A R G E S I M   B E N C H M A R K S

Four Modelling Approaches for ARGESIM Benchmark C3 'Generalized Class-E Amplifier' implemented in Dymola

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Simulator: Dymola—**Dy**namic **Mo**deling **La**boratory—is suitable for modeling of various kinds of physical systems and the combination of systems of different domains. It supports hierarchical model composition, libraries of truly reusable components, connectors and composite acasual connections. Model libraries are available in many engineering domains.

Dymola has a powerful graphic editor for composing models. Dymola is based on the use of Modelica models stored on files.

Dymola has powerful experimentation, plotting and animation features. Scripts can be used to manage experiments and to perform calculations. Automatic documentation generator is provided.

Model: The basic class-E power amplifier was introduced by N.O. Sokal and A.D. Sokal in their classic paper from 1975. It is a switching-mode amplifier that operates with zero voltage and zero slope across the switch at switch turn-off. The actual numerical example is taken from J.C. Mandojana, K.J. Herman and R.E. Zulinski. They use the following equivalent circuit of a generalized class-E amplifier as a test example for a procedure to evaluate steady state boundary conditions by means of MAT-LAB. Figure 1 shows Class-E Amplifier: The component values are: VDC= 5 V, L1 = 79.9 μH, C2 = 17.9 nF, L3 = 232 μH, C4 = 9.66 μF and RL = 52.4Ω.

The time dependent resistor $R(t)$ models the active device acting as a switch with an ON-resistance of 0.05Ω and an OFF-resistance of $5M\Omega$. An extreme ON-resistance of value zero ohm will of course result
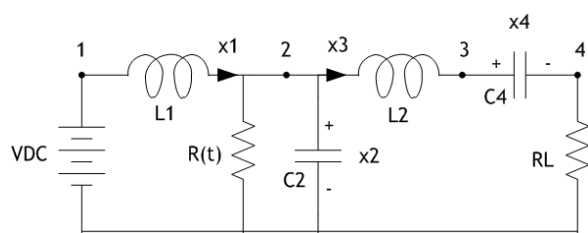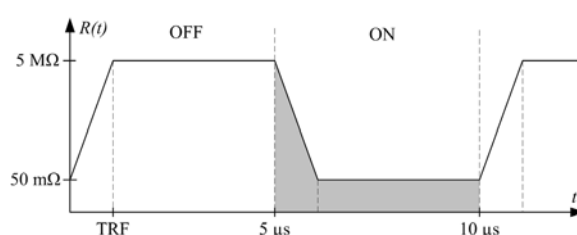

Figure 2. Time dependent resistor $R(t)$, not to scale.

in a pathological system i.e. the old story of what happens when an ideal capacitor with a certain charge is suddenly short circuited. Furthermore the *DC* voltage source will be short circuited through the ideal coil $L1$. Figure 2 shows function of time $R(t)$. The duty ratio is 50%. The period is $10\mu s$ (frequency 100kHz). The rise/fall time *TRF* is 1fs.

The equations describing the circuit may be the state-equations where inductor currents and capacitor voltages are chosen as system variables. By using the Kirchhoff voltage and current laws we get the following differential equations:

$$dx1 / dt = (-x2 + VDC) / L1$$
$$dx2 / dt = (x1 - x2 / R(t) - x3) / C2$$
$$dx3 / dt = (x2 - RL * x3 - x4) / L3$$
$$dx4 / dt = x3 / C4$$

The aim was to implement these equations into Dymola structure. Therefore four different ways has been chosen to model these equations.

The first solution is by using modelica text language. Designing the model is relative easy in modelica by using the exact equation above in the equation section. The time dependent resistor is modelled in the `algorithm` section and the whole modeling code has the following structure:

```
1  model C3Dymola_textv2
2    constant Real L1 = 79.9E-6;
3    constant Real C2 = 17.9E-9;
4    ...    // The same for the other values
5    Real x1, x2, x3, x4;
6    Real Rt;
```


Figure 1: Class-E amplifier

```
 7   Real t_red;
 8   Real IRT;
 9   Real VRL;
10   Real k;
11   ...
12   equation
13     t_red = mod(time, 10E-6);
14     k = ((5e+6)-(5e-2))/TRF;
15     ...
16   algorithm
17     if (0<=t_red) and (t_red<TRF)
18        then Rt:=(5e-2) + k*t_red;
19     elseif (TRF<=t_red) and (t_red<(5e-6))
20        then Rt:=5e+6;
21     elseif ((5e-6)<=t_red) and
                   (t_red<((5e-6)+TRF))
           then Rt:=(5e+6) - k*(t_red - (5e-6));
22     elseif ((5e-6)+TRF<=t_red) and
                   (t_red<(10e-6))
23        then Rt:=5e-2;
24        else Rt:=-5;
25     end if;
26   equation
27     L1 * der(x1)= -x2 + VDC;
28     C2 * der(x2)= x1 - (x2/Rt) - x3;
29     L3 * der(x3)= x2 - (RL*x3) - x4;
30     C4 * der(x4)= x3;
31 end C3Dymola_textv2;
```

Listing 1: C3 basic model implementation in Dymola Text mode

The second solution is using a block diagram model. The differential equations above [(1) to (4)] were built by block integrator, add/subtract and gain, also a division block for $x2 / R(t)$ and constant block for VDC. The time dependent resistor is built by trapezoid source block by defining its parameters as follows:

Amplitude	5e+6	Offset	5e−2
Rising	1e−15	Falling	1e−15
Width	5e−6	Period	10e−6

The trapezoid source block is shown by Figure 3. The model of the system block in the diagram layer is shown in Figure 4.
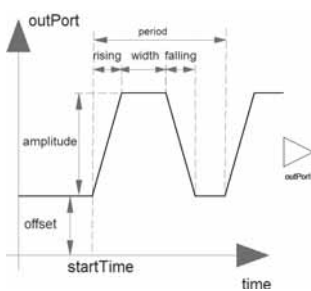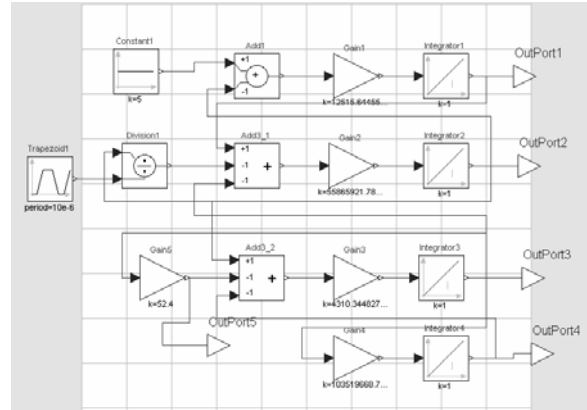
Figure 4. Model of the Differential Equation System in block style (block diagram)

The third solution is by using a state graph model. Designing the model based on second solution by adding a triggered trapezoid block as time dependent resistor by defining its parameter as follows:

Amplitude	5e+6	Offset	5e−2
Rising	1e−15	Falling	1e−15

The triggered trapezoid block used in the third modeling approach is shown in Figure 5.

Also by adding greater equal, less equal block and stategraph model block such as initial step, step and transition to activate triggered trapezoid from input trapezoid source block, which have the same parameter from second solution. Greater equal and less equal block will determine what state will be activated in stategraph model, is it state off (when $R(t)=5M\Omega$) or state on (when $R(t)=5m\Omega$). Basically the stategraph model consists only of 1 initial step, 2 transition blocks and 1 step block. The initial step block will represent state off and step block will represent state on. State off will change to state on whenever transition block 1 active, which being controlled by output from less equal block and state on will change to state on whenever transition block 2 active, which being
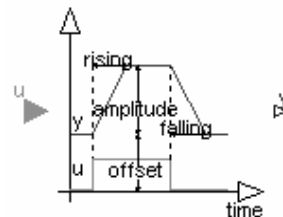
Figure 3. Trapezoid source block.

Figure 5: Triggered Trapezoid Block with input u and output y, whereby u is a logical variable and y is of type Real.
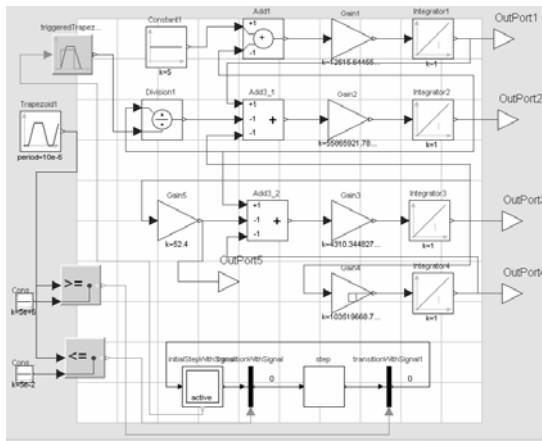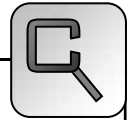
Figure 6. Model of the System (stategraph)

controlled by output from greater equal block. When-ever initial step active, it will send trigger signal to activate triggered trapezoid block, which will have output as a trapezoid signal. The model of the system for stategraph model is displayed in Figure 6.

The fourth solution is using the electrical model equivalent circuit. Designing the model using com-ponents from the Modelica standard library `Mode-lica.Electrical.Analog.Basic`, like resistor, induc-tor, capacitor, ground and constant voltage. The time dependent resistor $R(t)$ was built by using the com-ponent `VariableResistor` from the electrical library and trapezoid source defined in the block library, which has the same parameters as defined in second solution.as input of variable resistor. The model of the system for electrical model is shown in Figure 7.

All block models are built in the `Diagram` layer of the Dymola modeling interface without using the `Equa-tion` layer. Setting up the simulation parameters, simulation process and plotting the result are done in `Simulation window` of Dymola.

A-Task: To calculate the eigenvalues of the system when $R(t) = 50\,\text{m}\Omega$ and in case when $R(t) = 5\,\text{M}\Omega$ is done by calling the function `eigen-Values` (included in Modelica standard library 2.2) and putting the values of all variables into a matrix syste. The matrix system for Task A is defined as follows:

$$\begin{pmatrix} 0 & -1/L1 & 0 & 0 \\ 1/C2 & -1/[R(t)C2] & -1/C2 & 0 \\ 0 & 1/L3 & -RL/L3 & -1/L3 \\ 0 & 0 & 1/C4 & 0 \end{pmatrix}$$
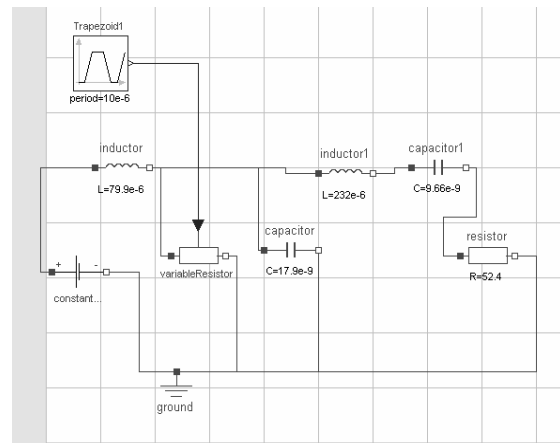

Figure 7: Electrical model representation of the Class-E Amplifier as defined in ARGESIM Benchmark 3 in the `Diagram` layer of Dymola.

ON period	OFF period
−1,1303e+005 + 6,5835e+005i	−5,4708 e+004 + 1,0407e+006i
−1,1303e+005 − 6,5835e+005i	−5,4708 e+004 - 1,0407e+006i
−6,258e+002	−5,8228e+004 + 5,3275e+005i
−1, 117e+009	−5,8228e+004 - 5,3275e+005i

Table 1: Eigenvalues of $R(t)$ in the ON – and OFF – periode of the system

It took 0.5 sec to execute Task A for all solutions. The result of eigenvalue analysis is shown in Table1 for all solution.

B-Task: To simulate the system in all four im-plementations, the Dassl integration method was used (settings: 1000 as number of intervals, 0…100μs as simulation time interval and 1e-4 as a relative tolerance). Under the initial value zero, for $x1, x2, x3$ and $x4$, the result for variable current switch resistor $IR(t)$ and output voltage VRL is given by figure 8. It took 0,047s, 0,047s, 0,063s and 0,047s to simulate the Task B for 1st, 2nd, 3rd and 4th solution respectively.
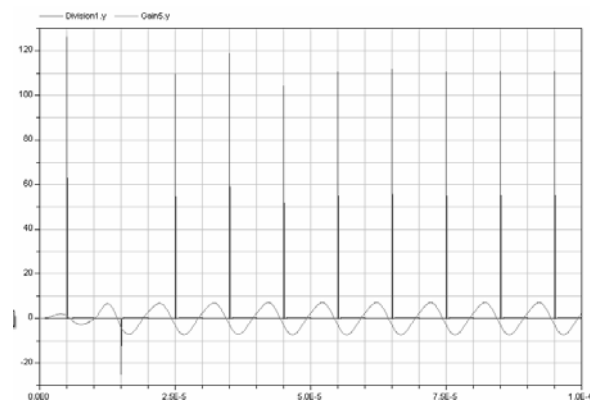

Figure 8: Time Curve $IR(t)$ and VRL

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C-**Task:** The parameter of *TRF* is varied between $1fs, 10ps, 1ns$ and $100ns$. Initial value for Task C is the final solution given by Task B. The time interval is $0...9\mu s$. Changing the time curve plot into phase plot works by one mouse click, choosing independent variable instead of time. As result, the phase plane curves $dx3/dt = VL3$ as a function of $x3 = IL3$ are given by Figure 9. It took 0,031s, 0,025s, 0,047s and 0,015s to simulate Task C for 1st, 2nd, 3rd and 4th solution respectively.

Resumé: Dymola is a powerful modeling and simulation tool that aids implemrntation of ordinary differential systems in different ways. By calling eigenvalue function for doing Task A it overs a simple way for additional system analysis. Using right mouse click to change between plots based on time and plots based on independent variable uses the strength of the included plotting and representation tool. Comparing to other component based simulation tool Dymola works very fast. Each of the tasks is calculated in less then $0.51s$ on a standard PC.

The ranking of solutions based on simulation time from fast to slow is:

1. Textual mode
2. Electrical model
3. Block Diagram model
4. Stategraph model

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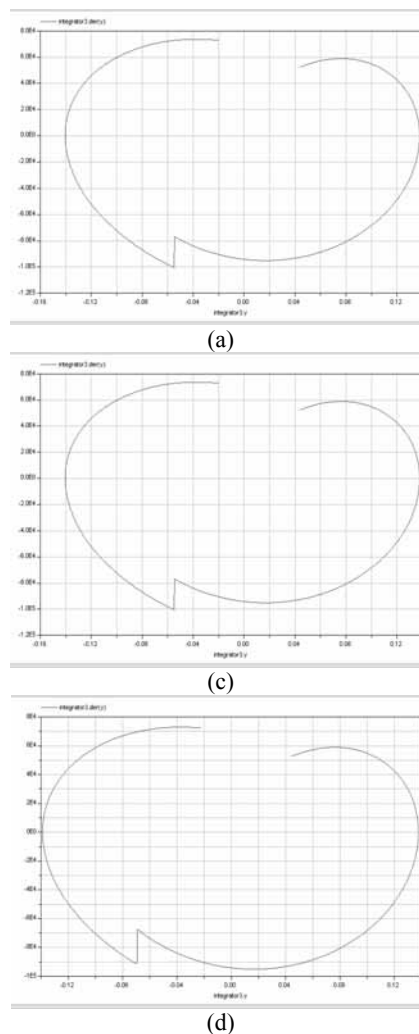Wiedner Hauptstraße 8-10, 1040 Vienna, Austria
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Figure 9. Phase plane curve VL3 function IL3 for TRF (a) 1e-15s (b) 1e-11s (c) 1e-9s (d) 1e-7s