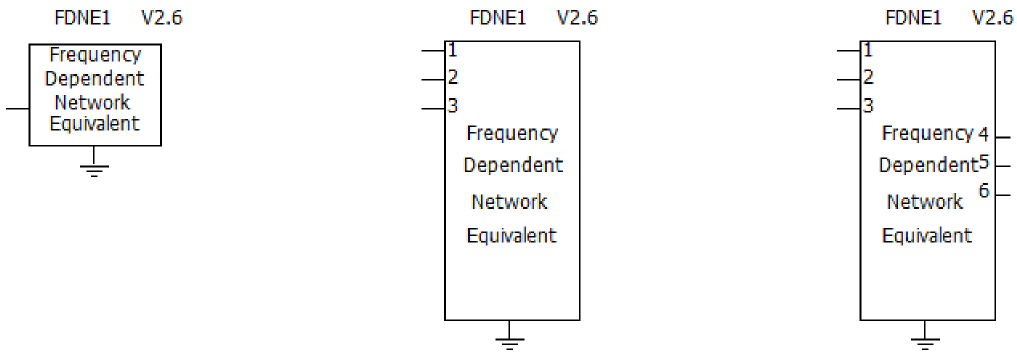


1. Description

This component creates a multi-port, frequency-dependent network equivalent from a given set of characteristics, such as impedance (**Z**), admittance (**Y**) or scattering (**S**) parameters. This model first approximates the frequency-domain response with a rational function using the Vector Fitting (VF) [1], Relaxed Vector Fitting (RVF) [2] or Modal Vector Fitting (MVF) techniques [3]. Once the frequency-domain response is expressed in rational form (pole/residue) or state-space form, an EMT-type, frequency-dependent network equivalent can be constructed, consisting of admittances and current sources [4].

intermediate library downloaded from the MHI Knowledge Base.

e.g. for PSCAD V4

https://www.pscad.com/knowledge-base/article/525

for PSCAD V5

https://www.pscad.com/knowledge-base/article/808

3. Input Data

Input to this component is the frequency-dependent characteristics of the network to be represented by an equivalent and is provided as a text file. The input data may be given in one of the following formats:

- Output from the Interface to Harmonic Impedance Solution*
- Impedance Parameters
- Admittance Parameters
- Scattering Parameters
- Admittance as ABCD Parameters
- Scattering as ABCD Parameters
- Sequence Parameters

*Note: In Harmonic impedance solution, the “Impedance Output Type” should be set to “Phase Impedances”.

4. Power Injections (to Maintain Terminal P,Q,V,δ Conditions)

The FDNE can be used to model a portion of a network (sub-network) using parameters such as impedance or admittance (i.e., these parameters only represent a passive network). However, the sub-network may consist of active elements such as voltage sources etc. The effect of active elements can be modeled by defining power injections at the terminals. This will give accurate power flow and terminal voltages. The terminal conditions can be defined either by voltage, angle, active and reactive power, or direct current injections at terminals.

5. Passivity Enforcement

Time domain simulations involving FDNE can be sometimes unstable. This is primarily due to passivity violations [5]. Passivity enforcement algorithms are implemented to enforce stability for the frequency range defined in the passivity identification.

6. Input Parameters

Configuration

Parameter	Type	Description
Name	Text	Enter a unique name. Each FDNE component in a project should possess a unique name: A detailed log file is created in the project temporary folder and is useful when finding errors. This log file contains information such as curve-fitting results, etc.
View	Choice	Select compact or expanded. The compact is the general multi-port connection (up to 100 nodes). Scaler/tap array component can be used to connect the external network. The expanded connections are limited to 10.
Total Number of Ports	Integer	Enter the number of ports (electrical connections)
Number of Ports on One Side	Choice	Enter the number of ports to the other side of FDNE (Applicable only if the View is expanded) This parameter may be used to configure port positions on the component graphic. E.g. this may be useful to model a frequency depended transformer with primary and secondary terminals on two sides.
Reference Port	Choice	Select **Ground** or **External Connection**. If **External Connection** is selected, the reference will be made available for external connection on the component graphic, via a connection port.
Detailed Log File	Choice	Select **Create** or **Do Not Create**. A detailed log file is generated, if "Created" is selected in the temporary directory. It is always advisable to check any error/warning messages, fitting accuracy etc in the log file. Also additional files are created (see Output Data)
Input Data File	Text	Enter the name of the input data file.
Path to Input File	Choice	Select **Relative** or **Absolute**. Select **Relative** if you are giving the input data file name as relative to the current working folder. Use absolute path if you are giving the data file name as an absolute path (ex. C:\temp\harm.out).
Data Format	Choice	Select From **Harmonic Impedance Component**, **Impedance Parameters**, **Scattering Parameters**, **Admittance Parameters**, **Admittance as ABCD Parameters**, **Scattering as ABCD Parameters** or Sequence parameters Select the type of input data to be used to calculate the network equivalent. See Input Data File Format for details.

Curve-fitting options

Parameter	Type	Other	Description
Curve-fitting Technique	Choice		Select from three available techniques to fit the frequency-domain data **Fast Vector Fitting (FVF)**, **Fast Relaxed Vector Fitting (FRVF)** or **Fast Modal Vector Fitting (FMVF)**. FVF method – original vector Fitting method [1] FRVF provides an improved pole relocation, hence increases the accuracy of the fitting [2]. FMVF enforces accuracy of admittance and impedance parameters simultaneously [6]. It provides a major improvement in accuracy for cases with high ratios between the largest and smallest eigenvalues.
Type of Rational Function	Choice		Select from **Proper** or **Strictly Proper** Typically, the default setting "Proper" is fine for many characteristics. However if you want to enforce the admittance to be zero at high frequencies, use "Strictly Proper". If a "strictly proper" rational function is selected, the order of numerator will be less than denominator order. On the other hand, if a "proper" rational function is selected, the order of numerator and denominator will be equal. The main difference is that a proper approximation will never grow unbounded as the frequency approaches infinity, while a strictly proper approximation will approach zero as the frequency goes to infinity.
Maximum Fitting Error (%)	REAL	Literal	Enter the maximum error allowed for the curve fitting process [%]. The program will incrementally increase the order of the approximation to fit the data until this error criterion is met. However, the resulting number of poles is not allowed to exceed the specified **Maximum Order of Fitting**.
Starting Order of Fitting (Symbol: ORDER_ST)	INTEGER	Literal	Enter the staring order for fitting the transfer function (usually 1) By default, the selected curve-fitting technique starts the rational approximation from an order of 1 and increases the order until the fitting error is less than the user-specified value. In case some information regarding the system is known, one can start the fitting process from a higher order, saving computational time and recourses.
Order Incrementation (Symbol: ORDER_INCR)	INTEGER	Literal	This is the amount by which the order is increased in each step. Increasing this value can lead to a faster convergence.
Maximum Order of Fitting (Symbol: ORDER)	INTEGER	Literal	Enter the maximum number of poles to be used for curve-fitting. The order of rational function on the K^{th} step will be: ORDER_ST+(K-1)*ORDER_INCR <= ORDER However, overfitting and passivity violations can happen if the order is increased excessively.
Type of Weighting	Choice		Select from **Common** or **Independent** If "common" is selected, a united weighting factor is applied to all the matrix elements in a specific frequency. If "independent" is selected, matrix elements are weighted independently.

Weighting Scheme	Choice		Select from **User-Defined** or **Strong Inverse** or **Weaker Inverse** If "user-defined" is selected, the user can enter the weighting factor applied at different frequency intervals (W1, W2 and W3). If "Strong Inverse" is selected, the frequency-domain response becomes weighted with the inverse of its magnitude $(1/\lvert f(s)\rvert)$. This is useful when a frequency-domain response has both large and small values and the fitting error needs to be minimized over all the elements. If "weaker inverse" is selected, the square root of the inverse of the magnitude $(1/\sqrt{\lvert f(s)\rvert})$ is applied as the weighting factor.
Steady State Frequency	REAL	Literal	Enter the system steady-state frequency (F0) [Hz]. This is only important, if you want to define different weighting factors between different bands of frequencies (see below).
Weighting Factor for Minimum to Steady Sate Frequency **(Symbol: W1)**	REAL	Literal	Provide a weighting factor for the frequency range **Fmin** to **F0**. **Note**: **Fmin** is the minimum frequency defined in the data file.
Weighting Factor for Steady State Frequency **(Symbol: W2)**	REAL	Literal	Provide a weighting factor for the steady-state frequency **F0**.
Weighting Factor for Steady State to Maximum Frequency **(Symbol: W3)**	REAL	Literal	Provide a weighting factor for the frequency range **F0** to **Fmax**. **Note: Fmax** is the maximum frequency defined in the data file.

Power Injections

Parameter	Type	Description
Enable Power Injections	Choice	**Yes (boundary conditions)** to enable power injections through terminal conditions of the FDNE **Yes (Current Injections)** to enter current injections directly at terminals (see Power Injections for more details)
Input Data File	Text	Name of the input data file. (see Power Injections for more details)
Path to Input File	Choice	Select **Relative** or **Absolute**. Select **Relative** if you are giving the input data file name as relative to the current working folder. Use absolute path if you are giving the data file name as an absolute path (ex. C:\temp\harm.out).

Passivity Enforcement

Parameter	Type	Description
Enforce Passivity	Choice	**Yes (perturbation method)** (Enforce stability of time domain simulation by linear constrained optimization algorithm) **Yes (filter method)** (Enforce stability of time domain simulation by linear constrained optimization algorithm) **No** (No stability enforcement) If the simulation is unstable, use either perturbation method or filter method. (see passivity enforcement techniques for details)
Maximum error	Real	Maximum percentage error allowed after passivity enforcement.
Maximum iterations	Integer	Maximum number of iterations for passivity enforcement algorithm
Starting frequency	Real	Starting frequency for passivity violation identification in Hz
End Frequency	Real	End frequency for passivity violation identification in Hz
Number of samples	Real	Number of samples used for passivity identification
Frequency scale	Choice	Select Log or Linear for passivity identification.

7. Output Data

These output files are created in the project temporary folder when "Detailed Log File" is created. It is **always advisable** to check log files to make sure that FDNE is accurate.

The file names can be divided in to two parts (first part of the file name and rest of the file name).

Rest of the File Name	Description
.log	Log file
_Y_MAG.out	Magnitude of actual and fitted admittance
_Y_ANG.out	Angle of actual and fitted admittance

These output files may be useful to diagnose any problems/errors that may occur. The curve-fitting detailed output files are also created for all the input types except ABCD parameters.

The first part of the file is fdne_<instance number>_<call number>. The component instance number and call number are used to create detailed output files
(e.g. fdne_<instance number>_<call number>.log).

8. Power Injections

The FDNE without power injections represents only the passive network. The power injections option can be used to maintain steady state power flow, when connected to the rest of the network. If the boundary/terminal conditions are known, (e.g. Bus voltages, power flow (P,Q) at terminals of FDNE based on solved load flow or the original network), FDNE automatically calculated power injections. For each frequency power injections are calculated as,

$$I = YV + (P - jQ)/\mathrm{conj}(V)$$

Where Y is the admittance of FDNE at desired frequency

V is the terminal voltages vector at each frequency

P,Q are the active and reactive power flow (from FDNE to the network)

8.1. Power Injections Data File Format

This file is used to define voltage, angle, active and reactive power at terminals of FDNE. Harmonics can be added as well by defining terminal conditions at different frequencies.

```
!   Comment line
NC    ! number of ports (should match FDNE interface ports)
NF  ! (number of power injections at different frequencies)
0.1  ! (ramp time)
F1 ! frequency
V1    Angle1  P1  Q1                    ! V, angle P,Q for port 1 for frequency F1
V2    Angle2  P2  Q2                    ! V, angle P,Q for port 2 for frequency F1
V3    Angle3  P3  Q3                    ! V, angle P,Q for port 3 for frequency F1
F2 !  frequency
V4    Angle4  P4  Q4                    ! V, angle P,Q for port 1 for frequency F2
V5    Angle5  P5  Q5                    ! V, angle P,Q for port 2 for frequency F2
V6    Angle6  P6  Q6                    ! V, angle P,Q for port 3 for frequency F3
```

Alternatively if the current injections at the terminals of FDNE are available, this can be directly entered.

8.2. Current Injections Data File Format

This file is used to define voltage, angle, active and reactive power at terminals of FDNE. Harmonics can be added as well by defining terminal conditions at different frequencies.

! Comment line

NC ! number of ports (should match FDNE interface ports)

NF ! (number of power injections at different frequencies)

0.1 ! (ramp time)

F1 ! frequency

Mag1 Angle1 ! Magnitude and angle for port 1 for frequency F1

Mag2 Angle2 ! Magnitude and angle for port 2 for frequency F1

Mag3 Angle3 ! Magnitude and angle for port 3 for frequency F1

F2 ! frequency

Mag4 Angle4 ! Magnitude and angle for port 1 for frequency F2

Mag5 Angle5 ! Magnitude and angle for port 2 for frequency F2

Mag6 Angle6 ! Magnitude and angle for port 3 for frequency F2

Units

Paremeter	Description	Units
Frequency		Hz
V	Magnitude of voltage at each terminal (port) Rms, port to ground	kV
Angle	Angle of the voltage (with respect to sinusoidal waveform)	Deg.
P	Per port	MW
Q	Per port	Mvar
Ramp time	Ramp time of the current sources	seconds
Mag	Magnitude of the current (Rms)	kA
Ang	Angle of the current	Deg.

9. Passivity enforcement techniques

If the simulation is unstable, passivity enforcement technique can be used to enforce stability. There are two methods of passivity enforcement.

Perturbation Method	Filter Method
Enforce passivity by linearization and constrained optimization	Enforce passivity by applying filters
Minimize errors while enforcing passivity	Error is not minimized (for small passivity violations the correction to be done is small, hence error is small)
Due to inherent limitations of optimization and linearization, the algorithm may not be converged for given accuracy level	
Applicable to small systems	Applicable to very large systems

10. Additional Notes

FDNE is an advanced tool to model system characteristics. However this model should be used cautiously for accurate and meaningful results.

- FDNE assumes that the input parameters such as impedance or admittance are passive, e.g., in case of impedance data, the resistive part should be always positive at each frequency. A non-passive model may give unstable simulations.
- The input data such as impedance or admittance is defined for several frequencies (i.e., discrete data). The FDNE approximates the samples with a continuous impedance function ensuring the accuracy at each sample frequency. This continues function is defined from zero to infinity. So at any other frequencies, FDNE represents an impedance value defined by the continuous function. This will affect the accuracy of the simulation, when energized at that frequency. For example, let us assume that the input data file contains impedance parameters for 100 frequency samples ranging from 120 Hz to 5 KHz. The data does not contain power frequency sample (60 Hz). When the circuit (including FDNE) is energized with 60 Hz, FDNE represents an impedance (at 60 Hz) defined by the continuous function, which may not be accurate. This will affect the accuracy of the simulation. To overcome this, it is better to add additional impedance sample at 60 Hz (or in general any interested frequency).
- Ideally it is better if the data samples include a few low frequency points (e.g., 1 Hz) and power frequency (60 Hz) as well. This will improve the stability of the simulation (less likely to have passivity violations).
- It is assumed that the frequency dependent parameters are smooth in magnitude as well as angle. A non-smooth frequency response can lead to poor curve-fitting results and hence inaccurate simulation (e.g., adding artificial impedances to the existing smooth data may lead to poor curve-fitting results).

- The frequency-domain response is assumed to be close to a minimum-phase function. A non-minimum-phase function may require a very high order transfer function to achieve the specified accuracy (e.g., the transfer impedance/admittance of a long distributed-parameter transmission line may significantly deviate from a minimum-phase function).

- If impedance data is provided, it is converted to admittance data before the fitting process is started ($Y = Z^{-1}$). Here, it is assumed that the inversion of the impedance matrix is possible (it is not singular).

- It is assumed that the system matrix (Z or Y) is symmetrical (e.g., Z(i,j) = Z(j,i)).

11. Input Data File Format

See PSCAD help for FDNE Model Input Data File Format for all parameters except sequence impedance parameters.

11.1. The sequence parameters

The input data file contains sequence impedances for three phase system (i.e. only for three port), The file format is:

PSCAD V5.0 master library only

Frequency (Hz), real(Z1), imag(Z1), real(Z0), imag(Z0) ! Note that Z1 and Z0 are sequence parameters in ohms.

e.g,

20, 2.395, 23.124, 1.83, 32.144

50, 4.355, 33.114, 1.34, 68.145

PSCAD V5 intermediate library (and future versions)

Number of ports

Number of frequency samples

Frequency (Hz), real(Z1), imag(Z1), real(Z0), imag(Z0) ! Note that Z1 and Z0 are sequence parameters in ohms.

e.g,

3

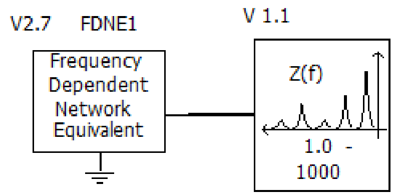
200

20, 2.395, 23.124, 1.83, 32.144

50, 4.355, 33.114, 1.34, 68.145

Support for Harmonic impedance solution

FDNE can be directly connected to the Harmonic impedance solution (see scan_FDNE.pscx). **Note that PSCAD Harmonic impedance component in master library does not work. You have to use intermediate library Harmonic impedance component.**



12. FAQ

Q1. How do I know that FDNE is accurate?

1. In the Configuration, set "detailed log file" to "create"
2. In the PSCAD temporary folder for the case, open log file (.*log). Check the maximum fitting error as a percentage. If the fitting error is too high, the simulation may be not accurate and there can be increased chance of unstable simulation. To reduce fitting error, increase the maximum order of the function and check the input data.
3. You can also check the " _Y_MAG.out" and "_Y_ANG.out" files. These files contain the actual and fitted data (magnitude and angle). It is better to plot the actual and fitted admittance functions as a function of frequency and see if the fitted function is in close agreement with the actual function (based on given data).
4. You can also connect the Harmonic Impedance component to compare impedance parameters for defined frequency range.

Q2. How do I select the frequency range for passivity identification?

It depends on the highest transient in the simulation. For example, if you are studying lightning surges, the highest frequency can be 1 MHz and the minimum frequency can be 0.5 Hz or less. The program checks the passivity violations for the number of frequency samples within the lowest and highest frequency range.

Q3. When to enable passivity?

If the time domain simulation is unstable, you can enable passivity enforcement to enforce stability.

Q4. Passivity algorithm (perturbation method) does not work:

The algorithm is based on linearization and constrained optimization. These algorithms work fine if the passivity violations are small.

Q5. There-phase configuration

If the parameters (e.g. impedance/ admittance) are decoupled (e.g. there are no mutual between phases or only positive sequence is available), it is better to use three independent FDNEs (one for each phase) instead of one FDNE (dimension 3) to represent three phases.

13. References

For more details, please see the following references:

[1] B. Gustavsen, A. Semlyen, "Rational approximation of frequency domain responses by vector fitting," IEEE Trans. Power Del., Vol. 14, No. 3, July 1999.

[2] B. Gustavsen, "Improving the pole relocating properties of vector fitting," IEEE Trans. Power Del., Vol. 21, No. 3, July 2006.

[3] B. Gustavsen, C. Heitz, "Fast realization of the modal vector fitting method for rational modeling with accurate representation of small eigenvalues," IEEE Trans. Power Del., Vol. 24, No. 3, July 2009.

[4] B. Gustavsen, H. M. Jeewantha De Silva, "Inclusion of rational models in an electromagnetic transients program: Y-parameters, Z-parameters, S-parameters, Transfer functions," IEEE Trans. Power Del. Vol. 28, No. 2, April 2013.

[5] Fast Passivity Enforcement for Pole-Residue Models by Perturbation of Residue Matrix Eigenvalues, BjØrn Gustavsen, IEEE Transactions on Power Delivery, Vol. 23 , No 4 , Oct. 2008.

[6] B. Gustavsen and C. Heitz, "Modal Vector Fitting: A Tool For Generating Rational Models of High Accuracy With Arbitrary Terminal Conditions," in IEEE Transactions on Advanced Packaging, vol. 31, no. 4, pp. 664-672, Nov. 2008, doi: 10.1109/TADVP.2008.927810.

14. Application example

14.1. Example 1

In electromagnetic transients studies, only a limited part of a large network system is usually required to be modeled in detail. The computation time can be remarkably saved by representing the remaining part of the system by a reduced network equivalent. In this example, FDNE can be used to model a reduced network equivalent circuit.

Identification of Study area

In IEEE example (Original_network.pscx), the network is divided in two segments. Study area is the retained area for detailed transient studies. The external area will be later replaced with FDNE. The boundary buses are WINNEBAGO3 and KOSSUTH.

Impedance parameters using Harmonic impedance solution

In the Scan_network.pscx, impedance of the external area is measured for frequencies ranging from 0 to 2000 Hz in 10 Hz increments. The Impedance "Output Type" is set to Phase Impedance". In determining the frequency range, following factors needs to be considered.

a. Frequencies that are interested in the study

b. Accuracy of the curve-fitting in FDNE

Some complicated networks may contain many resonance points when plotted impedance as a function of frequency. This requires a very high order transfer function in curve-fitting of FDNE leading to problems such slow simulation and possible unstable simulations. The upper bound of frequency range can be reduced, until the curve-fitting results are satisfactory. This is a trial and error approach.

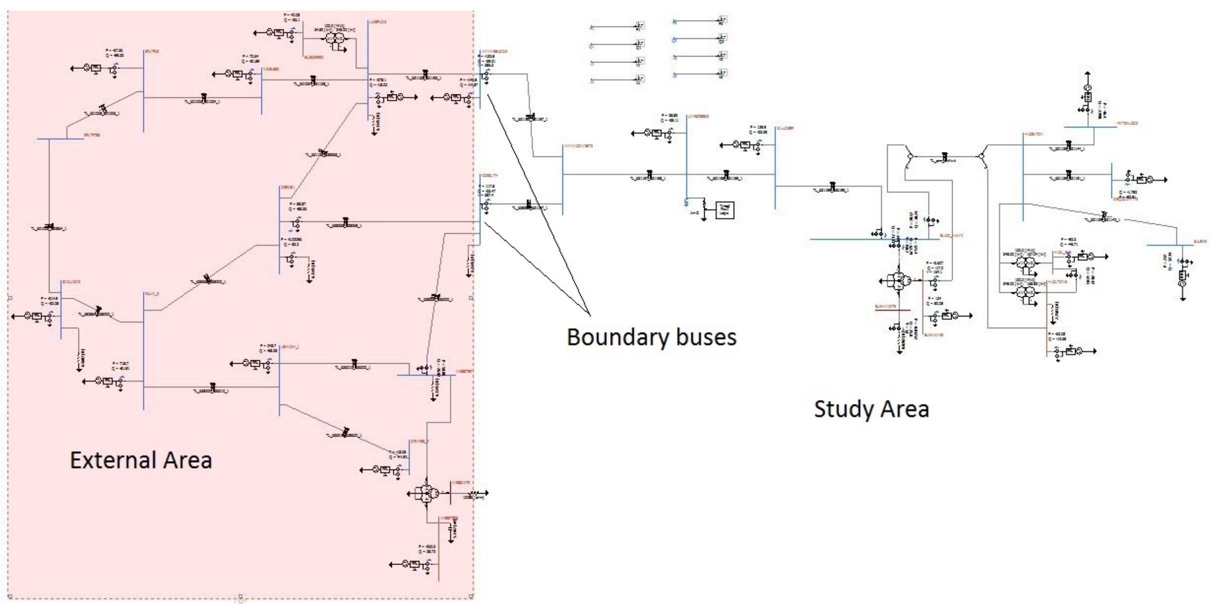


Figure 1: Original network

FDNE to represent external area

In FDNE_network.pscx, the external area is replaced with FDNE. The Data format is set to "From Harmonic Impedance component". The total number of ports is 6 (the dimension of the external network is 6 as seen from boundary buses WINNEBAGO3 and KOSSUTH).

Check log files

The "Detailed log file" is set to "Created". Run the simulation and go to the PSCAD case temporary directory. Open FDNE*.log file. This file contains information of any errors and curve-fitting results.

Maximum Fitting Error Requested:	0.1000 %
Maximum Number of Poles:	30
Maximum Fitting Error:	**0.0923%**
Number of Poles:	**21**

The order of the transfer function is 12 and the fitting error is less than 1% (0.7896%). You can also plot actual and fitted frequency dependent admittance and see if the results are satisfactory (see FDNE*_Y_MAG.out, FDNE*_Y_ANG.out)

Compensate for power sources

The FDNE only represents the passive equivalent network of the external area. To maintain correct power flow, the effect of active power sources in external area is approximated by defining the terminal conditions at boundary buses. In Original_network.pscx, a multi-meter is placed (the direction is away from external area) to measure P,Q,V and angle. At steady state, the terminal values (per phase) can be measured as,

For boundary bus WINNEBAGO3 (nodes 1 to 3)

Active power, P = -132.5/3

Reactive Power, Q = -39.21/3

Voltage, V = 356.3/sqrt(3)

Angle of voltage, A = -37.77 deg

For boundary bus KOSSUTH (nodes 4 to 6)

Active power, P = -117.5/3

Reactive Power, Q = -23.47/3

Voltage, V = 357.4/sqrt(3)

Angle of voltage, A = -36.47 deg

Hence the power injection data file is (PQVD_60.txt),

```
!   Voltage, angle P and Q at terminals of FDNE
6  ! 6 ports/nodes
1  ! only one frequency
0.1 ! ramp time in seconds for current injections
60.0 ! frequency
  205.7099  -37.7700  -44.1667  -13.0667 ! V, angle, P,Q  respectively for node 1
  205.7099 -157.7700  -44.1667  -13.0667 ! V, angle, P,Q  respectively for node 2
  205.7099   82.2300  -44.1667  -13.0667
  206.1776  -36.4700   39.2000   -7.8233
  206.1776 -156.4700   39.2000   -7.8233
  206.1776   83.5300   39.2000   -7.8233
```

14.2. Example 2

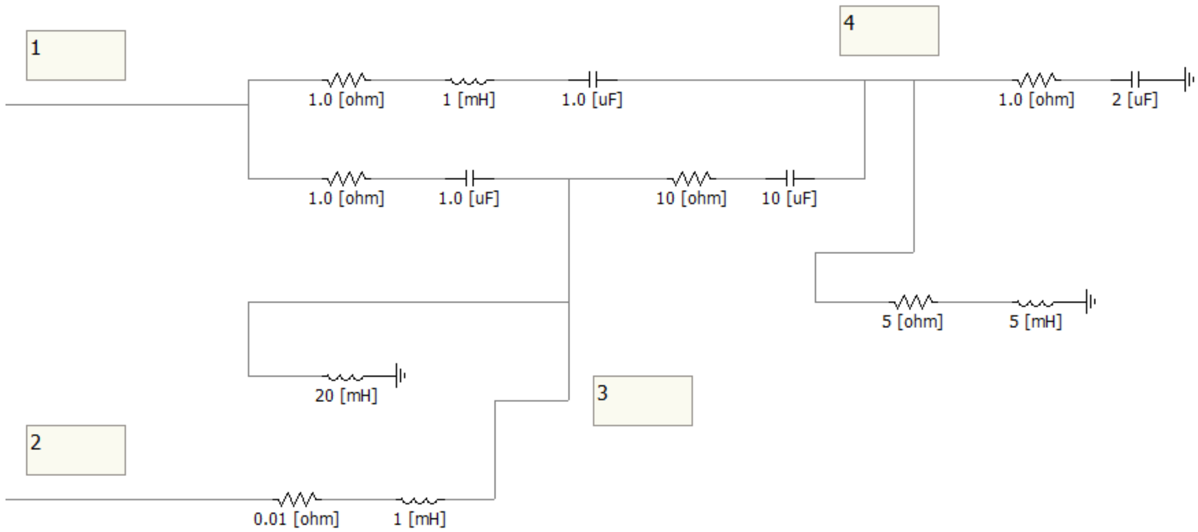


Figure 2: The RLC network

In this simple example (simple_network.pscx), the above RLC network is represented using FDNE and compared with original RLC network. The boundary buses are 1 and 2. The network is represented in the following text files for different data format.

File name	Data format
Z1.txt	Impedance Parameters
Y1.txt	Admittance Parameters
S1.txt	Scattering Parameters
ABCD1.txt	Admittance as ABCD Parameters
SABCD1.txt	Scattering as ABCD Parameters

DOCUMENT TRACKING

Rev.	Description	Date
0	Initial	09/Oct/2021