EMTP-EMTPWorks Simulation Options

Jean Mahseredjian, 15/10/2014 15:10:00
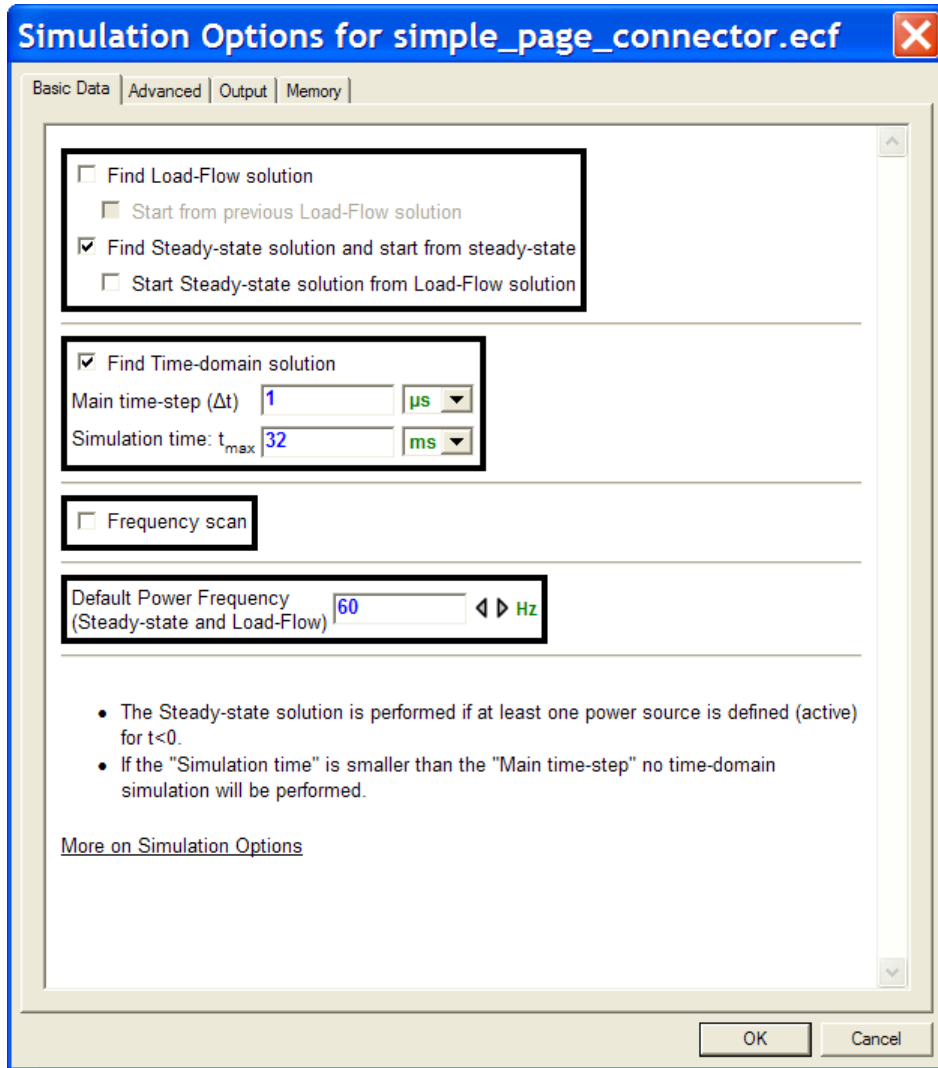
Simulation
Options

1 Introduction

The Simulation Options are available through the menu "Simulate>Advanced>Simulation Options" or through the "Simulation Options" device from the options.clf library.
The Simulation Options are used to used to select numerical solution method data. Most of the available options can be left to their default values.

2 Basic Data tab

The first data tab is for entering the most useful data for conducting a simulation.

In a given generic electrical network, EMTP distinguishes between power devices and control devices. The power devices are electrical devices with a specific model. The control devices are block-diagram based, they are not represented using an electrical circuit, but mathematical and logical equations. The control devices can be also used for creating model equations. There is a specific measurement (sensor) and actuator interface between the control devices and the power devices. An assembly of control devices is named a control system.

Simulation Options for simple_page_connector.ecf

Basic Data | Advanced | Output | Memory

- ☐ Find Load-Flow solution
  - ☐ Start from previous Load-Flow solution
- ☑ Find Steady-state solution and start from steady-state
  - ☐ Start Steady-state solution from Load-Flow solution

- ☑ Find Time-domain solution
- Main time-step (Δt) [1] [µs ▼]
- Simulation time: t_{max} [32] [ms ▼]

- ☐ Frequency scan

- Default Power Frequency (Steady-state and Load-Flow) [60] ◀ ▶ Hz

- The Steady-state solution is performed if at least one power source is defined (active) for t<0.
- If the "Simulation time" is smaller than the "Main time-step" no time-domain simulation will be performed.

More on Simulation Options

[OK] [Cancel]

EMTP has 4 distinct simulation options (see also tooltip for each option):

❑ Load-Flow solution

The electrical network equations are solved using complex phasors. The active (source) devices are only the Load-Flow devices (LF-devices). A load device is used to enter PQ load constraint equations.

Only single (fundamental) frequency solution is achievable in this version. The solution frequency is specified by 'Default Power Frequency' and used in passive network lumped model calculations.

Future EMTP versions will include a harmonic load-flow.

The same network used for transient simulations can be used in load-flow analysis. The EMTP Load-Flow solution can work with multiphase and unbalanced networks.

The control system devices are disconnected and not solved.

This simulation option stops and creates a solution file (Load-Flow solution data file). The solution file can be loaded for automatically initializing anyone of the following solution methods.

The 'Start from previous Load-Flow solution' is used to restart the Load-Flow from a previous solution. This option is not useful when the solution is found without convergence problems and the number of iterations is low. It may help to reduce the number of iterations when trying to improve convergence tolerance or provide better initial conditions for complex cases.

To learn more about this option, click on its help link (see tooltip).

❑ Steady-state solution

The electrical network equations are solved using complex phasors. All devices are given a lumped circuit model. This option can be used in the stand-alone mode or for initializing the time-domain solution.

A harmonic steady-state solution can be achieved.

The control system devices are disconnected and not solved.

Some nonlinear devices are linearized or disconnected. All devices have a specific steady-state model.

The steady-state solution is performed if at least one power source device has a start time (activation time) lower than 0.

The "Start Steady-state solution from Load-Flow solution" is used to initialize the steady-state solution from proper Load-Flow solution. This is a useful option for performing complete simulations from Load-Flow to time-domain.

❑ Time-domain solution

The electrical network and control system equations are solved using a numerical integration technique.

All nonlinear devices are solved simultaneously with network equations. A Newton method is used when nonlinear devices exist.

The solution can optionally start from the steady-state solution for initializing the network variables and achieving quick steady-state conditions in time-domain waveforms.

The steady-state conditions provide the solution for the time-point t=0. The user can also optionally manually initialize state-variables.

The first time-domain solution is found at $t = \Delta t$ or $t = \Delta t / 2$ depending on the selected numerical integration method explained below.

❑ Frequency scan solution

This option is separate from the two previous options. All source frequencies are varied using the given frequency range and the network steady-state solution is found at each frequency.

EMTP uses fixed time-step numerical integration for solving the differential equations of the simulated networks. The integration time-step Δt must be selected to represent the phenomenon with the highest frequency in the network. The smaller is the Δt, the higher is the precision of the computations and the slower is the computational time. In some cases the user might change the Δt to visualize its impact before settling for a final value. Generally speaking, the Δt should be 10 to 100 times smaller than the period of the highest frequency.

The time-step Δt is the main time-step, since two integration techniques selectable on the next tab may apply halved time-step $\Delta t / 2$ integration under some conditions. The time-points are calculated using double precision real numbers, but due to computer precision and although EMTP controls the error accumulation in the time variable t, some time drift may still occur in the time-mesh. It is not recommended to use time-steps smaller than 1e-10.

The Simulation time t_{max} is the maximum simulation time. If $t_{max} < \Delta t$ then no time-domain simulation will be performed.

The steady-state and time-domain options can be selected together or independently. The frequency scan option can be selected alone. The frequency scan parameters are self-explanatory and tooltips are available. Some devices, such as frequency dependent transmission line models, provide separate data for each frequency. The scale used in this section must match the scale used for generating the data of such models.

The Default Power Frequency parameter is entered for allowing EMTP to convert data based on the frequency variables ω or f.

3 Advanced data tab

3.1 Numerical integration techniques

In time-domain it is needed to find a numerical solution for a set of differential equations. Generally speaking it is needed to find the solution for an ordinary differential equation (ODE) system given by:

$$\frac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x}, t)$$

$$\mathbf{x}(0) = \mathbf{x}_0 \tag{1}$$

where bold characters are used to denote vectors.

Three numerical integration techniques are available in EMTP.

The Trapezoidal method solution of the scalar version of equation (1) at a given time-point t is given by:

$$x_t = x_{t-\Delta t} + \frac{\Delta t}{2}\left[f_t + f_{t-\Delta t}\right] \tag{2}$$

This is an A-stable technique: remains stable when the actual solved system is stable.

The fundamental principle on which EMTP is based, is the fact that equation (2) can be used to discretize devices with differential equations. If the inductor (connected between nodes k and m) equation

$$v_{km} = L \frac{di_{km}}{dt} \tag{3}$$

is discretized with the trapezoidal algorithm equation (2) it becomes:

$$i_{km_t} = \frac{\Delta t}{2L} v_{km_t} + \frac{\Delta t}{2L} v_{km_{t-\Delta t}} + i_{km_{t-\Delta t}} = \frac{\Delta t}{2L} v_{km_t} + i_{history}$$

This is expressed by the circuit equivalent of Figure 1. The same principle can be applied to the capacitor.
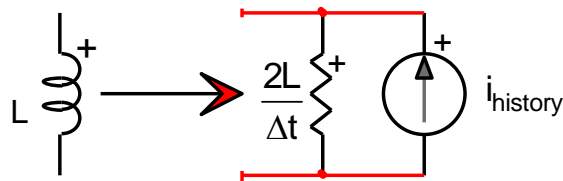

Figure 1 The discrete circuit equivalent of an inductance

After discretizing all devices, EMTP solves a set of algebraic equations in the form:

$$\mathbf{Ax} = \mathbf{b} \tag{4}$$

This system is solved at each time-point with the history current sources and independent current sources continuously updated in the **b** vector.

The fixed time-step principle is demonstrated in Figure 2. The solution between time-points is interpolated. The solution at t=0 is either 0 (zero-state), automatically found from a phasor (steady-state) solution or/and imposed manually. The first time-domain solution is found at $t = \Delta t$. Fixed time-step provides the best computational efficiency, but does not allow to control precision or practically speaking cannot adjust itself for the variable range of frequencies in a circuit. If the selected time-step is too large, some transients can be missed. It is needed to select the fixed time-step considering the highest frequency in a system. The argument against variable time-step is that when the fixed time-step is sufficiently small it is much faster than a variable time-step approach, requires much less memory and can achieve the same precision.
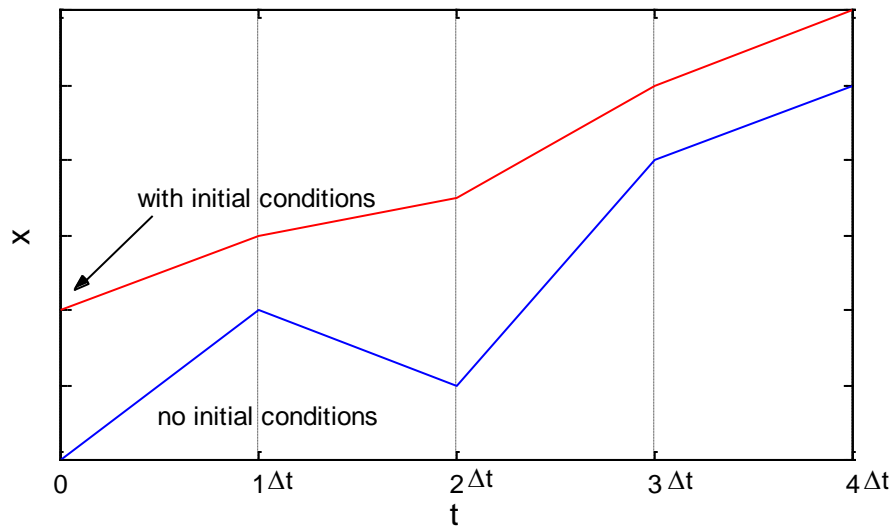
Figure 2 The fixed time-step principle

3.1.1 Trapezoidal integration option

This integration method will behave correctly in almost all EMTP simulation cases. An example of circuit is shown Figure 3. The switch is closed at t=0 and an energization transient is observed. The first time-points of the inductance voltage waveform are shown in Figure 4. A time-step of $\Delta t = 10\mu s$ is used.
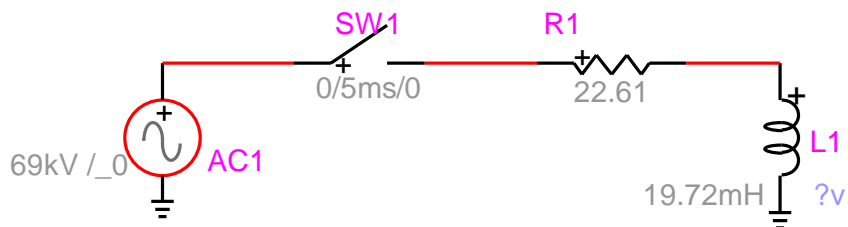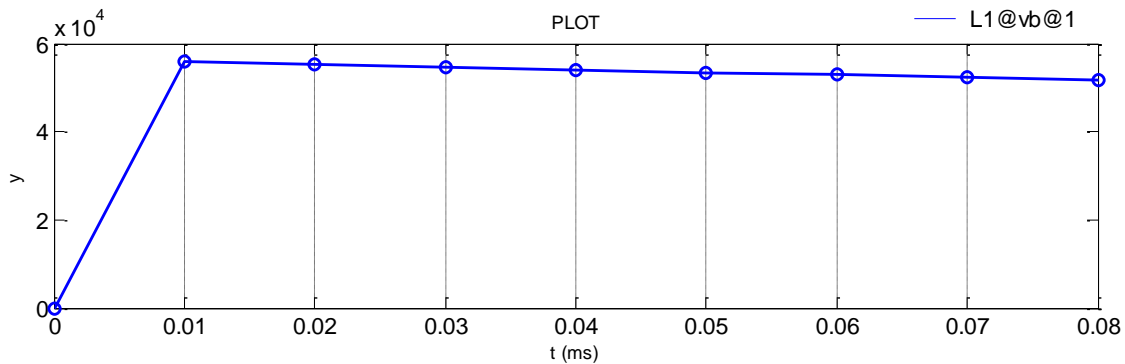

Figure 3 Test circuit

Figure 4 Inductance voltage waveform time-points for the circuit of Figure 3

In a second test, the switch is initially closed and allowed to open after 5ms. The waveform shown in Figure 5 starts from a steady-state solution at t=0. There appears to be a problem when the switch opens. The inductance voltage shows numerical oscillations. Zooming on these oscillations in Figure 6 shows their typical pattern for the integration step of $\Delta t = 10\mu s$. This is the main limitation of the trapezoidal integration technique: it oscillations at state variable current or voltage discontinuities. Although this problem can be disputed as a modeling choice problem, since normally there will be some stray capacitance to ground for providing current continuity, it is mathematically feasible to automatically eliminate numerical oscillations by reverting to the Backward Euler method at discontinuity detection. This is the topic of the next section.
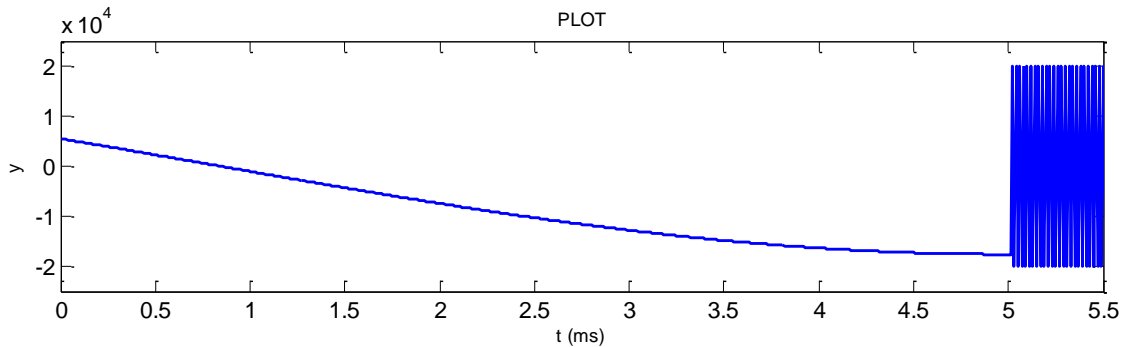

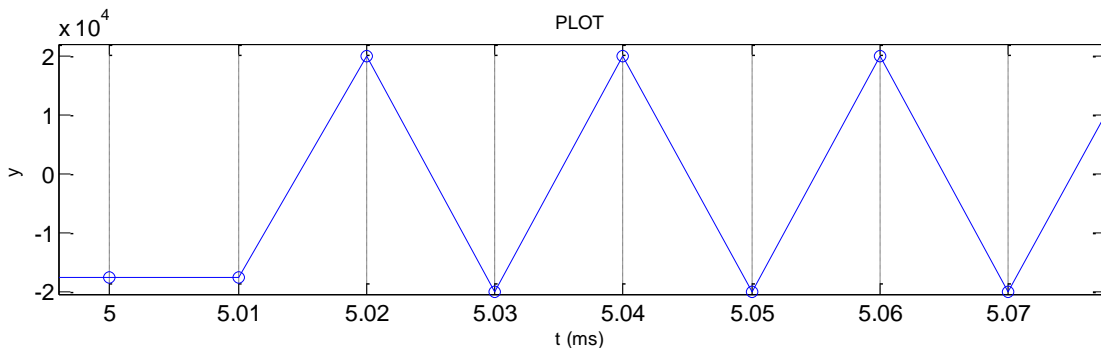**Figure 5 Inductance voltage waveform starting from steady-state**

Figure 6 Numerical oscillations in the inductance voltage waveform

3.1.2 Trapezoidal and Backward Euler integration option

The Backward Euler integration technique for the scalar version of equation (1) is given by:

$$x_t = x_{t-\Delta t} + \frac{\Delta t}{2} f_t \tag{5}$$

Contrary to the trapezoidal integration method, this technique does not carry a non-state variable term in its history, the inductance has only current history and the capacitor has only voltage history. That is why it will not encounter numerical oscillations at discontinuities.

The "Trapezoidal and Backward Euler" integration option is the default option. It is based on solving with the trapezoidal method and switching to Backward Euler only at discontinuities. The waveform of Figure 7 shows that at discontinuity point detection, the trapezoidal method is switched into two $\Delta t / 2$ Backward Euler steps. The simulation resumes with the standard trapezoidal integration after the discontinuity.
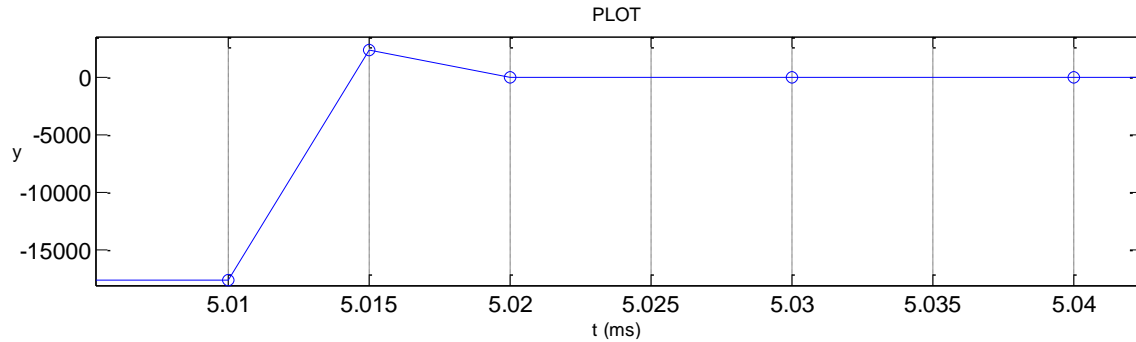
Figure 7 Elimination of numerical oscillations in the inductance voltage waveform

Discontinuities can be caused by start-stop events and by slope changes in nonlinear functions.
It is noticed that this option automatically starts with the Backward Euler method for the solutions at $t = \Delta t / 2$ and $t = \Delta t$.
The extra $t + \Delta t / 2$ solution point is called an intermediate solution.
In this version of EMTP, discontinuities are triggered only by power devices.
When decoupled circuits are available in the same design, they are solved using the same matrix and there is no internal distinction in EMTP. Switching to Backward Euler in one circuit will force the other circuit to do the same although only one circuit encounters a discontinuity.

3.1.3 Backward Euler integration option

This the less useful of the three options. The Backward Euler method does have numerical oscillation problems, but it is less precise than the trapezoidal method and that is why it is not recommended. The simulation of the circuit in Figure 3 using this option is shown in Figure 8. It appears that the actual time-step is always $\Delta t / 2$. Using this method is equivalent to the previous method going through discontinuity treatment on a continuous basis.
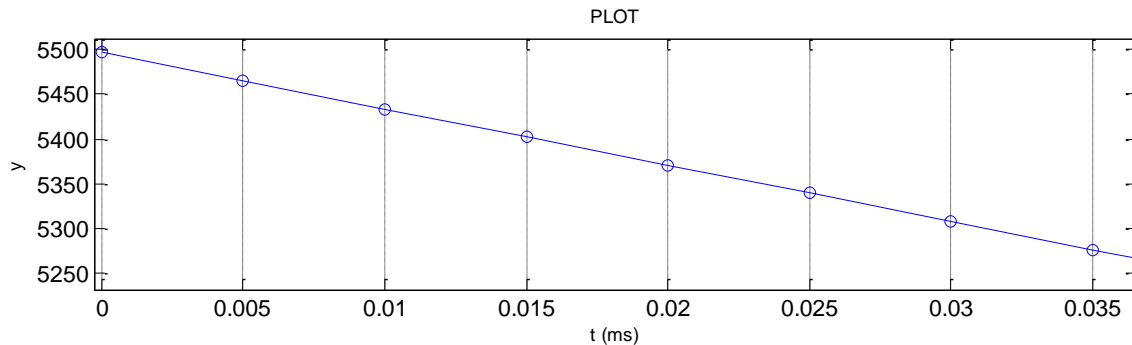

Figure 8 Simulation with Backward Euler integration, inductance voltage waveform

3.2 Solver for control devices

The settings of this section are global and apply to all control diagrams contained in a simulation.

3.2.1 Iterative Solver

The Iterative Solver is selected by clicking on the checkbox "Select Iterative solver for controls". Two self-explanatory parameters "Maximum number of iterations" and "Convergence tolerance" are available to control

the convergence process. This is option is not selected by default, since in most cases the standard solver (single pass approach) is able to find the correct solution. Selecting this option will increase the computation time.

The decision to iterate is dependent on the contents of the controls included in a simulation.

The control solver calculates in sequence the output value of every control element. When a control diagram includes no closed loops whatsoever, a single pass through the sequence of equations provides immediately a correct solution. Such an example is shown in Figure 9.
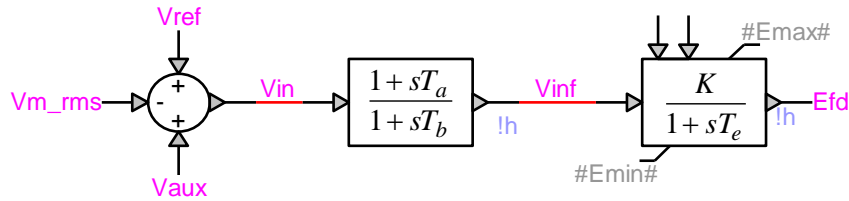

Figure 9 Control diagram without closed loops

When closed loops are present (Figure 10), but when such loops are only graphical and not mathematical because of the presence of delay elements in the loop (the output of a delay element does not depend on the present value of its input), a single pass again provides a correct solution.
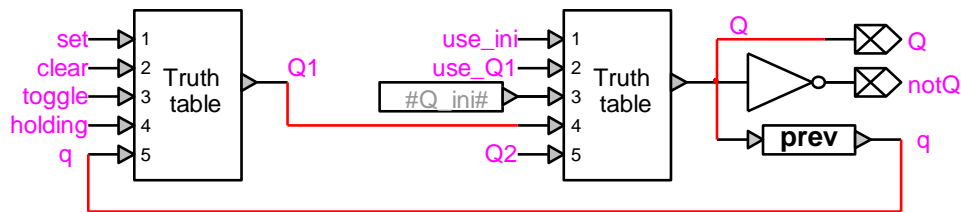

Figure 10 Control diagram with delay in closed loop

When mathematical closed loops (Figure 11) contain only linear relations between inputs and outputs, a single pass also provides immediately a correct solution, because the solver accounts automatically for linear loops.
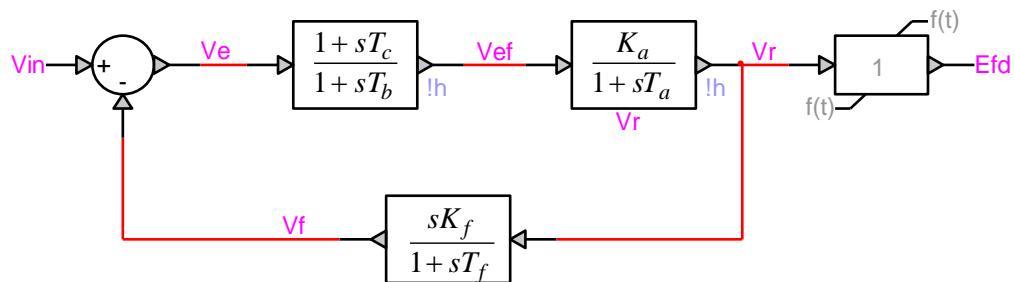

Figure 11 Linear closed loop

What remains are loops that contain nonlinear relations between inputs and outputs of one or more of their elements, such as in the example of Figure 12.

In many cases, the choice of a sufficiently-small time-step ensures that the variation in the value of a signal is itself sufficiently small (or relatively slow) so as not to jeopardize reaching an overall satisfying solution. In this

case, a one-pass solution may be locally inexact, but may nevertheless produce results that are globally correct if accepted slight shifts in the value of a signal or in the time at which a signal reaches a particular value. For example, a plot of the signal will show an overall correct shape, with slight vertical or horizontal variations in the instantaneous amplitude of the signal as compared with its exact value with respect to time. This is the rationale for the rule of thumb which recommends to re-run a simulation with a smaller time-step just to verify that the results thus obtained are not qualitatively different.
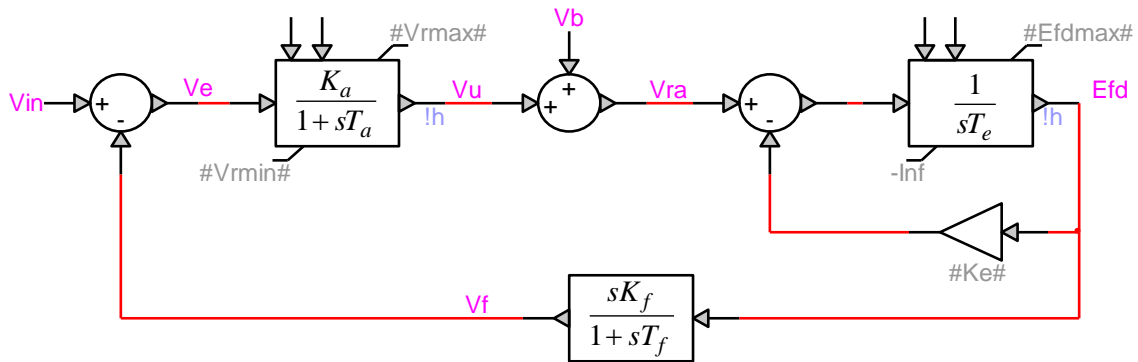

Figure 12 Nonlinear closed loop

In other cases where using a small-enough time-step may have provided an adequately-correct solution, the total solution cost may be a justification for selecting an iterated solution, which may provide correct or adequate solutions at much larger step values. This highlights the trade-off between step size and iteration.

Finally there are situations where using a small time-step is not sufficient for obtaining a satisfactory one-pass solution of nonlinear closed loops. This is where an iterated solution will make the difference between a correct solution, and an incorrect or even impossible (divergent or oscillating) one.

The control solver presently uses a Newton-type algorithm for controlling the convergence of an iterated solution.

3.2.2 Options

These options are available in the Advanced data tab.
- ❑ **Select Iterative solver for controls**: Turns on the iterative solver. Default is off and acceptable for most cases (see explanations above).
- ❑ **Allow iterations at t=0**: Turns on the iterative solver only for the first simulation time-point. This option allows a better start for the non-iterative solution and eliminates preliminary oscillations leading into the correct solution. It provides a better initialization for the following simulation steps. Default is on.
- ❑ **Maximum number of iterations**: Used to enter the maximum number of iterations for the iterative process. When this number is exceeded the iterative solver signals a divergent solution and stops the simulation.
- ❑ **Convergence tolerance**: This relative tolerance is applied on unknowns between iteration steps to detect convergence.
- ❑ **Relaxation factor**: Factor used to relax convergence. It is multiplied by the Convergence tolerance, as a last resort, when the maximum number of iterations is exceeded at a given solution time-point. Such a deception is acceptable and can provide correct global solution.
- ❑ Increased precision for discontinuities: This option is used to increase the precision of simulations when Step solution mode signals are used. The Ramp or Step solution mode of a primitive control device can be selected from its "Misc" data tab. Increased precision will cost more computer time.
- ❑ **Allow Step Solution mode**: global option, if you turn this option off, the Step Solution mode for control devices will not be allowed even if a device has this mode selected.

❑ **Show Step mode signals**: is used for control system signal scopes. When step mode signals are present, the scopes will show stepped transitions. Turning this option on doubled the size of the binary plot file. The "Misc" tab of primitive control devices (from control.clf) allows selecting the Ramp or Step solution modes. More help on this option can be found in the help section of this tab.

❑ Allow iterations at t=0: Select this option to make the Iterative solver turned on only at the first solution step at time t=0.

❑ **Maximum number of control system re-solve**: Maximum number of times the control system equations are resolved to account for state-change events in control devices. A reset or logical operation is a typical state change event. A limit detection is also a state change event. This option allows handling event sequences in looped sequences of elements when the iterative solver is off.
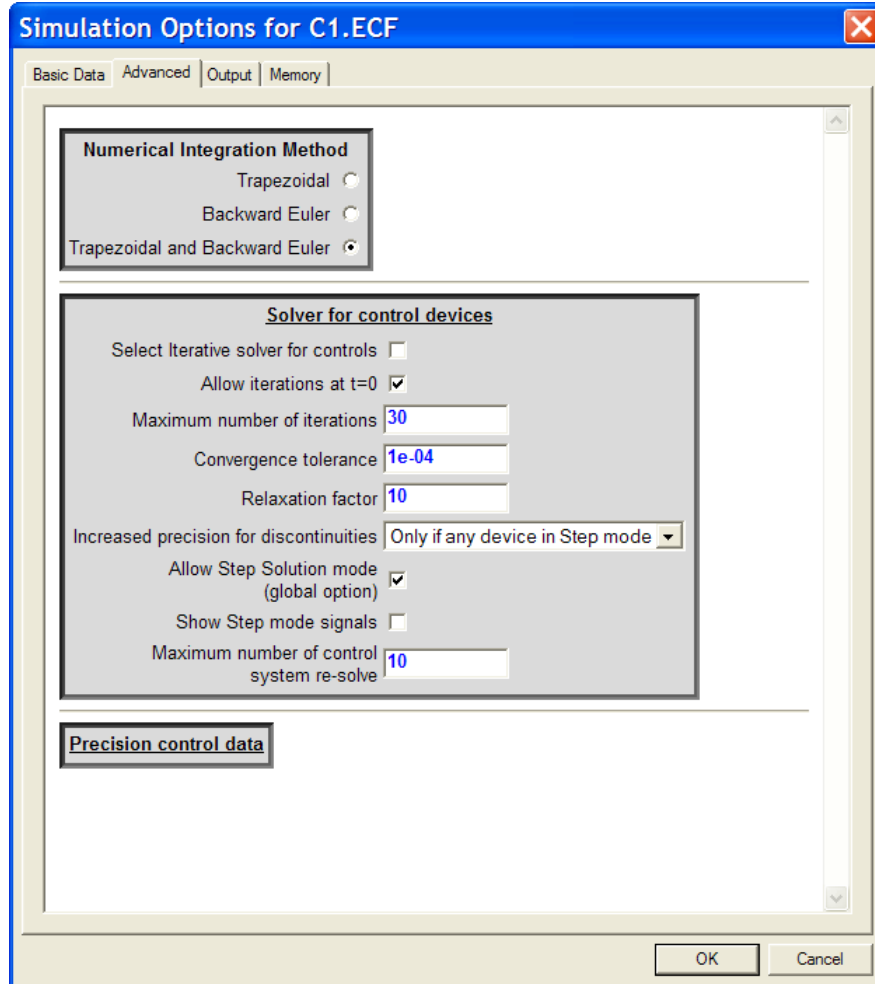
3.3 Precision control data

This section provides access to simulation control parameters that can become useful mostly for some unique cases and require advanced understanding of the underlying possibly numerical problem. The users should not normally modify this data.
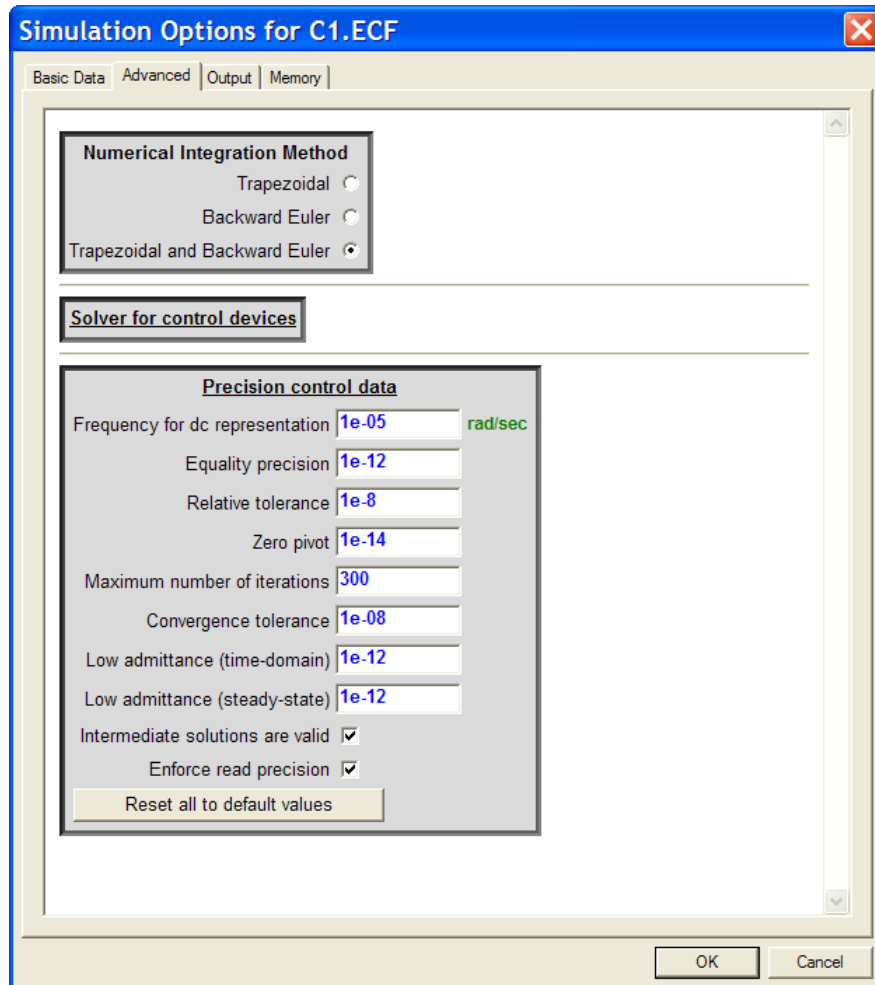
The "Frequency for dc representation" is used for the steady-state solution with active dc sources. It is impossible to use zero, since it will create poor conditioning in the system matrix and fail in most cases.

The "Equality precision" P is used as an absolute tolerance for equality precision between two real numbers. The "Relative tolerance" ρ is used as a relative tolerance for equality precision between two real numbers.
EMTP has a service module for interval precision computations. For each point δ on the real axis, EMTP defines a proximity margin $\Delta\delta$ applied at each side of δ. The size of $\Delta\delta$ is relative to the value of δ: $\Delta\delta = \mathrm{abs}(\delta)\rho$ with the exception that near zero, the value of $\Delta\delta$ has a lower bound of P.

The "Zero pivot" is the value used for signaling zero pivot conditions in linear algebra problems.

The "Maximum number of iterations" is a global variable used in the iterative Newton method for solving nonlinear functions. The user may increase this number when convergence problems are encountered.

The "Convergence tolerance" is a global variable used for detecting convergence in the iterative Newton method for solving nonlinear functions. Devices may also have a local convergence tolerance parameter. This tolerance is not applicable to control system devices.

The "Low admittance" specification is available separately for time-domain and steady-state. This parameter is used in EMTP for eliminating zero pivot conditions in the electrical system matrix. When EMTP detects such conditions it sends a warning message:
Automatic Fixing Zero Pivot conditions in time-domain, possible causes: bad data or floating network.
In most cases this is not an important problem. It is symptomatic of poorly grounded electrical network. It can occur when a device has no connection to ground, when a transformer has a floating delta side or when switch type devices are connected in series. It occurs when a given node voltage may have an infinite number of solutions. EMTP uses the "Low admittance" parameter to correct such problems by artificially grounding a node through a high impedance value. There are cases where this may still fail and the user must fix the problem by changing the case to make it physically more realistic.

When an Intermediate solution occurs as in Figure 7, then such solution can create a high impulse condition which may trigger other events, such as a gap flashover due to a voltage impulse. The "Intermediate solutions are valid" checkbox allows turning off or on the significance of the intermediate solution in threshold testing.

The "Enforce read precision" checkbox is used to turn on extra precision control features when inputting real numbers from the Netlist. This option is useful for more precise (less noisy) data conversion due to units.

4 Output tab

All simulations have input data and output data. There are two types of outputs: waveform data and ASCII output. The waveforms are from selected scopes.

Tooltips can be used to obtain more information on the options available in this tab. More information on output files can be obtained from the help section of the "Input Output files" device in options.clf library.

The first part of this tab is for controlling the output rates in saving waveforms. The normal fixed output rate means that waveform data is saved at every time-point. In some cases this can generate very large or extremely large binary files where waveform data is saved. The rate modification allows decreasing the binary file size.
In some other cases the user may wish to study only parts of the simulation in details. This service is provided by the "Variable output rate for waveforms" option.

It is recommended to leave the "High precision output" checkbox on. This makes EMTP save waveforms in double precision. It is automatically forced to be on when statistical analysis is turned on by the "Stat Options" device from the options.clf library.

The only available plot data file format in this version of EMTP is the "MPLOT" (also called "MCAT") format.

When the "Save scope names" option is turned off, scope data is referenced using device node names. It is not recommended to uncheck this option. This option is also enforced (turned on) by some simulation selections, such as the statistical analysis selection.

It is optionally allowed not to save intermediate time-points in waveform data through the "Save intermediate time-points" checkbox.

4.1 ASCII output options

In the ASCII output options, the user can select:
- ❑ HTML output: it is recommended to leave this option on.
- ❑ Dump decoded data: this checkbox makes EMTP dump the data it is decoding after assembling all subnetworks. If this option is on, EMTP will not perform any simulations. This option can allow debugging some complex designs with user defined scripting and special subnetwork functions.
- ❑ Dump compiled subnetwork data: allows to save an intermediate step in data file buildup. Same usage as the previous option.
- ❑ Dump developed subnetwork data: allows to save an intermediate step in data file buildup. Same usage as the previous option.

5 Memory tab

EMTP has fully dynamic memory and uses sparse matrix techniques. EMTP can solve very large systems. EMTP predicts and allocates memory according to the size of the solved network. There are however some network topologies that may fail the EMTP prediction techniques. In such cases an error message guides the user to increase the "Predicted number of nonzeros". This is a scaling factor multiplied by the number of rows in the main system matrix. It is recommended to increase by steps (20, 30…) to avoid using too much memory.

There are two more parameters that may be modified to increase available memory for sparse matrix storage.

The "Offset for sparse matrix storage (electrical network)" is used to increase sparse matrix memory for the electrical network. These are extra memory cells. It is recommended to increase by steps of 1000 cells and only when requested to do so by en EMTP error message.
The "Predicted number of nonzeros (control system)" is a scaling factor for control systems. It is recommended to increase by steps of 1 (from 5 to 6, for example) and only when requested to do so by en EMTP error message.

The "Predicted number of nodes" is not a limitation, it can just help the program to slightly speedup during initial data preparation stages.

6 Importance of steady-state initialization

The test case of Figure 13 is for performing a transient recovery voltage study on the breaker SW1. The single-phase fault must be applied when the network is in steady-state operation mode. If the steady-state solution is turned off, the time-domain solution starts from zero-state conditions and it is required to simulate for a very long period before the natural response of the system disappears and the system shows time-domain waveforms. It is also not obvious to predict how much simulation is needed. The volotage waveforms for BUS1 are shown in Figure 14.

The results with the steady-state solution turned on are shown in Figure 15. Almost perfect steady-state is achieved at simulation startup. The fault switch can be closed at any point to observe the related transients.
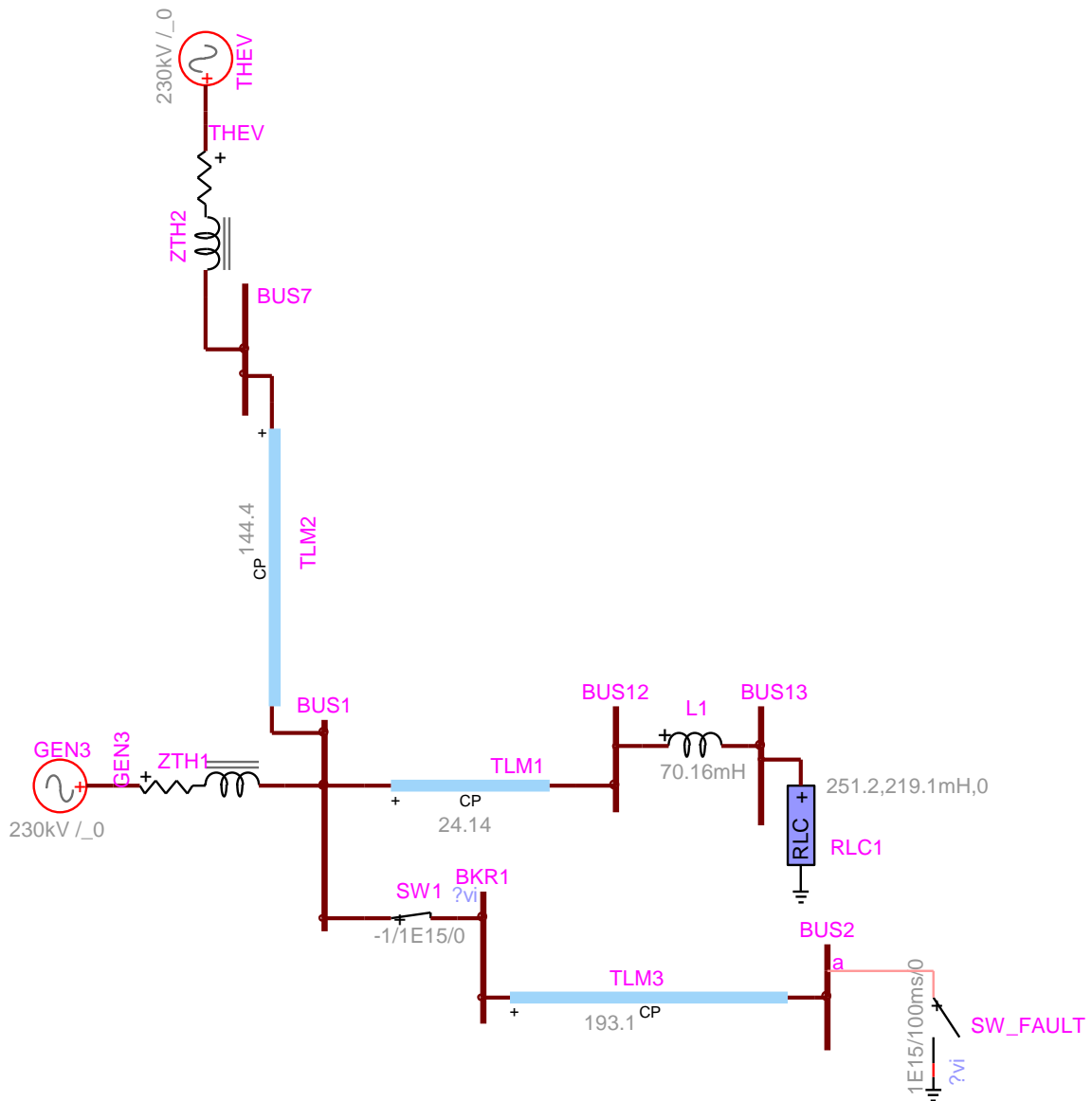
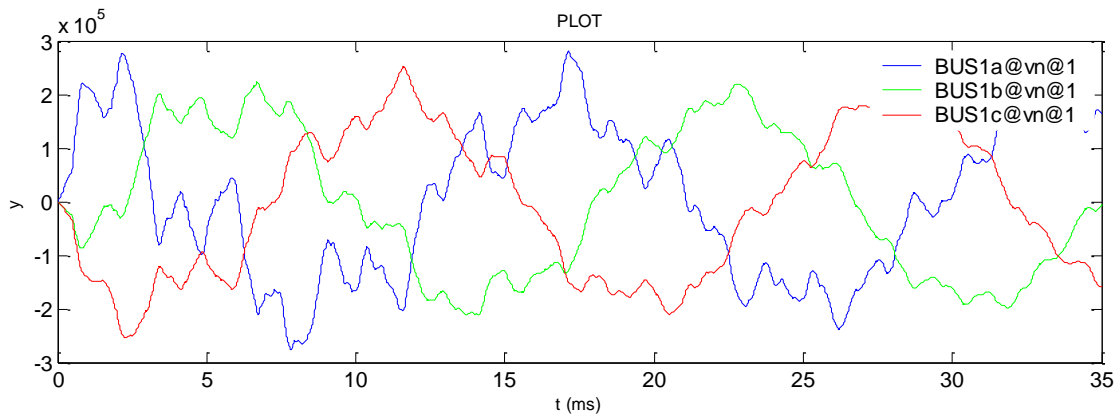**Figure 13 Test case for demonstrating initialization from steady-state (trv.ecf)**

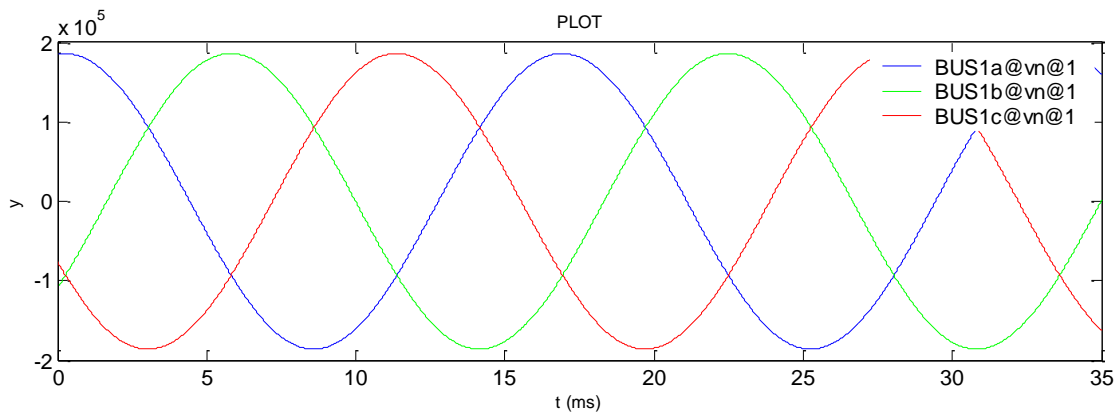**Figure 14 Transient waveforms at the BUS1 in Figure 13**

Figure 15 Steady-state solution in time-domain for BUS1 voltages in Figure 13

This version of EMTP can also compute a harmonic steady-state solution. An example is given in Figure 16. The sources of this test case have different frequencies. Source AC1 is at 60 Hz, source AC2 is at 180 Hz and source AC3 injects 360 Hz. The voltage of capacitor C2 is shown in Figure 17. It is in harmonic steady-state when the switch is closed. The harmonic sources are the current sources.
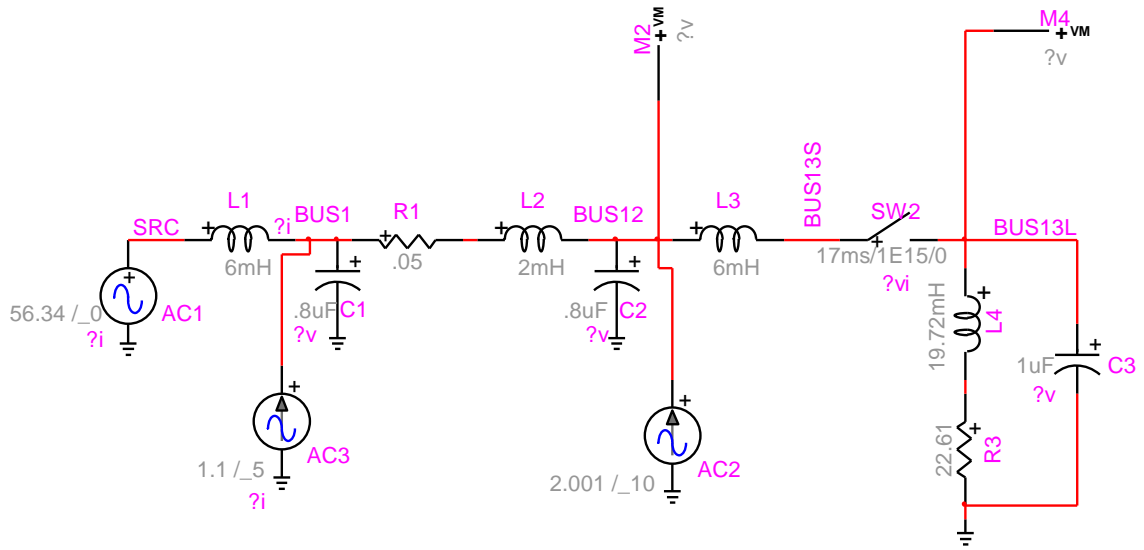
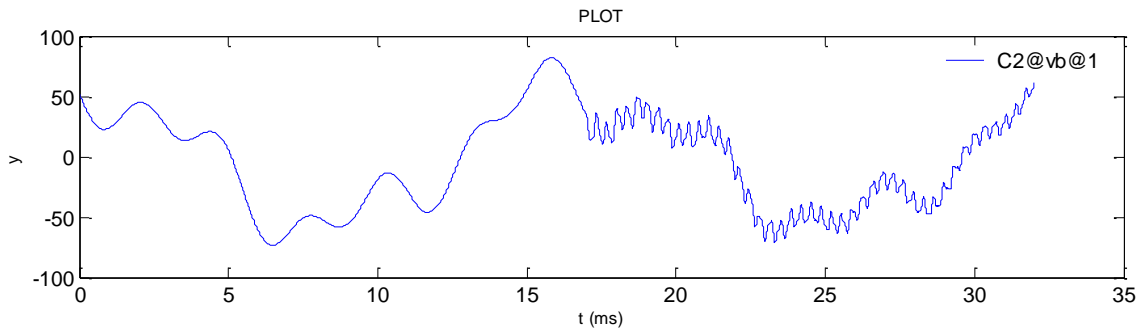**Figure 16 Example of initialization with harmonics (test2iwh.ecf)**

Figure 17 The voltage waveform for C2 in Figure 16

7 Frequency scan example

A "Frequency scan" selection is shown in Figure 18. The user can select both linear and logarithmic scales.

If a frequency scan is performed in the test case of Figure 16, then a steady-state solution is found at each frequency of the specified frequency range. The source amplitudes and phases are constant, but the frequencies vary. This option can be used to perform harmonic analysis. The results for the voltage measurement at the capacitor C1 are shown in Figure 19.
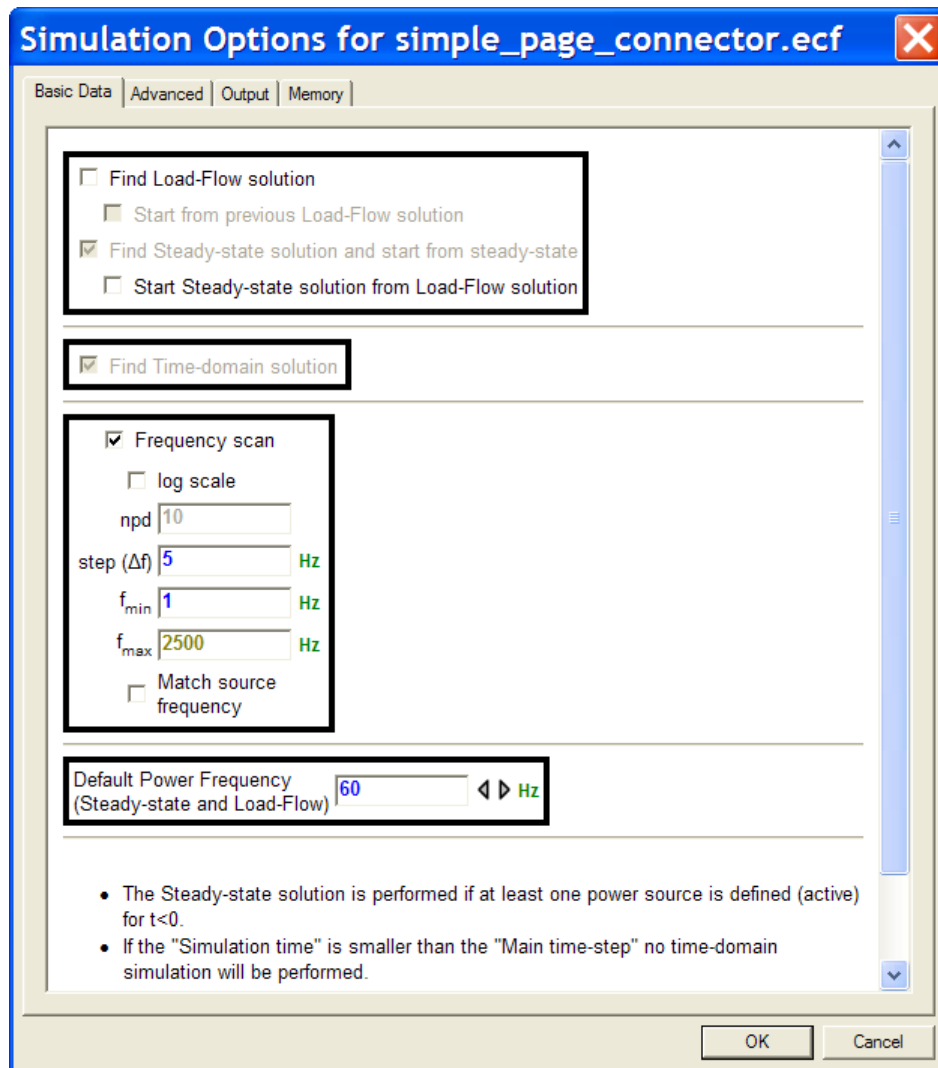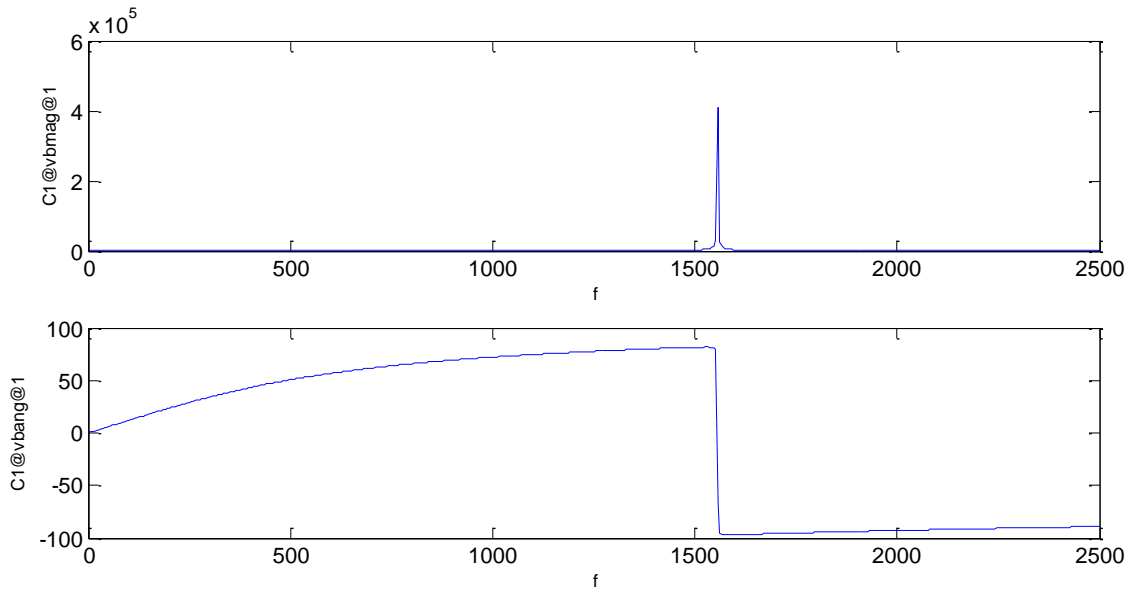

Figure 18 Frequency scan selection

Figure 19 Harmonic analysis for the circuit of Figure 16, C1 voltage and phase

Selecting the "Match source frequencies" option activates a source only when specified source frequency is matched in the frequency scan scale, the sources become inactive for all other frequencies. For the example of Figure 16, only 3 solution frequencies (source frequencies) will be sampled.

If it is needed to calculate the input impedance at a given time-point, the "Input Impedance" option from the options.clf library (see Figure 20) can be used from any point in the circuit. This device automatically kills voltage sources and current sources. The voltage sources are replaced by short-circuits and the current sources are replaced by open-circuits. The "Input Impedance" device can also work for 3-phase circuits.
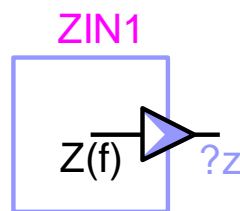

Figure 20 Input impedance calculation device