SystemC-AMS modeling of an Electromechanical Harvester of Vibration Energy

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Outline

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    - TDF Model of the Mechanical Resonator
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3. Results & Verification
    - General results
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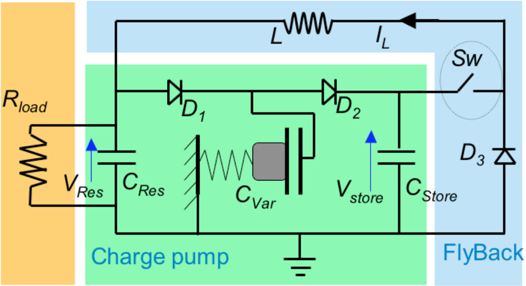
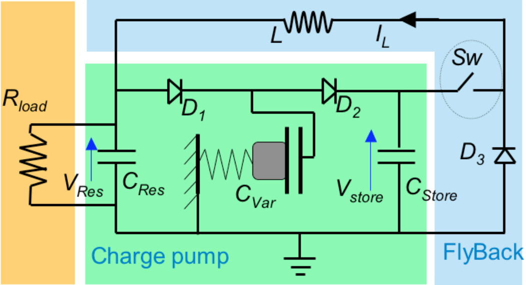
    - Further work

Overview of the Harvester



- Converts mechanical energy into electrical energy to drive the load.
- Heterogeneous: *a mechanical resonator* and a complex *electrical conditioning ciruit*
- Power source for wireless sensor networks

Summary of circuit operation



- When the switch is off: the charge pump transfers the charges from the large C_{res} to the small C_{store}.
- When the switch is on: the flyback circuit transfers the harvested energy to the inductor and then to C_{res}.
- The operating principle of the flyback: a Buck DC-DC converter
- Strongly discontinuous behaviour due to the switching

Modeling challenges

1. Highly non-linear (exponential diodes) and switching system
2. Processes with very different time constants: the flyback is $\pm$300 times "quicker" than the chargepump, but happening only <0.1% of the time.

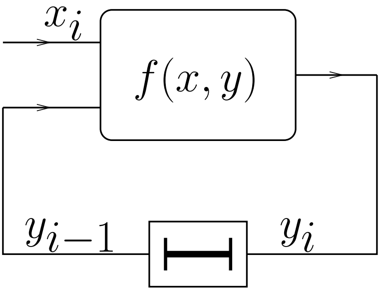
Generalities

1. Extension of SystemC
2. Environment for modeling analog and mixed systems
3. Two operating modes: TDF (non-conservative) and Linear Electrical Network (LinElec, conservative)
4. The data rate (modeling time step) is constant *for a given block* throughout the whole simulation.

Non-conservative TDF modeling in SystemC-AMS

1. It is possible to implement Simulink-like Flow Diagrams.
2. A scheduler: each block is called at each time step.
3. Particularity: absence of a non-linear solver.
4. The time step of the blocks is a multiple of the "global" system time step.

Non-conservative TDF modeling: example



$f(x,y)$: algebraic function
x: a known input

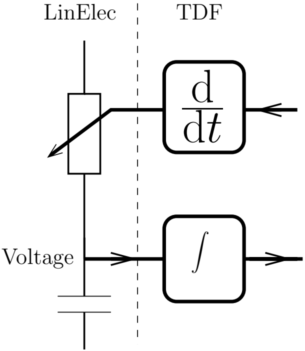
The output evolution law:
$y_i = f(x_i, y_{i-1})$

1. Example of an algebraic (memoryless) system with feedback
2. A delay is necessary.
3. If x changes slowly, the output is correct.

Linear Network modeling (LinElec)

1. Goal: modeling of linear electrical networks
2. Allowed components: resistors, capacitors, inductors and voltage/current sources
3. At initialization, a network matrix is calculated and inverted, then the network response is calculated in the time domain.
4. Connections to and from TDF blocks are possible.

Linear Network modeling: connection with the TDF domain



1. A value calculated by the LinElec solver can be used by a TDF block.
2. The parameters of some linear electrical components can be dynamically modified by a TDF block (e.g. changeable resistor).
3. Very important: at each parameter change, the network matrix is recalculated, which is a time-consuming operation.

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- Goals
    - Create a reusable model of the whole harvester in SystemC-AMS.
- Previous work
    - Study of the system and development of a VHDL-AMS model, presented at BMAS 2007.

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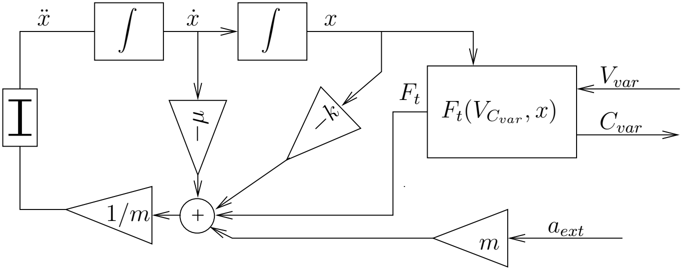
The resonator is modeled as a second-order lumped-parameter linear system:

$$-kx - \mu\dot{x} + F_t(V_{C_{var}}, x) + ma_{ext} = m\ddot{x}$$

- x is the mass displacement from the equilibrium position
- m is the mass
- k is the stiffness of the spring
- μ is the viscous damping constant of the resonator
- F_t is the force generated by the capacitive transducer C_{var}
- a_{ext} is the acceleration of the external vibrations

TDF Model of the resonator

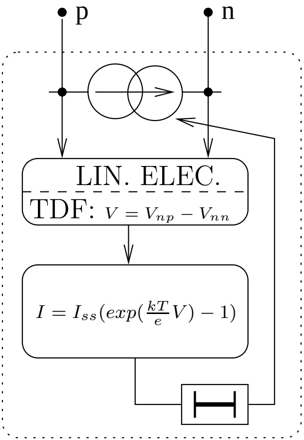


- Timed Data Flow implementation of the above equation: each operator is a SystemC-AMS TDF module.
- The block has one electrical input (V_{var}), one mechanical input (a_{ext}) and one electrical output (C_{var}).
- The loop requires one delay step.

Modeling electrical networks with SystemC-AMS

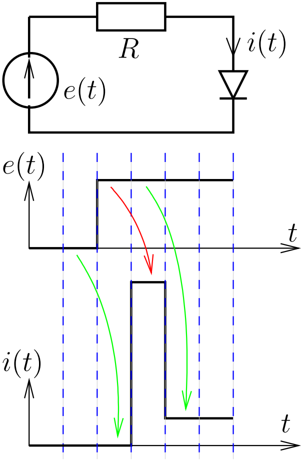
- Difficulty: only linear networks can be natively modeled by SystemC-AMS.
- "Natural" solution: model a non-linear network as a TDF system.
- For this, the system of equations should be represented as a TDF diagram.
- The problem: blocks with strong non-linearity and strong discontinuities due to switching.
- Impossible to have a convergence with the existing TDF solver.

A SystemC-AMS LinElec diode model: Approach I



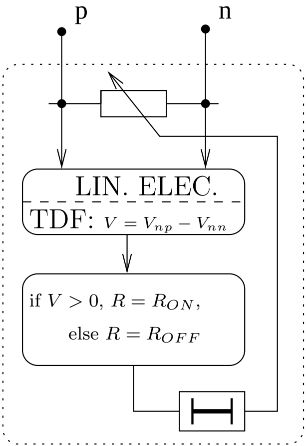
- A current source controlled by the voltage on its terminals, with exponential relation between the current and the voltage.
- This implementation contains a loop, thus a one-step delay is necessary.

SystemC-AMS Lin Elec diode model: drawbacks of approach I



- Bad solution: if the diode voltage becomes positive, during one step the diode generates a very large (exponential) current.
- This current injection strongly disturbs the state of the reactive elements.

SystemC-AMS LIN ELEC diode model: approach II



1. Model a diode as a resistive switch, i.e., as a voltage-controlled resistor.
2. A TDF module calculates the state of the diode (its resistance).
3. State (resistance) is updated after a necessary delay step.
4. The current value is still bad during one step, but the error is not exponential and can be tolerated.

Lin Elec diode: conclusions

- Completely "embedded": usable as a normal Lin Elec component.
- The current value is erroneous during one step, thus, the simulation step should be small enough to tolerate.
- A more complex diode model can be realized in a similar way, using a series-connected voltage source and resistor, both voltage-controlled.

Lin Elec diode: calculating the diode's state

Simple state calculation

```
SCA_TDF_MODULE(Electrical_diode_function){
        sca_tdf_in<double> voltage;
        sca_tdf_out<double> resistance;
        void process(){
                resistance.write(voltage.read()>0.?1e-9:1e10);
        }
        void set_attributes(){
                current.set_delay(1);
        }
};
```

More complex state calculation

```
        void process(){
                double volt = round_to_n_decimals(voltage.read, <precision>);
                double current = <realistic current diode law using volt>;
                if(current == 0. || volt < 0.1) //special cases
                        resistance.write(1e10);
                else
                        resistance.write(volt/current);
        }
```

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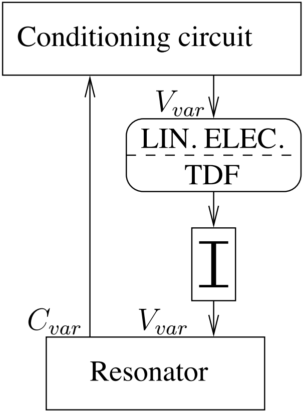

- Coupled electromechanical operation
- There is a loop: a delay step is necessary.
- The mechanical part's time step is 100 times higher than the conditioning ciruit's: the simulation runs 8 times faster (less matrix reinitialization).

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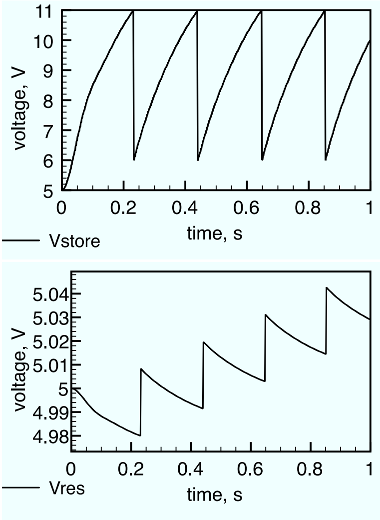
Global system operation



- top: evolution of the voltage on C_{store} during about 5 cycles. The switch closes at 11V and opens at 6V (on $V_{C_{store}}$).
- bottom: voltage accumulation on C_{res} with no load connected.
- The steep non-linear behavior is correctly modeled when the switch changes state.

Verification of the results

- The SystemC-AMS model is compared to a VHDL-AMS and a Simulink model.
- The VHDL-AMS model was presented at BMAS 07.
- Different diode models had to be used for the simulations to work.
    - VHDL-AMS a diode law with 3 regions (linear on/off zones, quadratic transition).
    - Simulink a quadratic diode law.
    - SystemC-AMS a two state diode law.

Summmary of results

Table: Relative differences in comparison with VHDL-AMS

	$V_{C_{store}}$	$V_{C_{res}}$	I_L
SystemC-AMS	0.495%	1.468%	0.595%
Simulink	0.886%	0.316%	0.100%

Table: Simulation time for 1 second of system operation (in min.)

SystemC-AMS	Simulink	VHDL-AMS
145	3.5	5.75

- The same system was modeled in VHDL-AMS, Simulink and SystemC.
- The relative difference was less than 2 %.

Further work

- Find the parameters for optimal energy gain, i.e. refine the switch model (VHDL-AMS/Simulink).
- Implement a higher level load (i.e. a processor) and use the system as power source (SystemC-AMS only).
- Find a TDF approximation of the conditioning circuit, to speed up the simulation (SystemC-AMS only).

Summary

- By combining TDF and Lin Elec modules we simulated non-linear Lin Elec components using the linear solver of SystemC-AMS.
- This allowed us to correctly model a (heterogeneous) electromechanical system ($<2\%$ rel. diff. with VHDL-AMS).
- The fixed time step slows down the simulation.