Techniques for Modeling And Simulation of Dynamic Overcontrained Connectors

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OpenModelica

Introduction and Motivation

- Increase flexibility for better modeling and simulation of Cyber Physical Systems
- Overconstrained connector semantics was introduced (2004)
  - MultiBody package of the Modelica Standard Library[1]
  - PowerSystems library[2]
- Current Modelica language specification only allows static connection graphs
- Limitation when modelling AC power systems using phasors

[1]Sven Erik Mattsson Martin Otter, Hilding Elmqvist. The new Modelica MultiBody library. In Proceedings 3rd International Modelica Conference, pages 311–330, Linköping, Sweden, Nov 3–4 2003.

[2]Hans-Jürg Wiesmann Rüdiger Franke. Flexible modeling of electrical power systems – the Modelica PowerSystems library. In Proceedings 10th International Modelica Conference, pages 515–522, Lund, Sweden, Mar 10–12 2014. The Modelica Association. doi:10.3384/ecp14096515.

Introduction and Motivation

- AC transmission systems
  - ➢Possible that, in case of severe perturbations, some key circuit breakers are switched open splitting a single synchronous system into multiple independent synchronous islands
- DOCC
  - ➢ Performance Benefits
  - ➢ Avoiding Singularities
- Increasing the flexibility of Modelica Models
  - Applicable to other modeling domains as well
    - AC power systems
    - Closed incompressible fluid networks

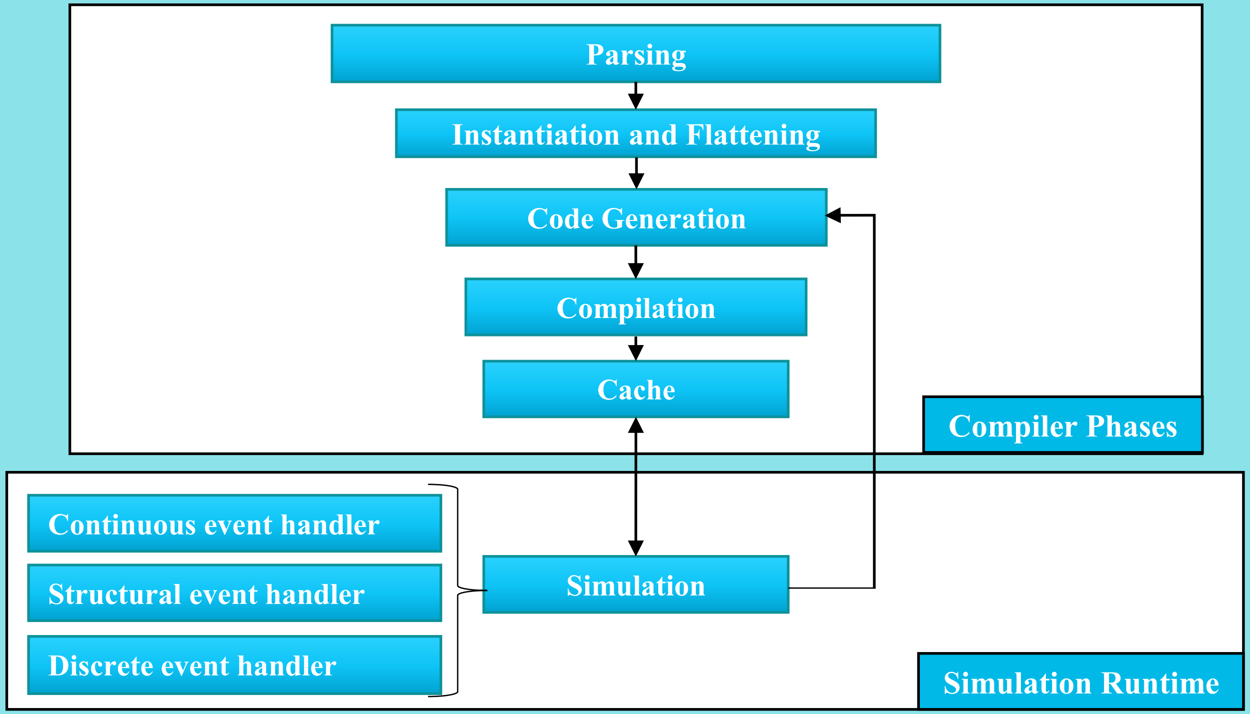
OpenModelica.jl

- A Modelica Compiler implemented in Julia
- Use the frontend of the OMC, translated into Julia
- Backend generating Julia code
- For this work
  - Implemented Discrete event handling
  - Backend Handling of OCC
  - Expanded the intermediate representations

➢ Feature

  ➢ Blurring the border between compilation and simulation

➢ Used for experimental features



Dynamic Overconstrained Connectors

- Currently, Overconstrained Connectors in Modelica can not be used in If-Equations[3]
  - Relaxing constraints
- Allowing a special If-Equation construct where the **Connectors.branch** operator is allowed
  - Allowing changing the connection graph dynamically at runtime
- Implementation in OM.jl

```
model TransmissionLineVariableBranch
  extends TransmissionLineBase;
equation
  if closed then
    port_a.omegaRef = port_b.omegaRef;
    Connections.branch(port_a.omegaRef,
                       port_b.omegaRef);
  end if;
end TransmissionLineVariableBranch;
```

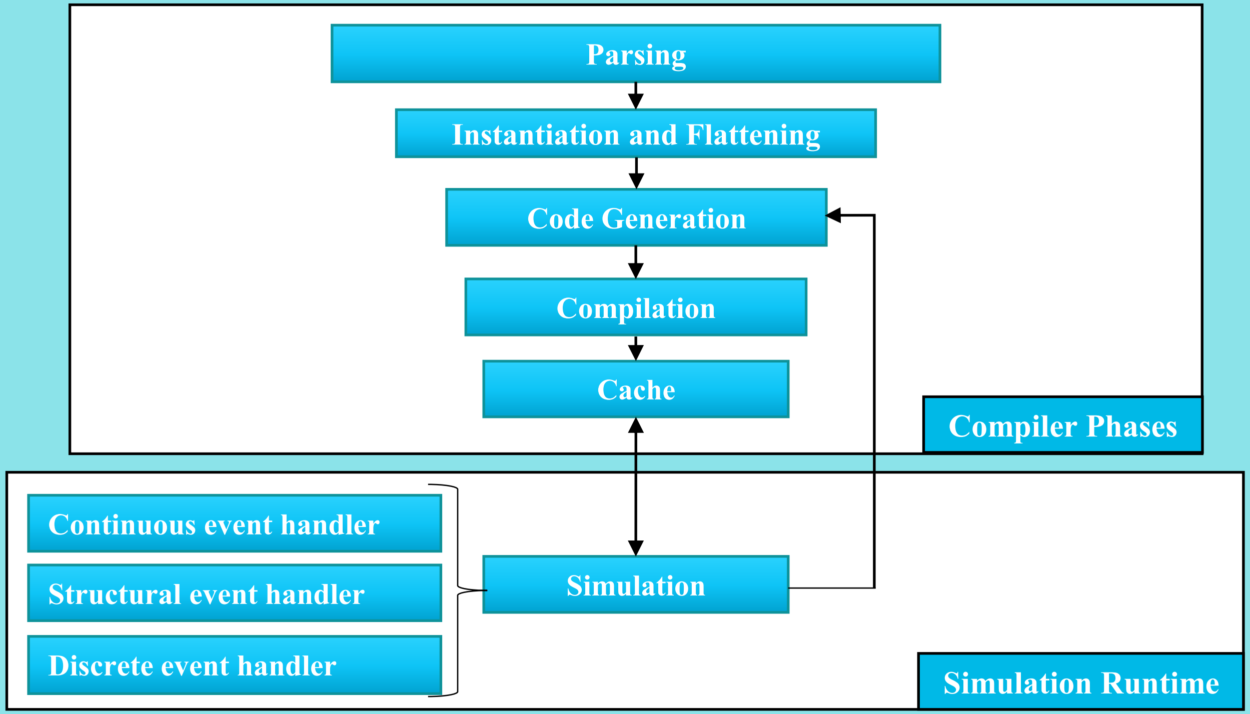

[3]https://specification.modelica.org/maint/3.5/connectors-and-connections.html#restrictions-of-connections-and-connectors

OpenModelica.jl

- A Modelica Compiler implemented in Julia
- Use the frontend of the OMC, translated into Julia
- Backend generating Julia code
- Does some things better than omc…

➢ Feature
  ➢ Vague border between compilation and simulation runtime

➢ Used for experimental features



Example Library

- Example Library to illustrate this construct (Dynamic Overconstrained Connectors)[1]
    - AC power systems
    - Closed incompressible fluid networks

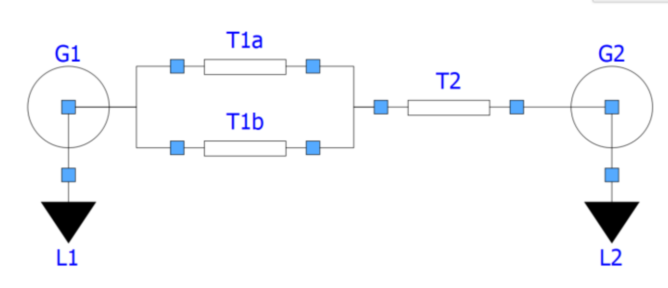


Figure 1. `System3` model diagram.

- Simplifying assumptions[2]
    - Purely inductive transmission lines
    - Idealized synchronous generators that impose a voltage at their port with fixed magnitude and a phase equal to the rotor angle
    - Droop-based primary frequency control of the generators
    - The reference frame for the phasors is rigidly connected to the rotor of the generator that is selected as the root node in the connection graph

[1] https://github.com/looms-polimi/DynamicOverconstrainedConnectors

[2] More information available in the paper

Implementation

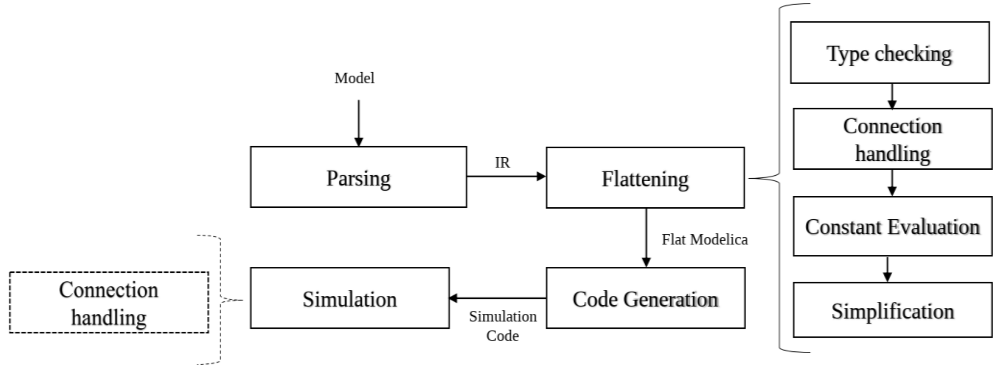
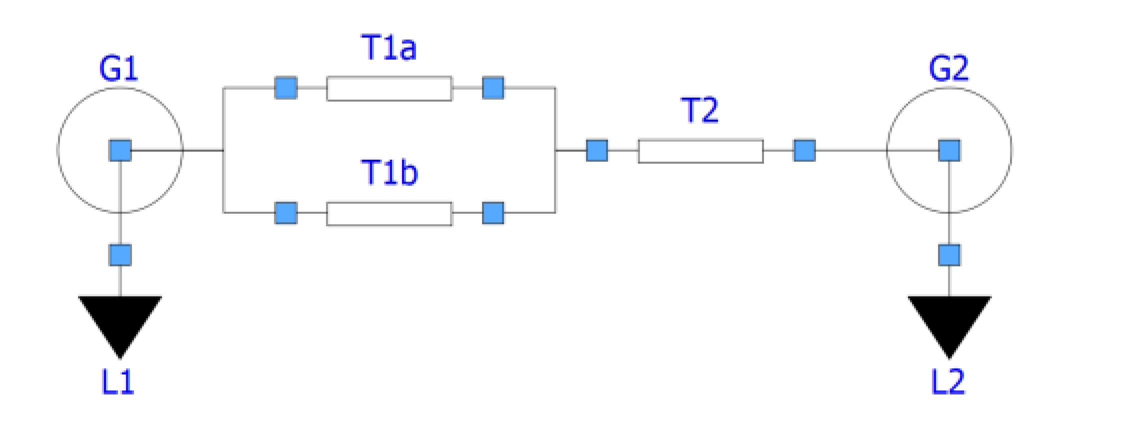


Figure 7. The translation process of a Modelica Compiler. The model is first translated to an internal intermediate representation (IR) where typing and type checking is performed and where the declared connections are handled and expanded before the simulation code is generated. The dashed box to the left shows where the new extension is handled in the compilation process.

- Implemented in OpenModelica.jl
- Runtime supports two alternatives
  - Reconfiguration/Recompilation of the System
  - Reinitialization without recompilation
- Constructs for handling Overconstrained Connectors (OCCs) are moved to simulation runtime
- Supports Dynamic Overconstrained Connectors (DOCC)
- Size of implementation
  - ~1000 LOC
  - Frontend procedures reused

Example System4

- *Same as System 3*
  - *Difference is the transmission line model*
- **The line breaker implements the proposed extension**
  - Dynamically removes the unbreakable branch between its to connectors when the susceptance B is brought to zero
- The OCC graph is split into two at time $t = 10$

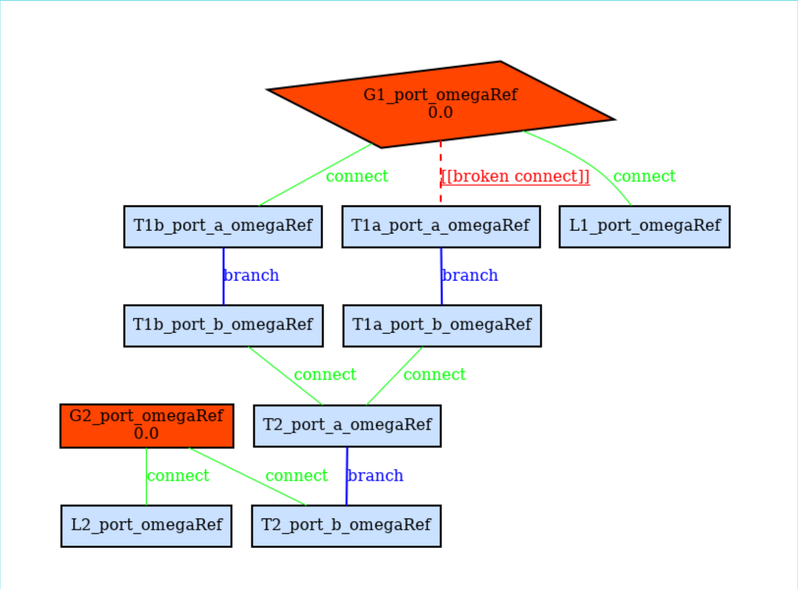


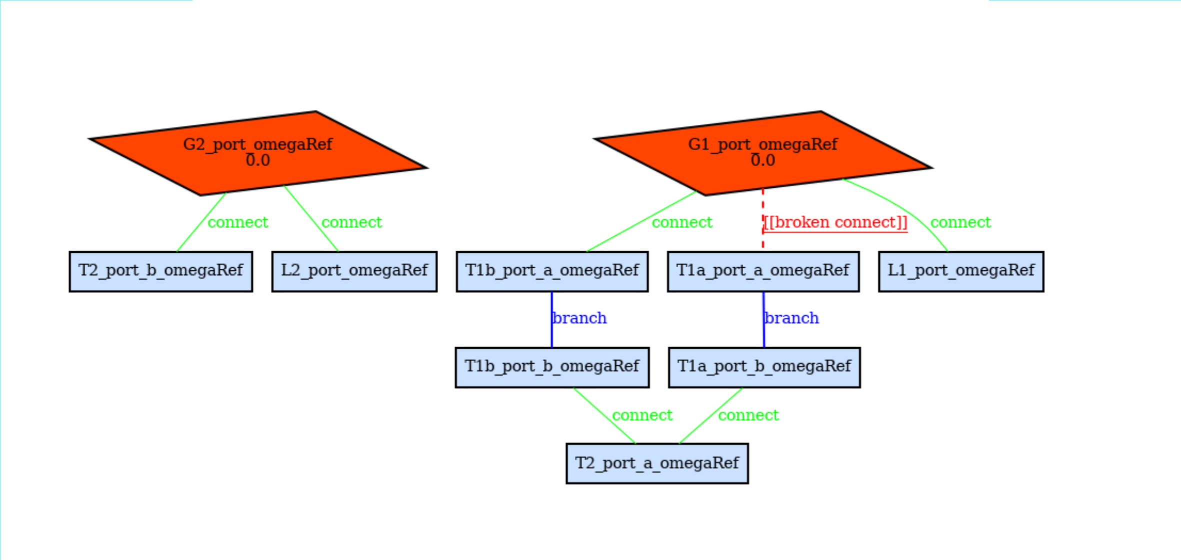

```
model TransmissionLine "Purely inductive transmission line model
  extends TransmissionLineBase;
equation
  port_a.omegaRef = port_b.omegaRef;
  Connections.branch(port_a.omegaRef, port_b.omegaRef);
end TransmissionLine;
```

```
model TransmissionLineVariableBranch
  extends TransmissionLineBase;
equation
  if closed then
    port_a.omegaRef = port_b.omegaRef;
    Connections.branch(port_a.omegaRef,
                       port_b.omegaRef);
  end if;
end TransmissionLineVariableBranch;
```

Example System4

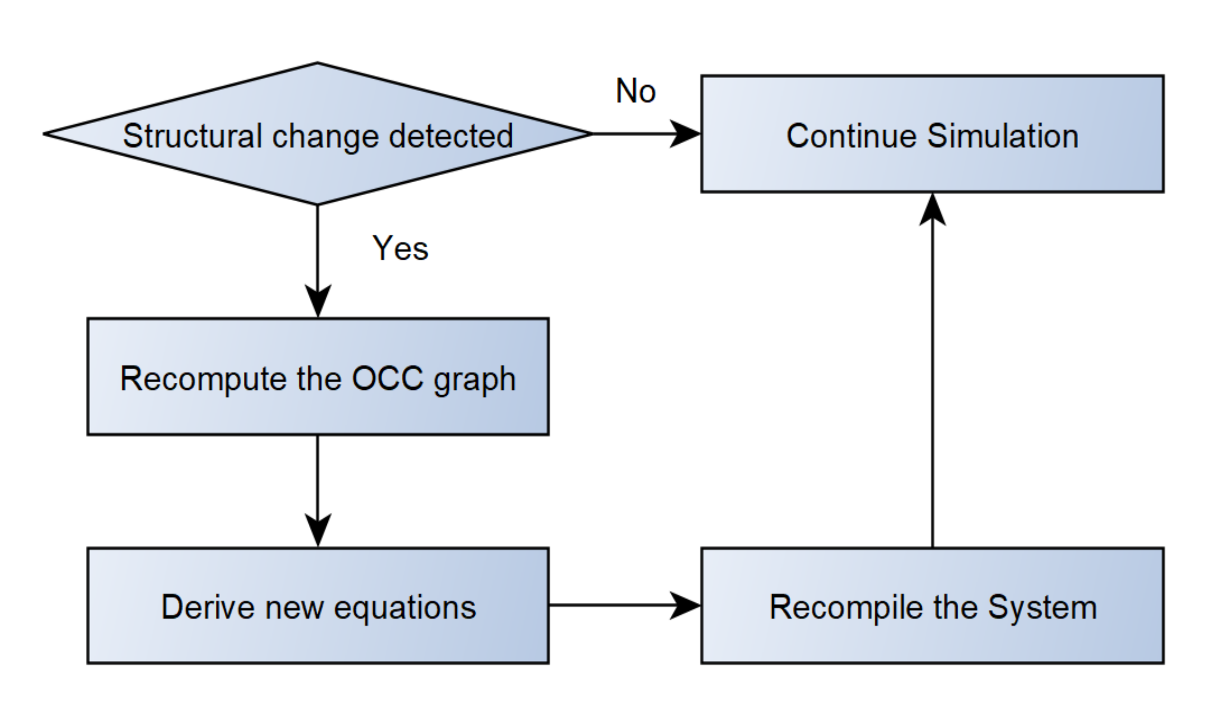
- Once the new frequency steady state is reached, phasors in both islands will remain constant
- Stiff solvers may take longer steps
- Phasor representation of currents and voltages in the connectors will be different
- Physically meaningful variables, specifically the generator frequencies G1.omega and G2.omega, G1.Pe, G1.Pc, G2.Pe, and G2.Pc will be the same





Runtime Recompilation

- Recompilation
  - At the time of the structural change recompile the system
  - System is initialized with the values of the variables before the structural change
  - Simulation is restarted
- Simple implementation for compilers/environments that support JIT
- *Recompilation should not be not needed*

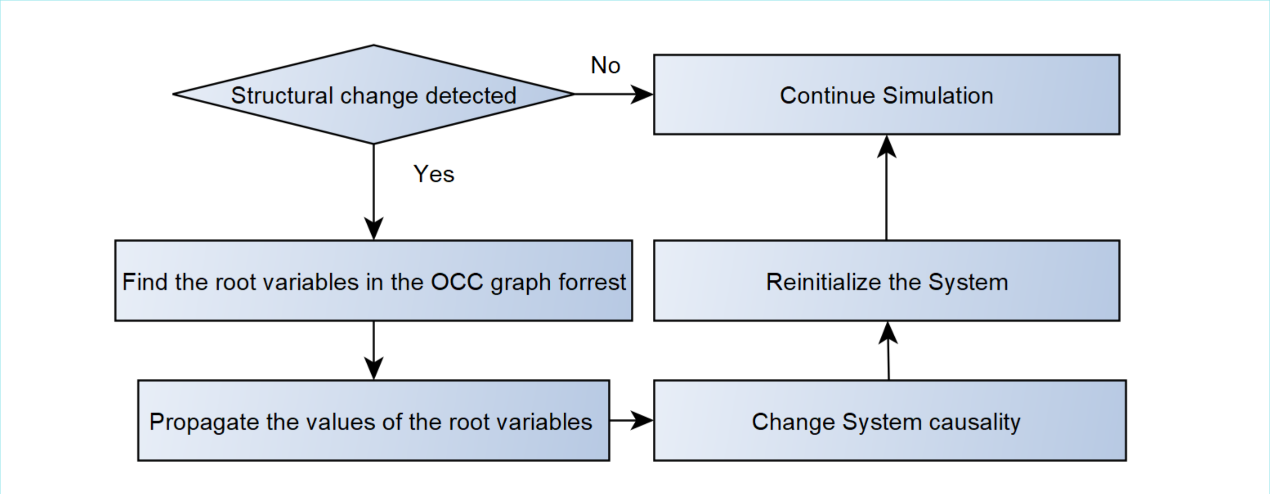


Runtime Reconfiguration

- Instead of Runtime Compilation
  - *Runtime Configuration*
- Extensions to the simulation runtime
- Pause the simulation at the time of the DOCC event
- Reinitialize

- Advantage
  - Reinitialization itself is less costly
- Disadvantage
  - More complicated implementation
  - DOCC chains need to be preserved, partially hinders optimizations

Runtime Reconfiguration Continued



- Detecting Structural Change
- Find the final roots in the OCC forrest
- Propagate the values of the root variables
- Change System Causality
- Reinitialize the System
- Continue Simulation

Runtime Reconfiguration, datastructures

Additions to the simulation runtime

- The New Frontend **NFOCConnectionGraph** module as a part of the Simulation Code IR
  - In Julia no change is needed since the frontend can called directly
  - The simulation runtime need to keep an instance of the current and previous virtual connection graph

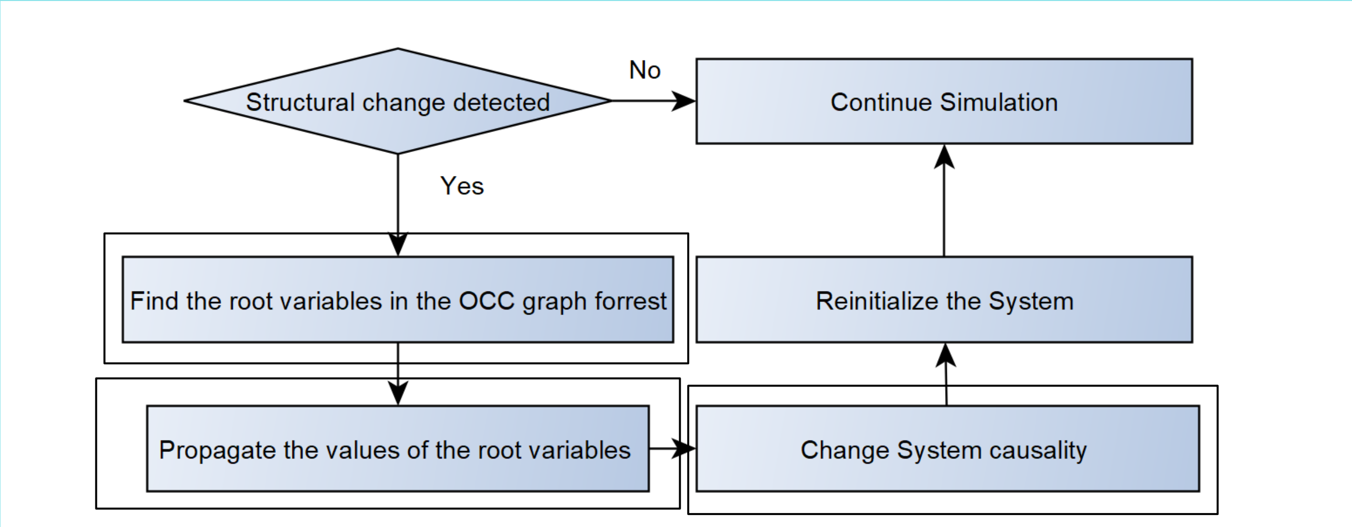
Tracking OCC Variables

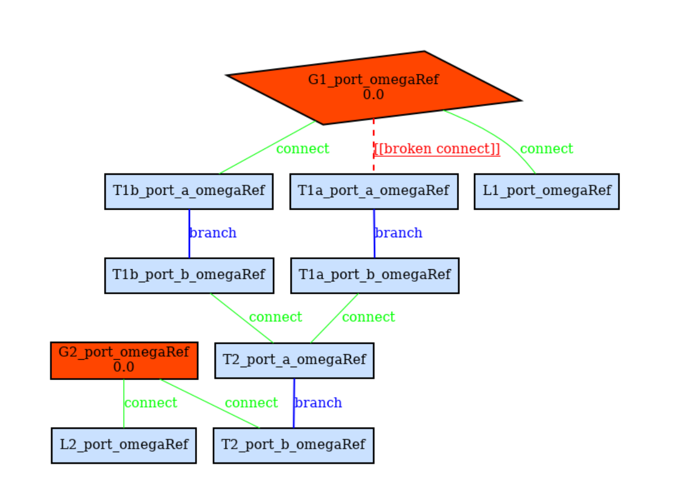
- Avoiding optimizations that breaks OCC chains

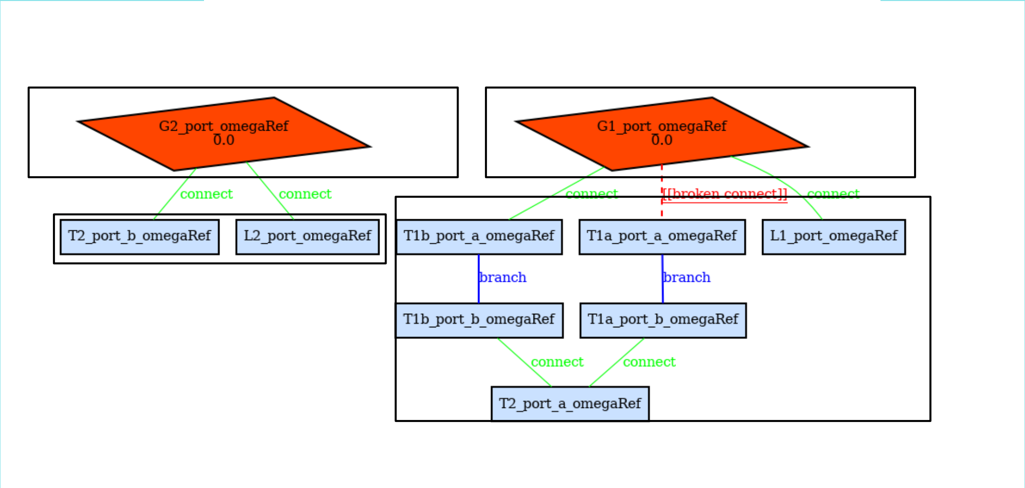
Structural Event Handler

- Supervise the simulation
- Update the Virtual Connection Graph

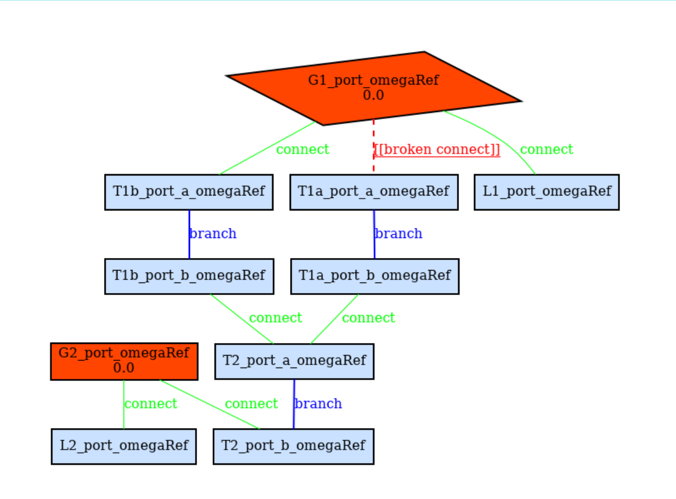
Runtime Reconfiguration

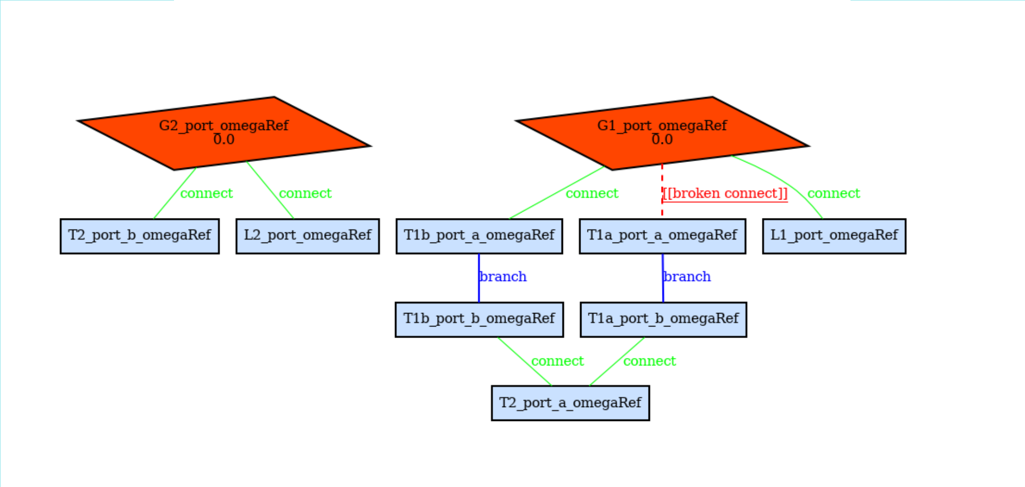






Runtime Reconfiguration Continued





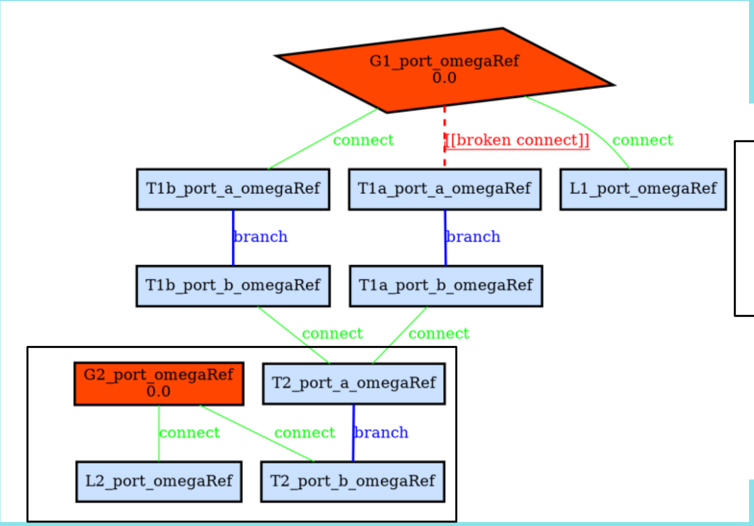
- The first two steps are the same as in the Recompilation scheme
- Change System Causality
  - Here one equation need to change
    - $G2_{omega} = G2_{port_{omegaRef}}$
- In OM.jl a single new equation is created and inserted
  - Swapping pointers in OMC

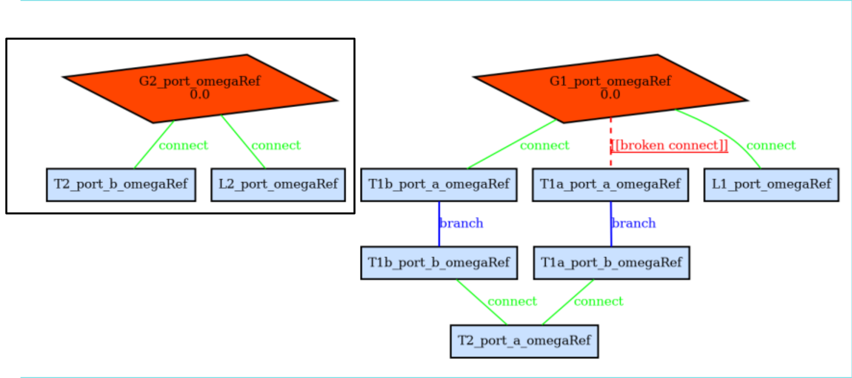
Runtime Reconfiguration

The first two steps are the same as in the Recompilation scheme

Change System Causality

- For System 4 only one equation need to change
  - I. $T2_{port_{b_{omegaRef}}} = G2_{port_{omegaRef}}$
  - II. $G2_{omega} = G2_{port_{omegaRef}}$
- Causality changes but the number of equation and variables in the system remains the same
- Change in equations may be achieved by swapping pointers in a Language such as C
  - No recompilation needed
- In Julia we insert new equations symbolically
- Ovearhead since optimizations are disabled for the equality chains involved in the Dynamic OCC Graph





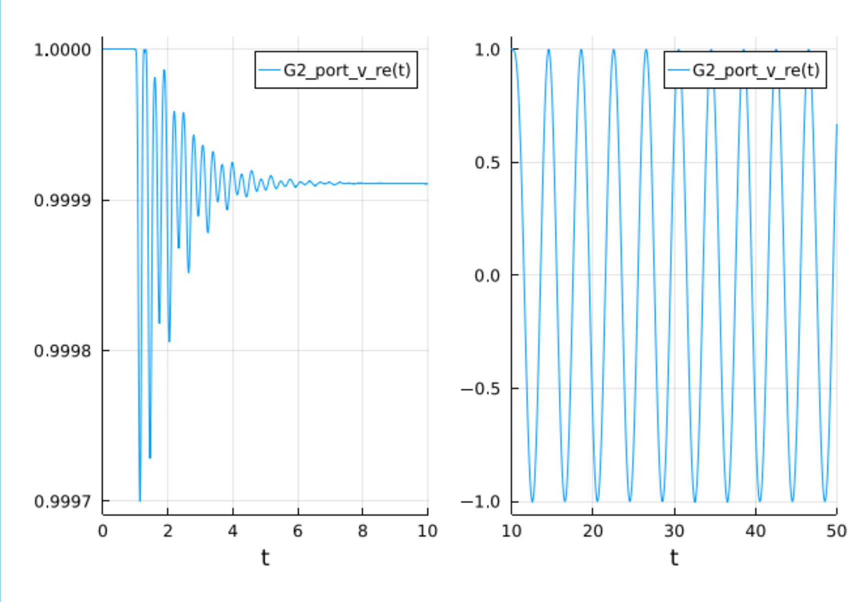
- Assignments for G1_port_omegaRef:
  1. T1b_port_a_omegaRef := G1_port_omegaRef
  2. T1b_port_b_omegaRef := G1_port_omegaRef
  3. T2_port_a_omegaRef := G1_port_omegaRef
  4. T1a_port_b_omegaRef := G1_port_omegaRef
  5. T1a_port_a_omegaRef := G1_port_omegaRef
  6. L1_port_omegaRef := G1_port_omegaRef

- Assignments for G2_port_omegaRef:
  1. T2_port_b_omegaRef := G2_port_omegaRef
  2. L2_port_omegaRef := G2_port_omegaRef
  3. Assignments for G1_port_omegaRef:

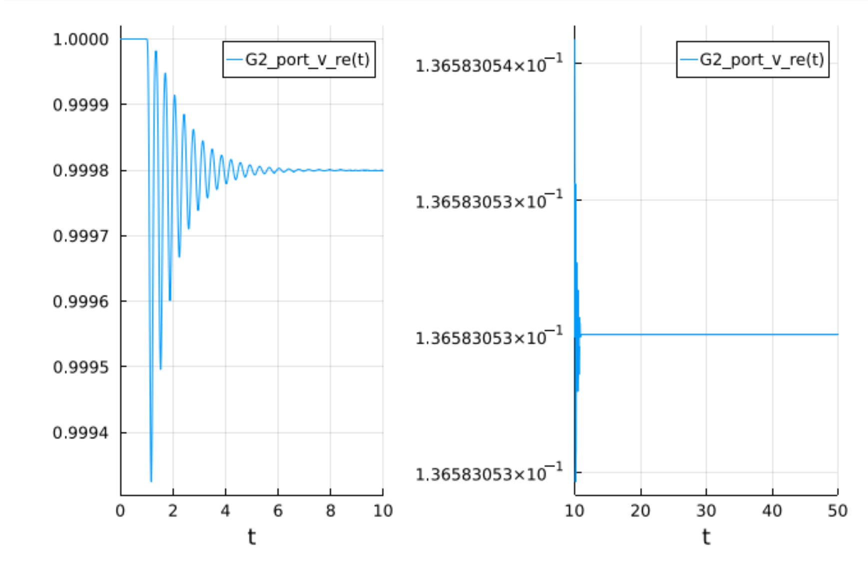
Applications

Applications

- DOCC allows stiff solvers to increase the step size in some situations, which leads to improved simulation performance*
    - ➢ See the plot of System 3 and the equivalent System 4 using DOCC to the right.
- DOCC allows for the successful simulation of models that existing Modelica tools cannot currently handle because of model singularities



Plots of the G2.port.v_re variable in System3 before and after the susceptance of line T2 is brought to zero at $t = 10$. The phasor oscillates forever because the system only has one root node also after the network splitting.



Plots of the G2.port.v_re variable in System4 before and after the susceptance of line T2is brought to zero at $t = 10$. The phasor remains practically constant after the splitting thanks to the correct choice of reference after the splitting.

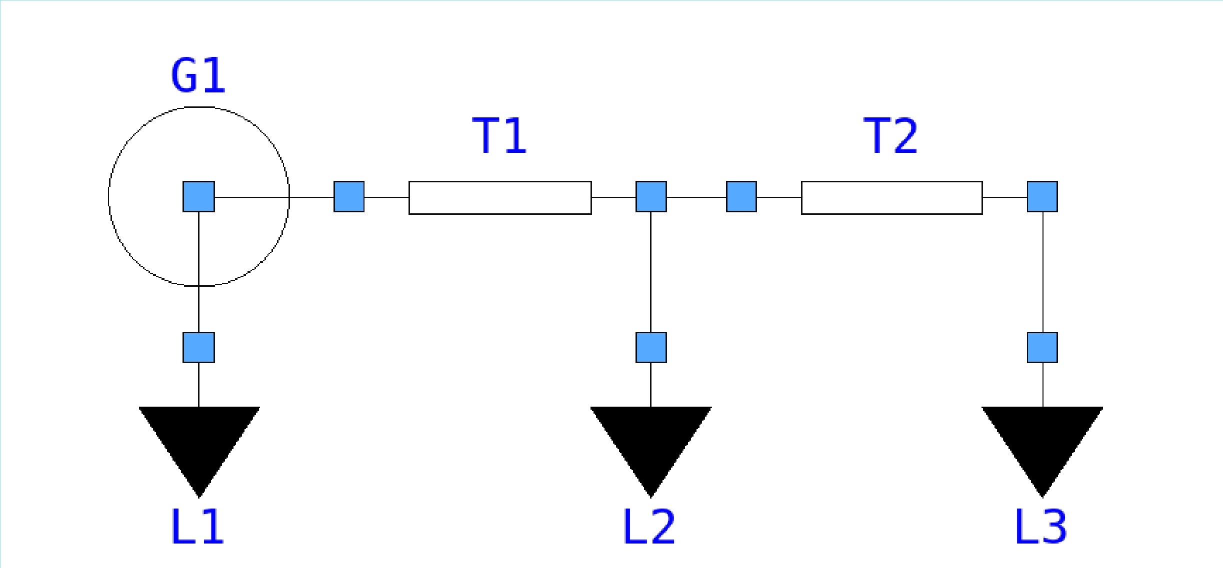
Applications

- Cost/Benefits
  - Recompilation is expensive
  - Reinitialization is not as expensive but not free
- Drastically reduce the number of Jacobians needed to be created
- Likely Outcome
  - Might not be a good modeling technique for smaller systems in terms of performance

System	Accepted Steps	Jacobians Created
System 3	565	605
System 4	125	132
System 7	374	389
System 8	169	175

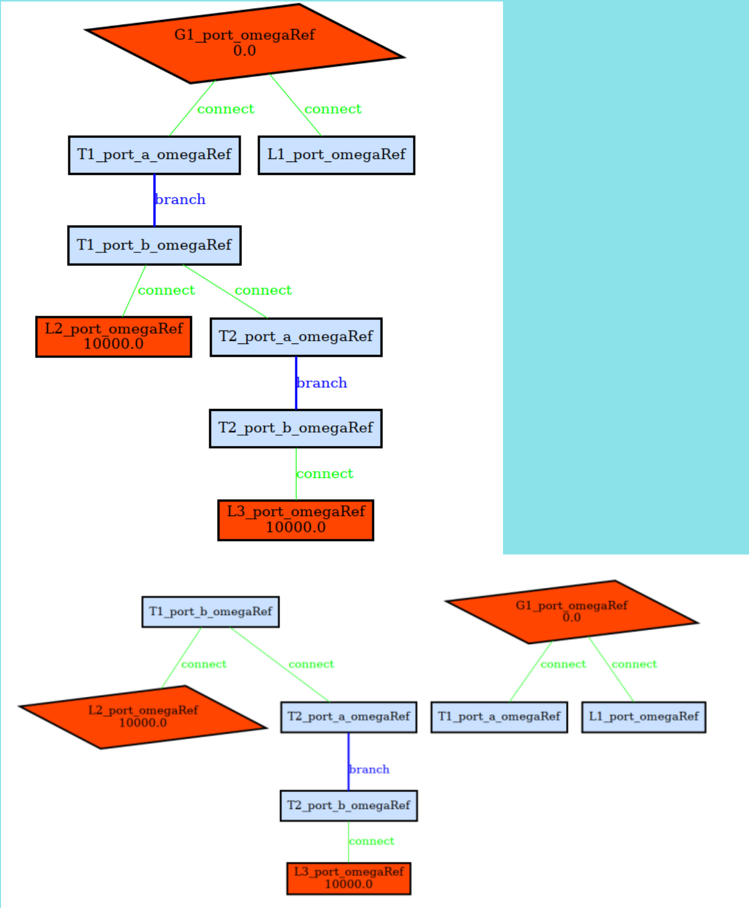
Applications

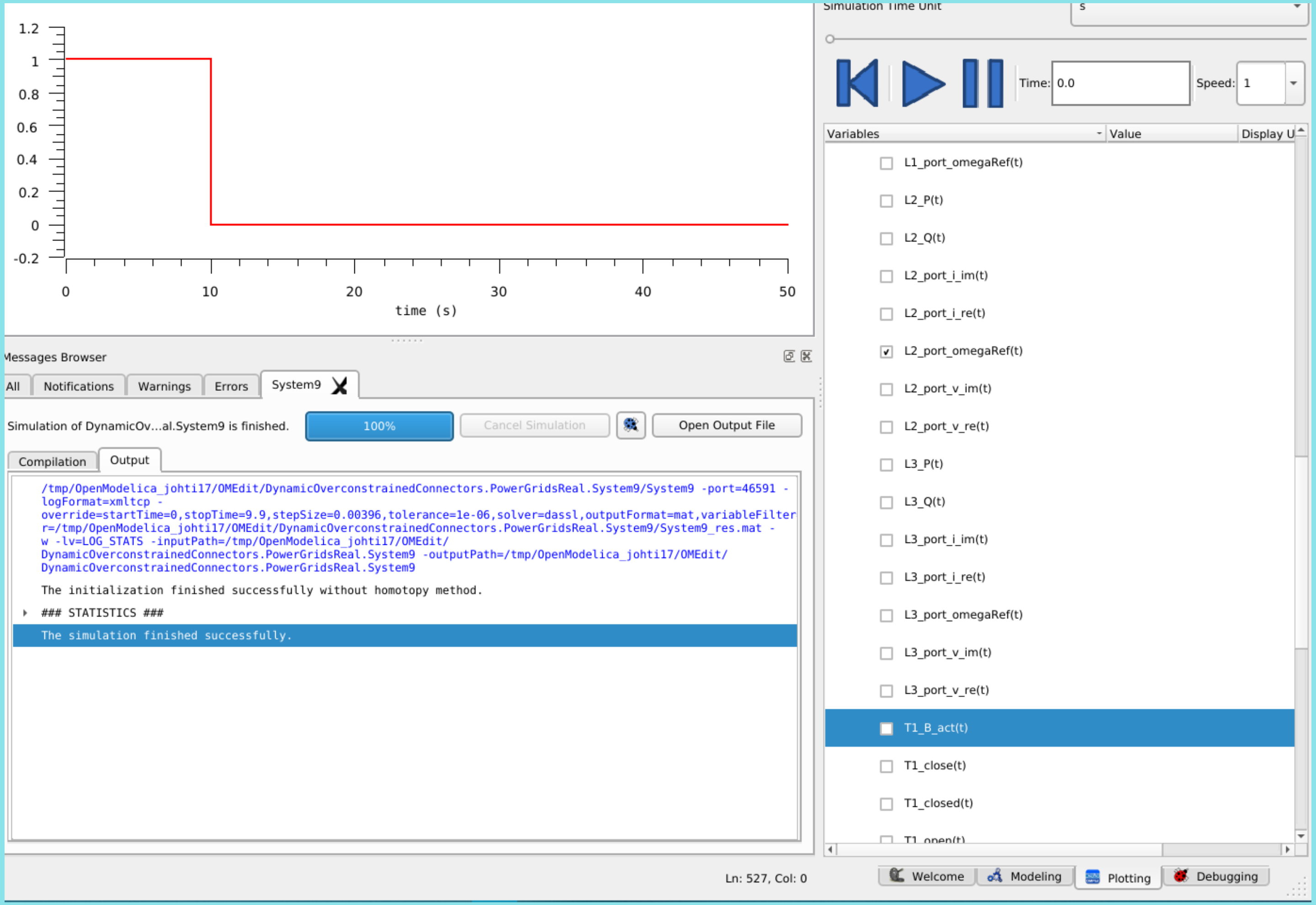
- DOCC allows for the successful simulation of models that existing Modelica tools cannot currently handle because of model singularities
- DOCC allows this type of systems to be simulated



https://github.com/looms-polimi/DynamicOverconstrainedConnectors

Applications





Future Work

- More experimentation
- Formalize backend methods
- Implementation in OMC
  - Mockup C program
  - Experiment with extending the Simulation runtime

Thank you for your attention

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Questions?