Physically Based Converter Models for High Fidelity Simulation and Stability Analysis

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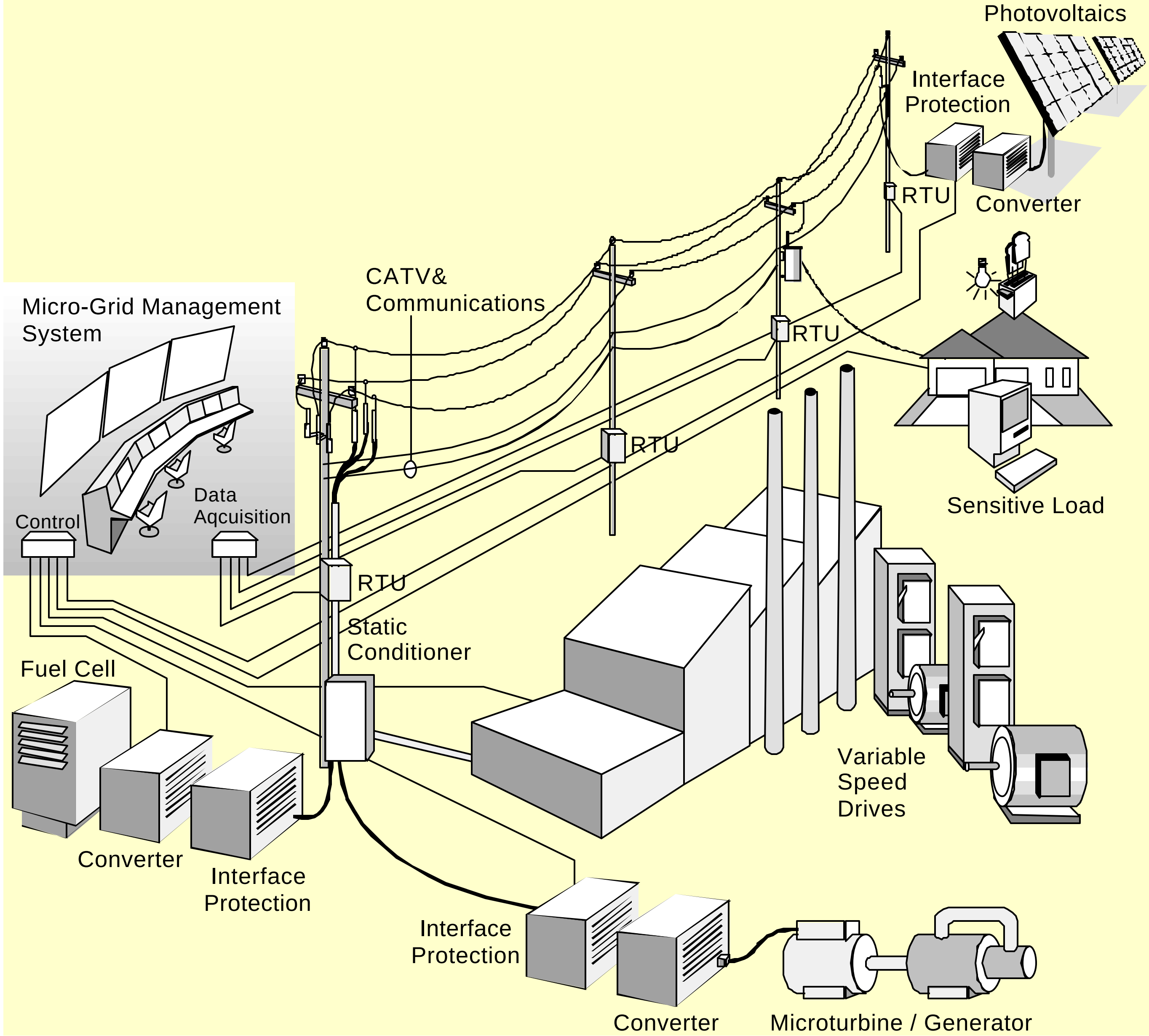
Technology Driven System Transformation

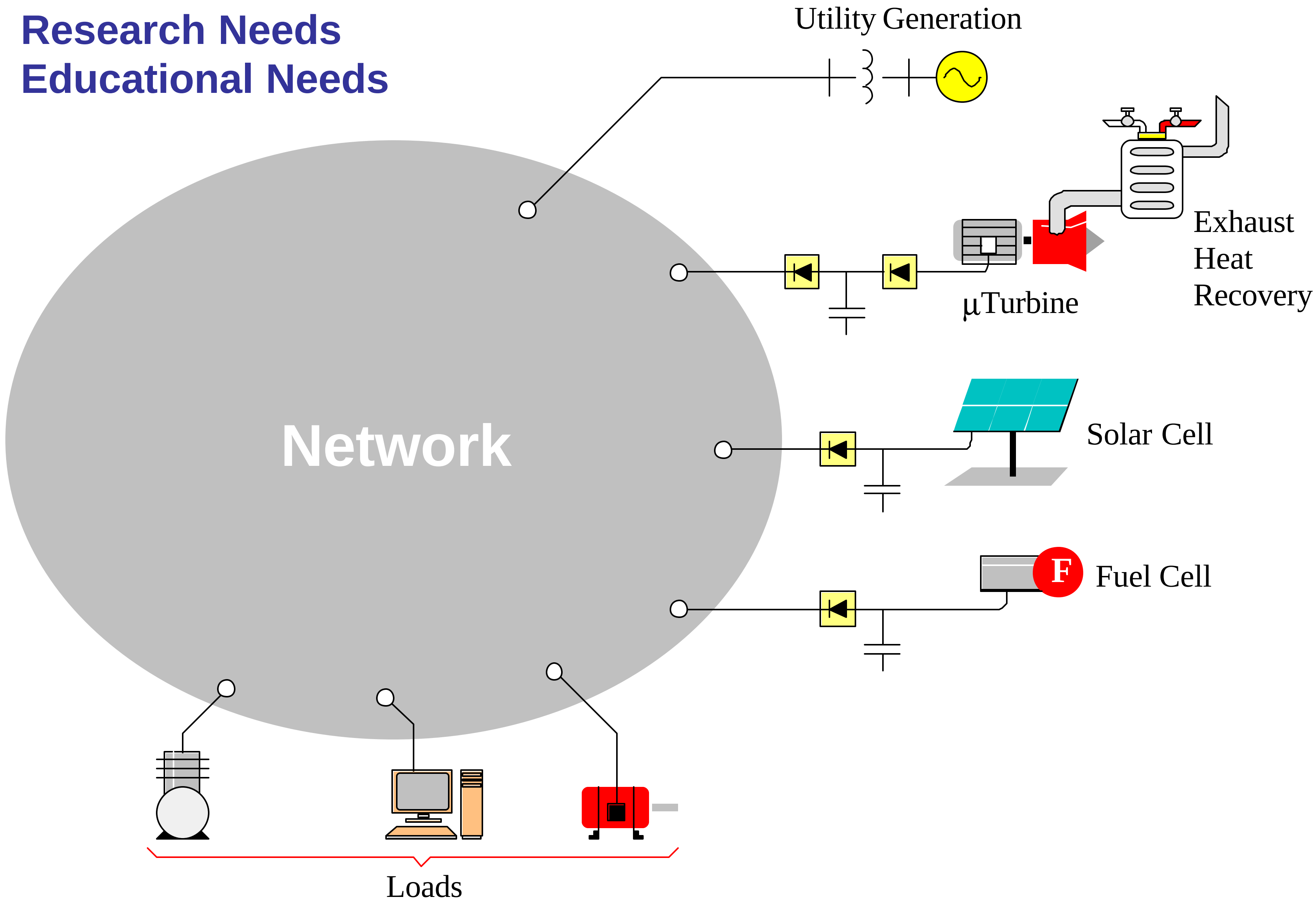
Promising Technologies

- **Fuel Cells**
- **MicroTurbines**
- **Photovoltaics**
- **PEBBs**

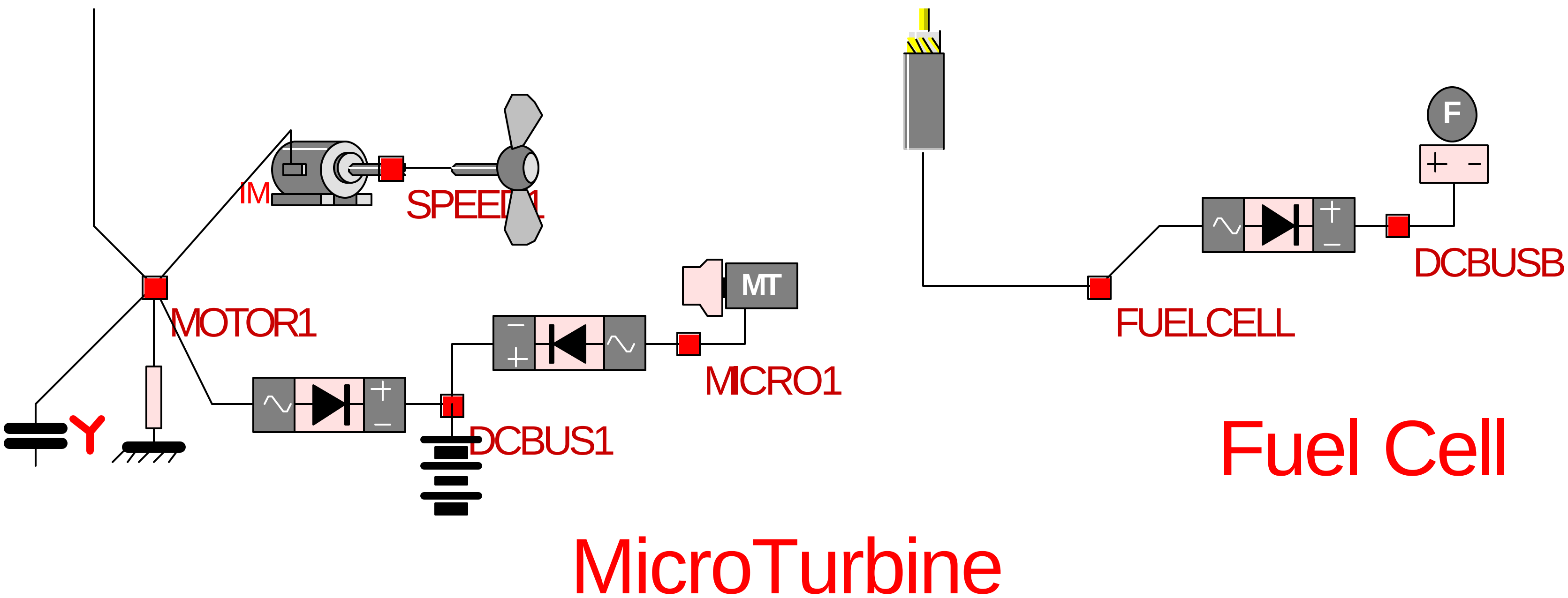


Future Power System

- Research Needs
- Educational Needs



Inertia-Less Interface – Ride Through
Limited Fault Currents - Protection



Technical Challenges

- InertiaLess Interface
- Protection/Control – Plug and Play
- Interactions of Controls
- Safety
- Load/Generation Control

Potential Benefits

- “Active” Load
- Combine Cycle Plants
- Premium Power Quality / Reliability
- Voltage Control

Partial Response to the Challenge:
High Fidelity Analytical Tools

- High Fidelity Models of Distribution System that May Contain 3-Wire, 4-Wire and 5-Wire Circuits.
- High Fidelity Models of Electronic Interface.
- Realistic Monitoring-Control-Protection Models.
- Applications:
  - Voltage Support at PCC,
  - Generation-Load-Frequency Control,
  - Controller Interaction,
  - Stability,
  - Protection

Partial Response to the Challenge:
High Fidelity Analytical Tools

Advantage: Avoid High Cost of Prototyping

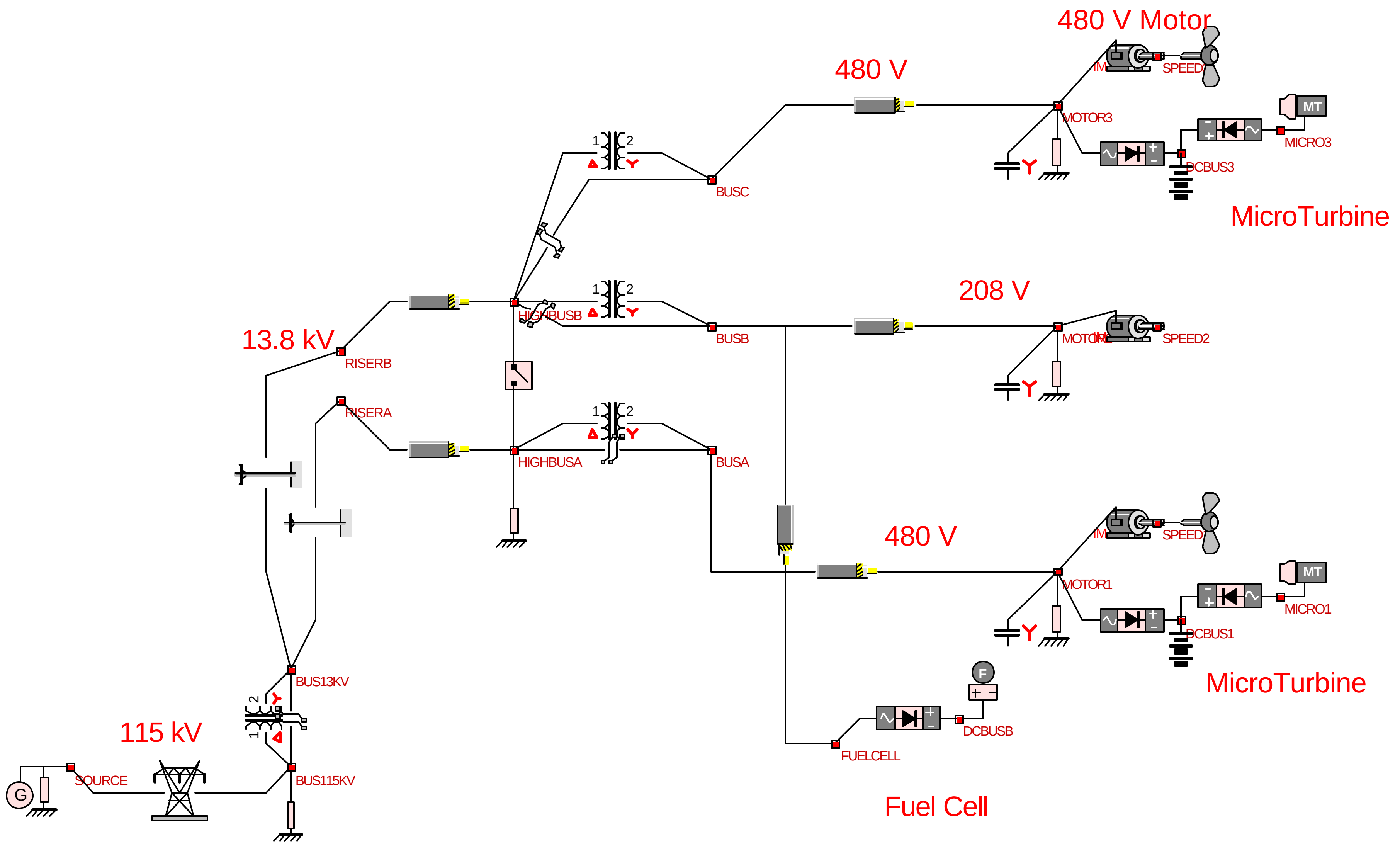
- High Fidelity Models of Distribution System that May Contain 3-Wire, 4-Wire and 5-Wire Circuits.
- High Fidelity Models of Electronic Interface.
- Realistic Monitoring-Control-Protection Models.
- Applications: Voltage Support at PCC, Generation-Load-Frequency Control, Controller Interaction, Stability, Protection

Physically Based Approach:

A Promising Road to High Fidelity Simulation Tools

- Component Modeling in Direct Phase Quantities without any approximating assumptions,
- Use of the Composite Node Concept. A composite node may consist of any number of nodes, for example: phase A, phase B, phase C, Neutral and Ground,
- Use of Quadratized Component Models i.e. Each Model Is Expressed in Terms of Equations of Order No Higher Than 2.

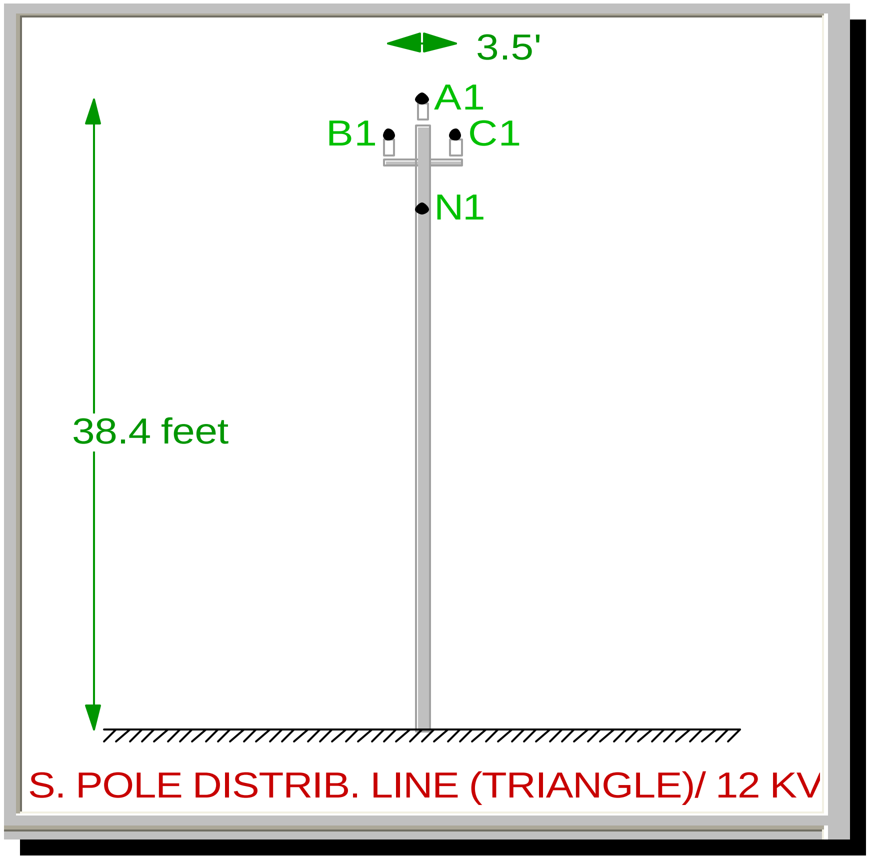
PBA: Distributed Energy Resources



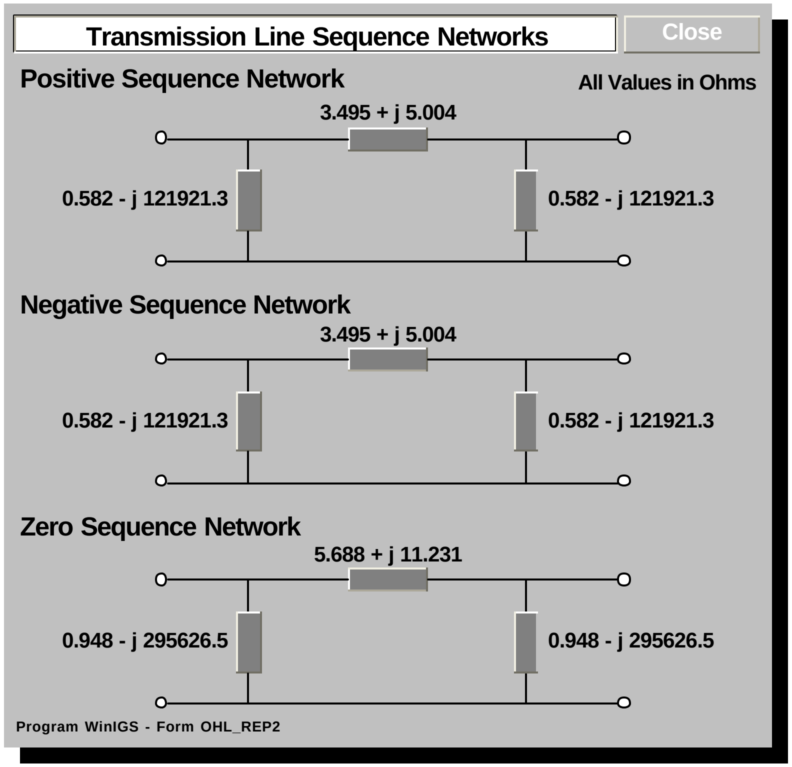
Physically Based Models

Example: Three Phase Power Line

Physically Based Model

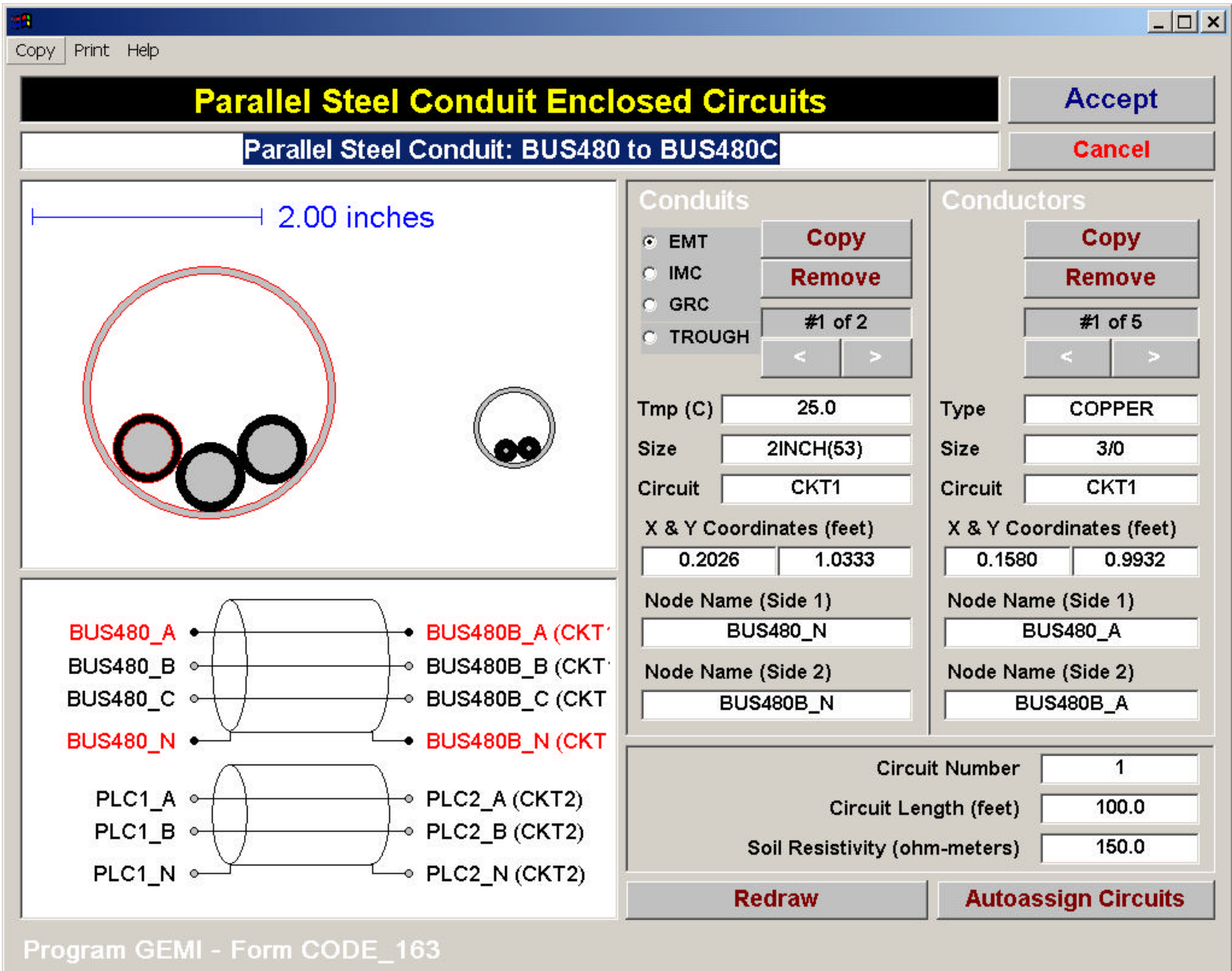


Sequence Parameter Model



Physically Based Models

Example: Metallic Conduit Enclosed Power Circuit



PBA: Unified Quadratized Models

$$\begin{bmatrix} i \\ 0 \end{bmatrix} = \begin{bmatrix} f_1(\dot{v}, \dot{y}, v, y, u) \\ f_2(\dot{v}, \dot{y}, v, y, u) \end{bmatrix}$$

$$z(t) = g_0(v,y,u,t)$$

i	Through Variables - Dependent Variables
v	Across Variables - External States
y	Internal State Variables
u	Controls - Independent
z(t)	Observation functions

Numerical Integration

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} diag(v(t), y(t)) F_1 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ diag(v(t), y(t)) F_2 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \vdots \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix}$$

PBA: Unified Quadratized Models

Component Model

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} diag(v(t), y(t))F_1 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ diag(v(t), y(t))F_2 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \vdots \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix}$$

Connectivity Constraints

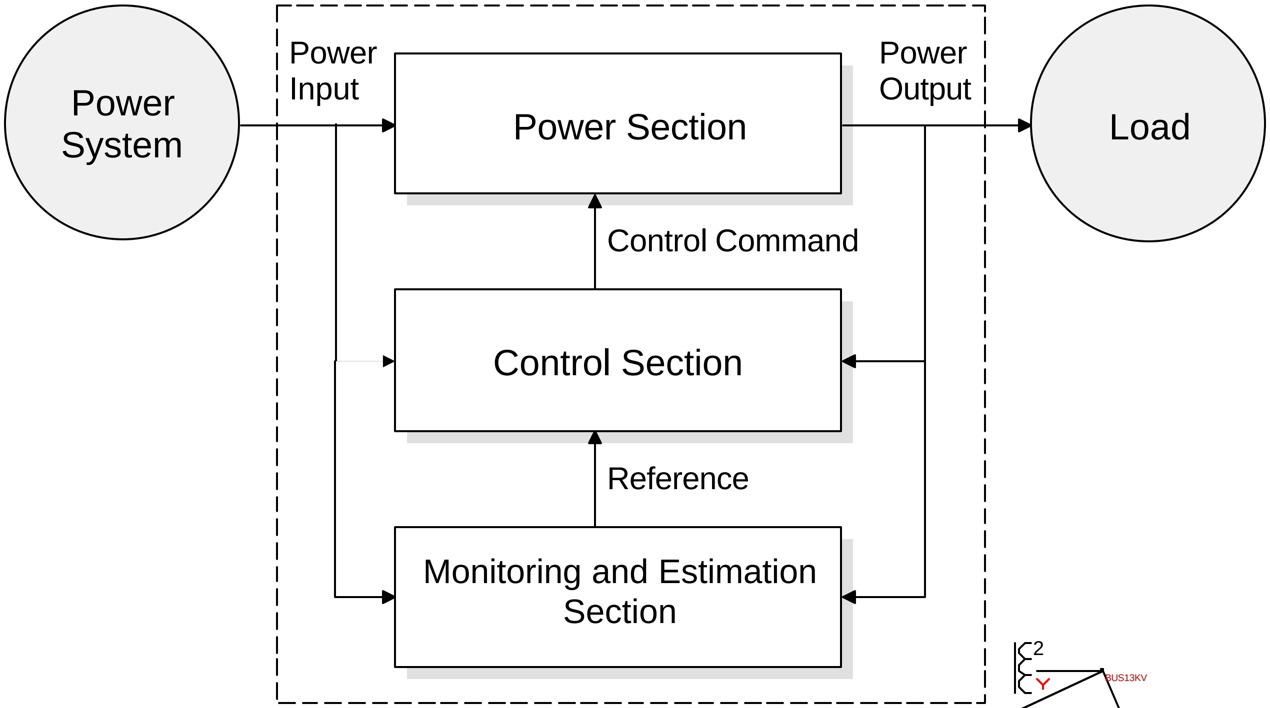
$$Ax(t) + \begin{bmatrix} diag(x(t)B_1(t)x(t) \\ diag(x(t)B_2(t)x(t) \\ \vdots \end{bmatrix} + b(t-h) = 0$$

Newton's Method

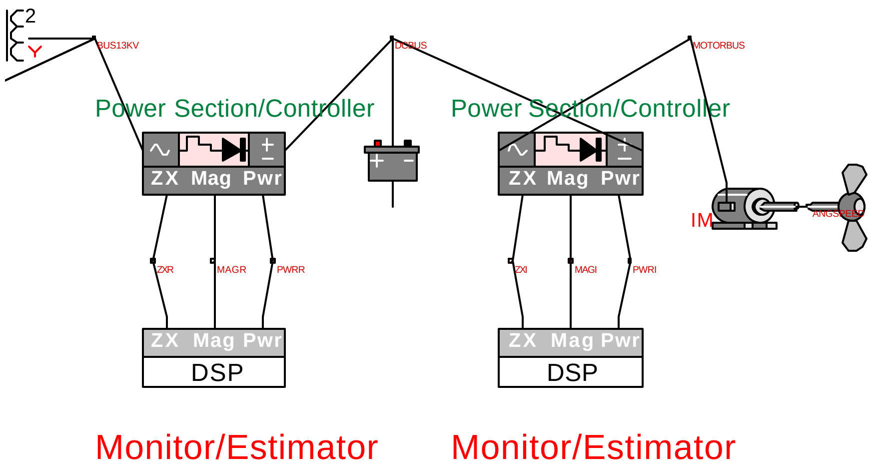
x(t)

Simultaneous Solution
Time Interval (t-h,t)

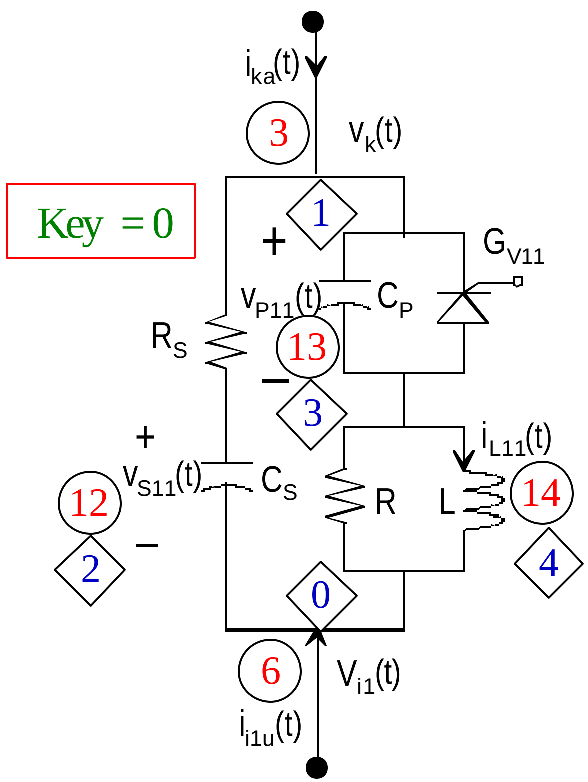
Interface Converters - Proposed Approach



Protection Should Be Incorporated in the Control Section



Valve State Equations



$$\begin{bmatrix} i_1(t) \\ 0 \end{bmatrix} = M_{valve} \cdot \begin{bmatrix} v\,(t) \\ y\,(t) \end{bmatrix} + N_{valve} \cdot \frac{d}{dt} \begin{bmatrix} v\,(t) \\ y\,(t) \end{bmatrix} + \begin{bmatrix} s_{valve1}(t) \\ s_{valve2}(t) \end{bmatrix}$$

$$M_{valve} = \begin{bmatrix} G & 0 & 0 & -G & 1 \\ 0 & G_S + G_V & -G_S & -G_V & 0 \\ 0 & -G_S & G_S & 0 & 0 \\ -G & -G_V & 0 & G + G_V & -1 \\ -1 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$N_{valve} = \begin{bmatrix} C_S & 0 & -C_S & 0 & 0 \\ 0 & C_P & 0 & -C_P & 0 \\ -C_S & 0 & C_S & 0 & 0 \\ 0 & -C_P & 0 & C_P & 0 \\ 0 & 0 & 0 & 0 & L \end{bmatrix}$$

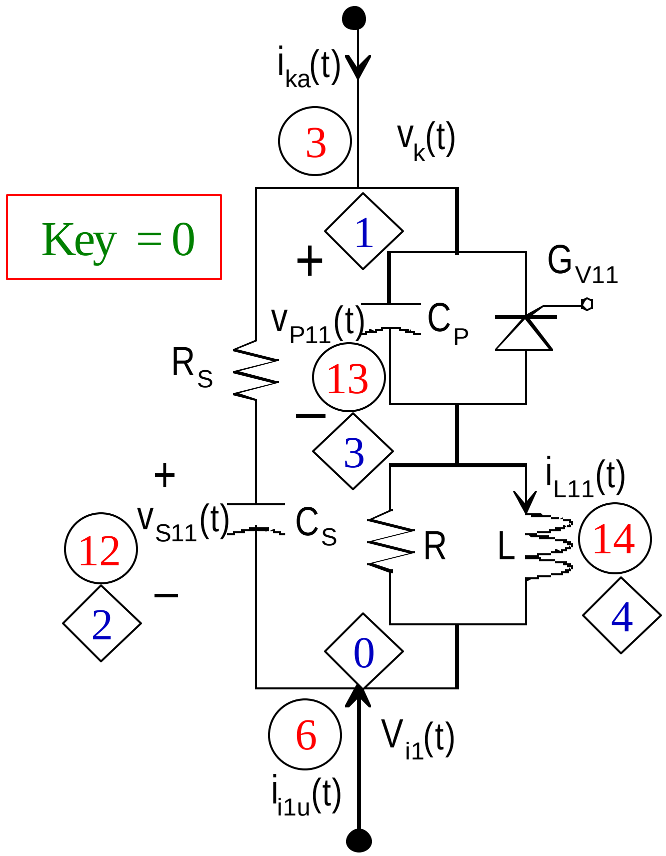
$$\begin{bmatrix} s_{valve1}(t) \\ s_{valve2}(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$i_1(t) = \left[i_{i1u}(t) \quad i_{ka}(t) \right]^T$$

$$v(t) = \left[v_{i1}(t) \quad v_k(t) \right]^T$$

$$y\,(t) = \left[v_{S11}(t) \quad v_{P11}(t) \quad i_{L11}(t) \right]^T$$

Valve Connectivity Table

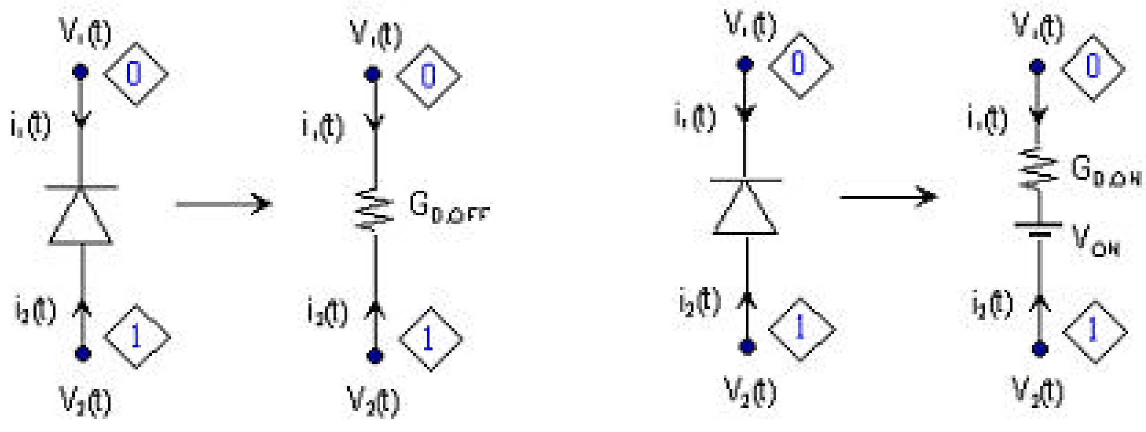


Valve Index	Pointer Entries
0	**6, 3, 12, 13, 14**
1	**0, 6, 15, 16, 17**
…	
11	**5, 11, 45, 46, 47**

Blue number – state index within valve

Red number – state index of converter

Clamping Diode Model



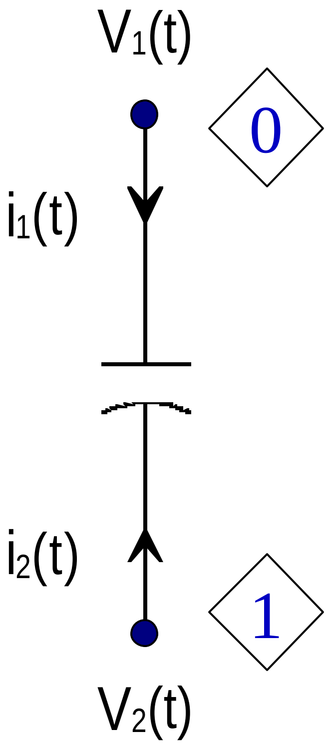
$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} = \begin{bmatrix} G & -G \\ -G & G \end{bmatrix} \cdot \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} - \begin{bmatrix} -V_D G \\ V_D G \end{bmatrix}$$

$$G = \begin{cases} G_{D,Off}, & if\ v_2(t) - v_1(t) < V_{ON} \\ G_{D,ON}, & if\ v_2(t) - v_1(t) \geq V_{ON} \end{cases}$$

$$V_D = \begin{cases} 0, & if\ v_2(t) - v_1(t) < V_{ON} \\ V_{ON}, & if\ v_2(t) - v_1(t) \geq V_{ON} \end{cases}$$

Diode Index	Pointer Entries
0	6, 4
1	4, 7
…	
5	4, 11

Smoothing Capacitor Model



Capacitor Model

$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} = \begin{bmatrix} C & -C \\ -C & C \end{bmatrix} \frac{d}{dt} \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix}$$

Capacitor Index	Pointer Entries
0	3, 4
1	4, 5

Converter State-Space Model

Application of connectivity constraints to the valve, diode and capacitor models yields the overall converter state space model.

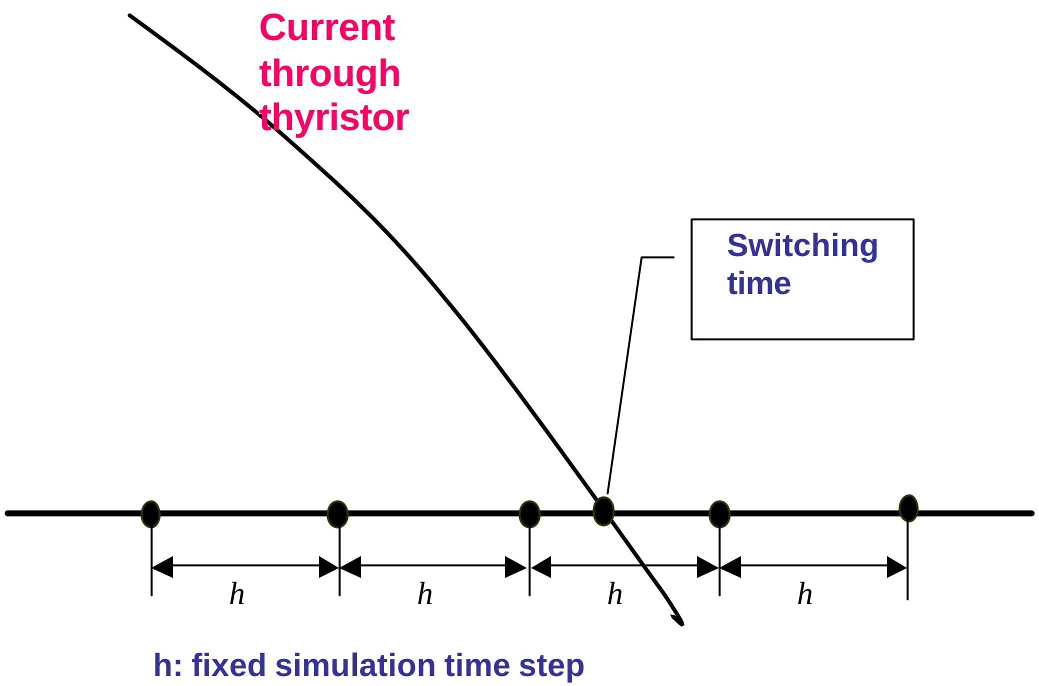
$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix}$$

Converter Algebraic Companion Form

Application of trapezoidal integration yields the Algebraic Companion Form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} v(t-h) \\ y(t-h) \end{bmatrix} - \begin{bmatrix} i_1(t-h) \\ 0 \end{bmatrix} + 2 \cdot \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix}$$

Multi-Rate Simulation



- Switching can occur between two fixed time steps. Using fixed time step will generate erroneous results;
- Our solution:
  - Detect upcoming switching in next time step;
  - Apply sub-step integration for [t-h,t] period.

Controls: Power Flow, Voltage Regulation, Harmonic Elimination, Unbalance Control, etc.

Example: Harmonic Elimination / Mitigation

Three-Level Converter Harmonics - Ideal

$$a_1 = \frac{4E}{p} \cdot \left(\sin a_1 - \sin a_2 + \sin a_3\right)$$

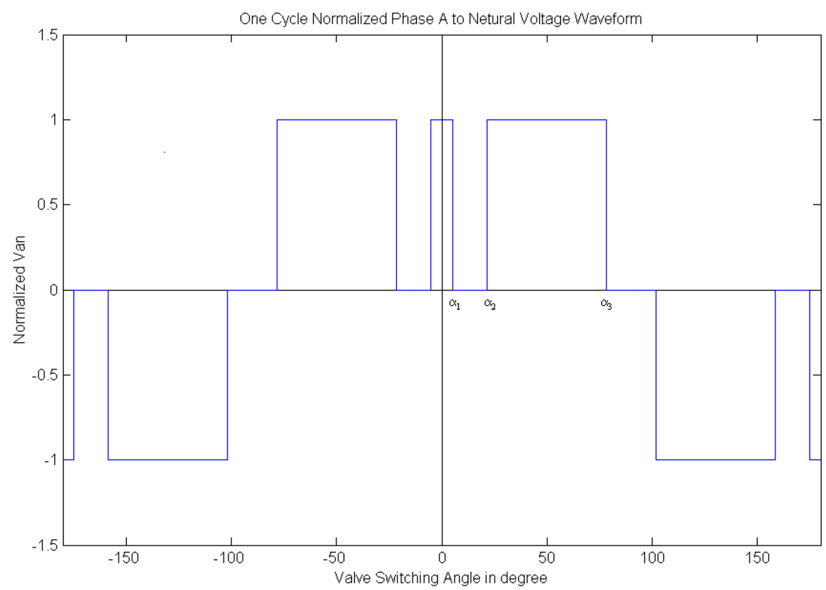
$$a_5 = \frac{4E}{5p} \cdot \left(\sin 5a_1 - \sin 5a_2 + \sin 5a_3\right)$$

$$a_7 = \frac{4E}{7p} \cdot \left(\sin 7a_1 - \sin 7a_2 + \sin 7a_3\right)$$

$$m = \frac{a_1}{\frac{4E}{p}}$$

To Eliminate 5th and 7th Harmonic
Set a5=a7=0.0

Solution for *m* = 0.7:



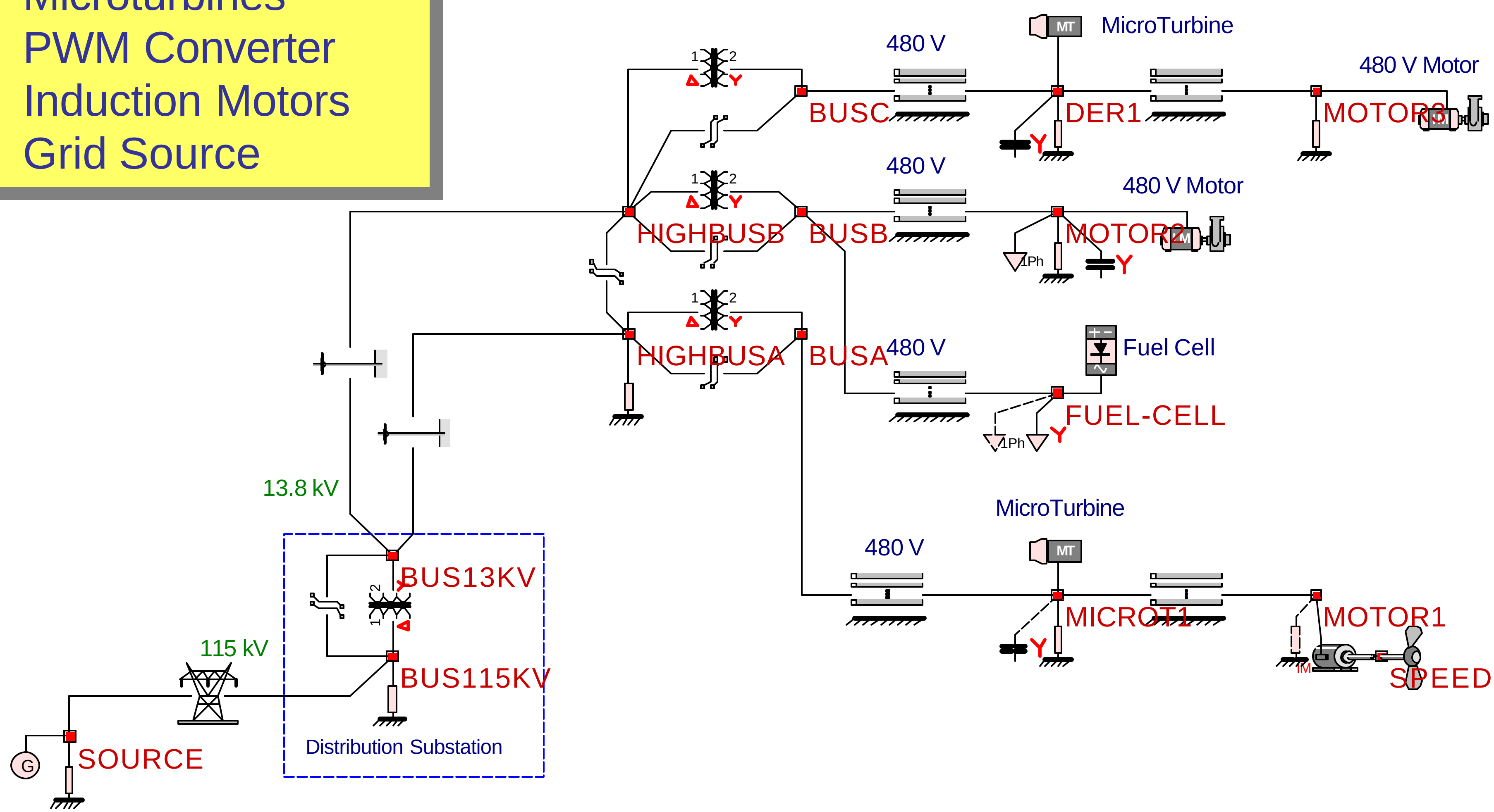
$$a_1 = 5.2^0, \quad a_2 = 21.7^0, \quad a_3 = 78.1^0.$$

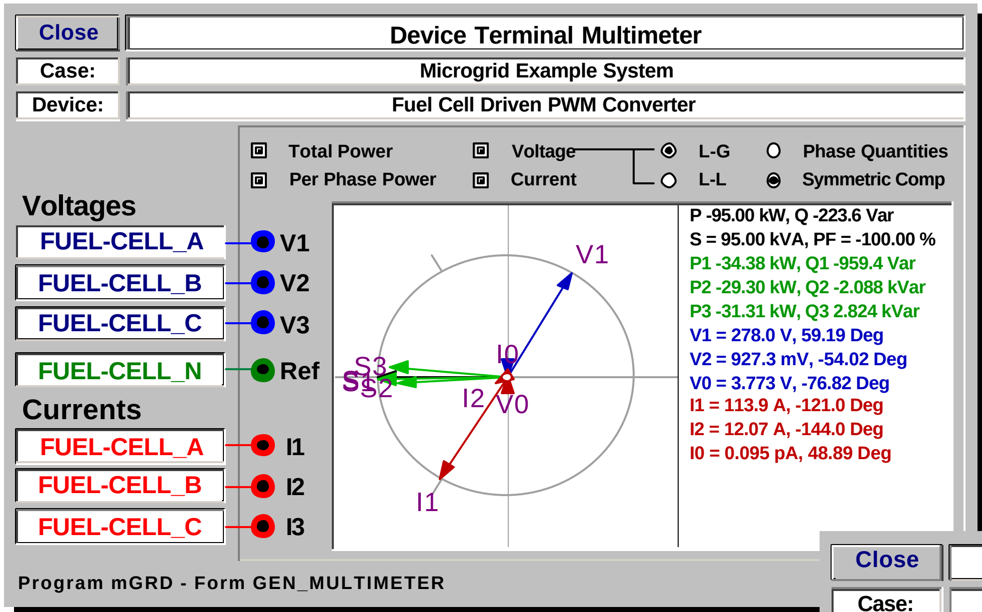
Applications

- Simulation of Potential Designs and Controls Schemes
- Virtual Prototyping
- Protection Schemes
- Small Signal Stability Analysis
- Safety Analysis
- Other

mGRD Network Modeling Capability

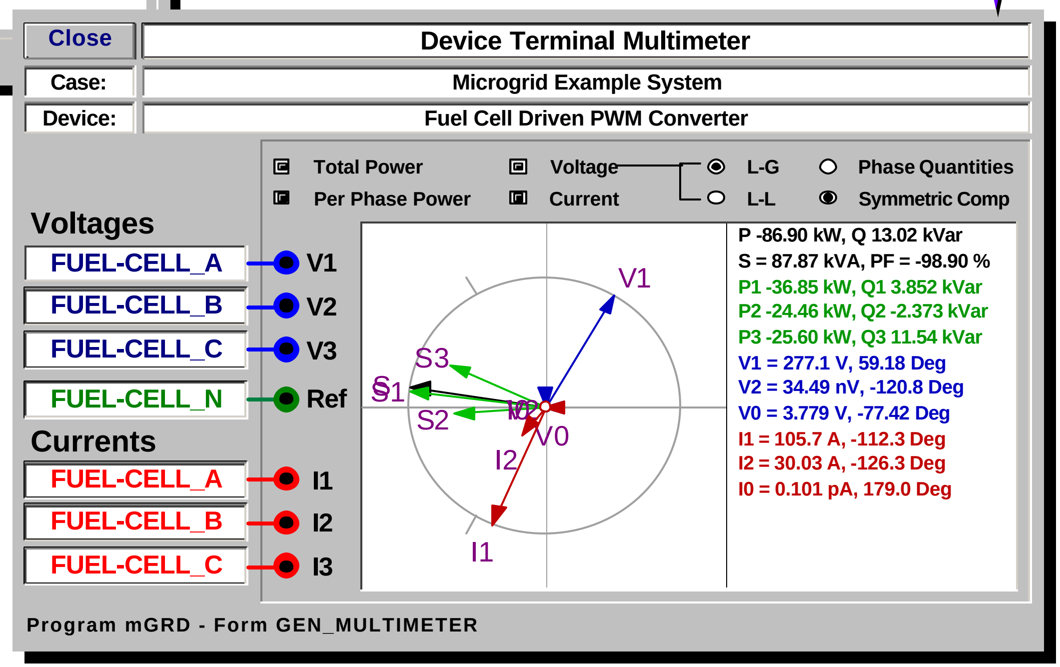
- Power Lines
- Transformers
- Microturbines
- PWM Converter
- Induction Motors
- Grid Source





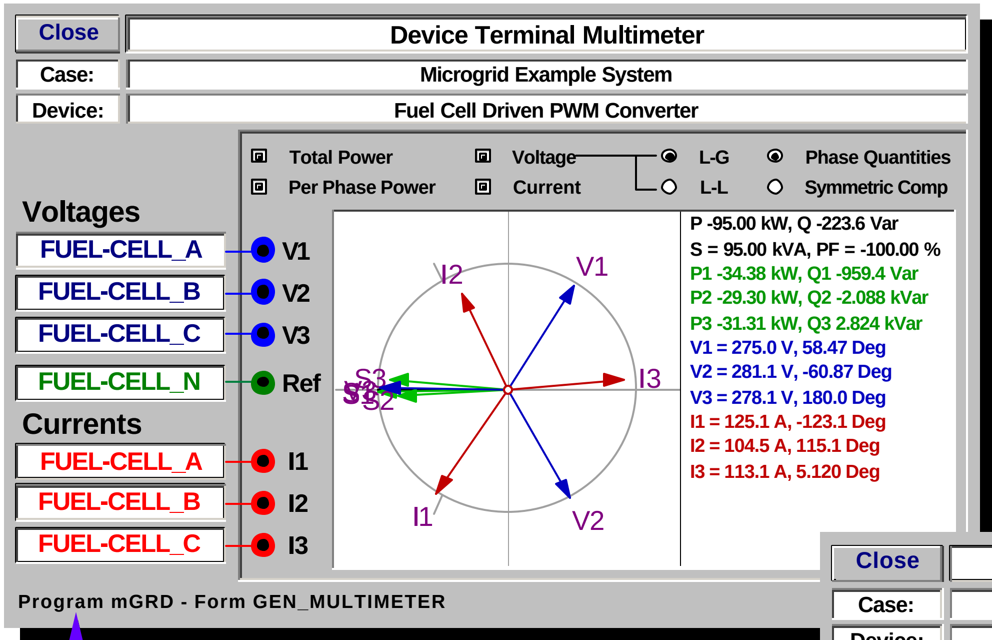
Solution with Fuel Cell in Negative Seq. Control

Solution with Fuel Cell in PV Mode



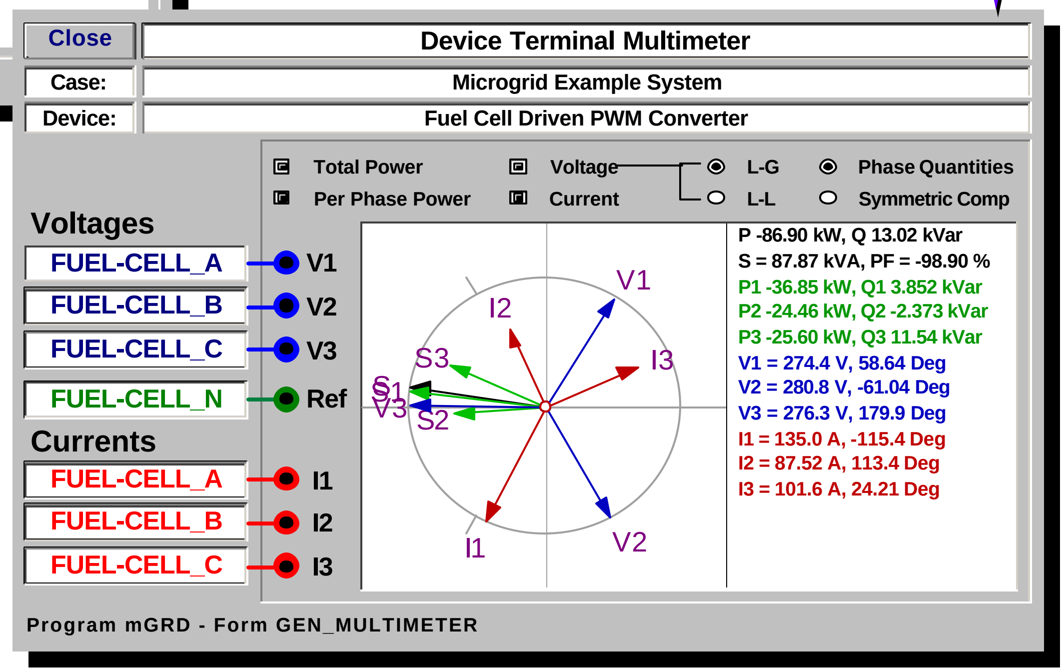
(Sequence Component Reports)

mGRD Application Example : Negative Sequence Control



Solution with Fuel Cell in Negative Seq. Control

Solution with Fuel Cell in PV Mode



(Actual Values Reports)

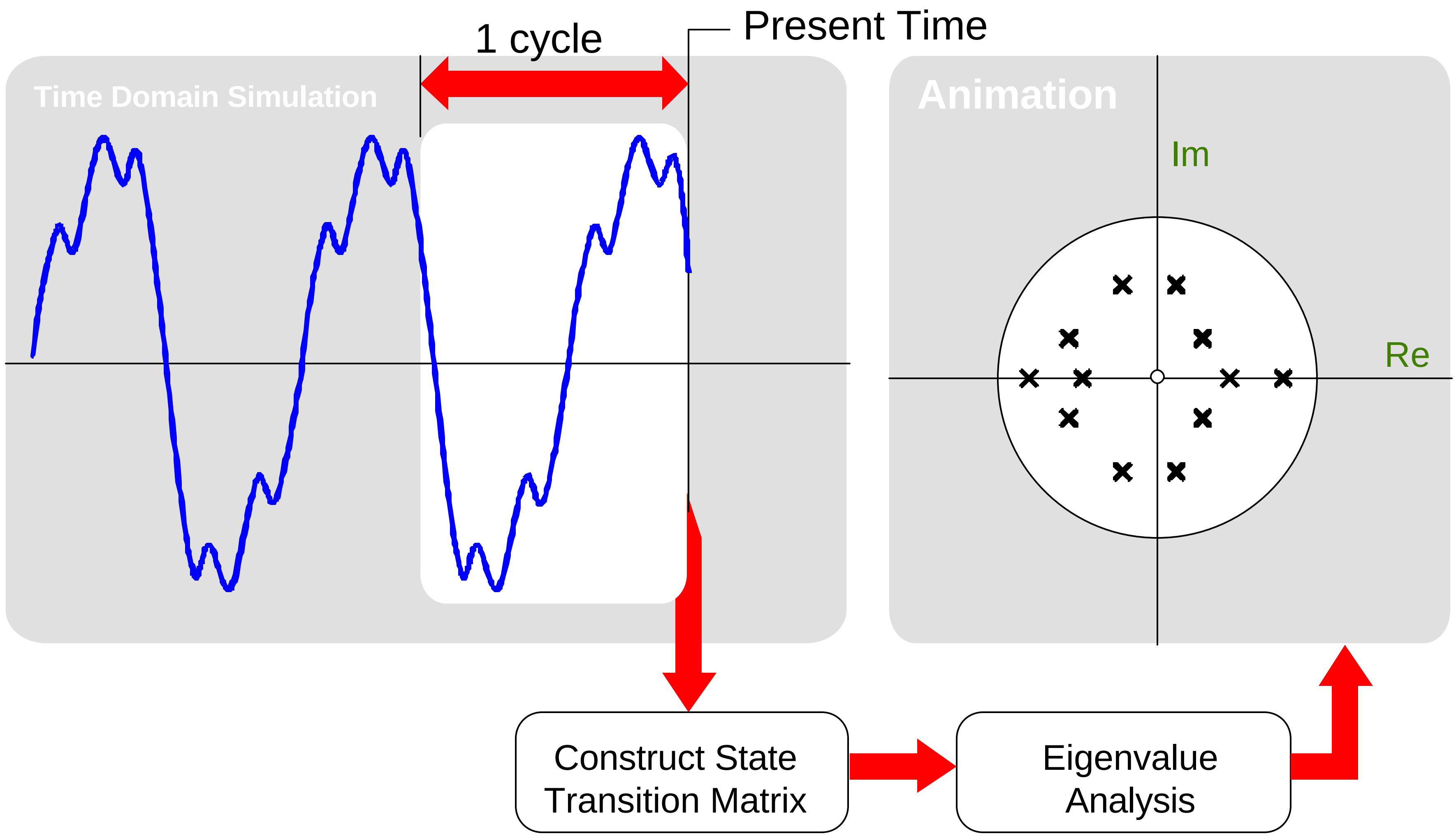
Motivation

- PEBB Based Systems Present Unique Stability Problems.
- Complex Interaction Among Switching Systems and Electro-Mechanical Systems
- Traditional Methods for Stability Analysis Have Limitations

Proposed Method

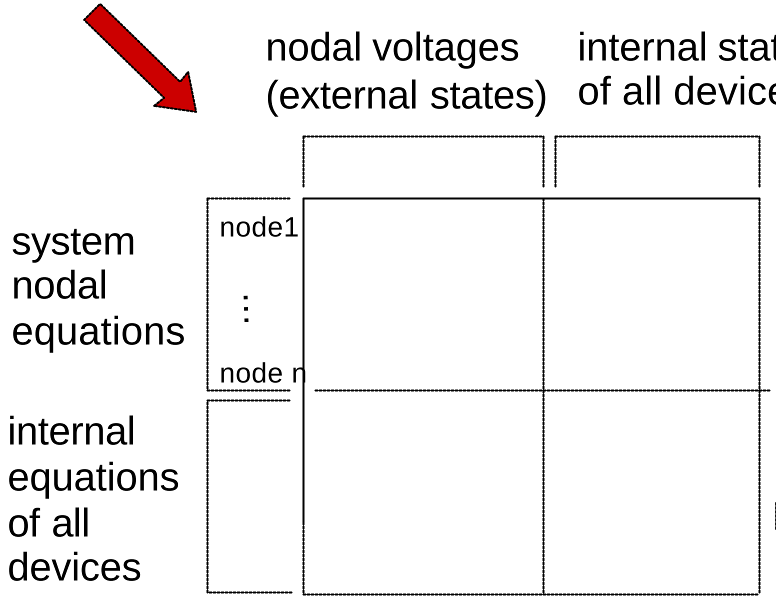
- Numerical Computations of the System Transition Matrix Over a User Specified Time Interval.
- Applicable to Switching Systems with Linear & Nonlinear Components

Small Signal Stability Analysis



Small Signal Stability Analysis

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = A_d x(t) + B_d x(t-h) + C_c u$$



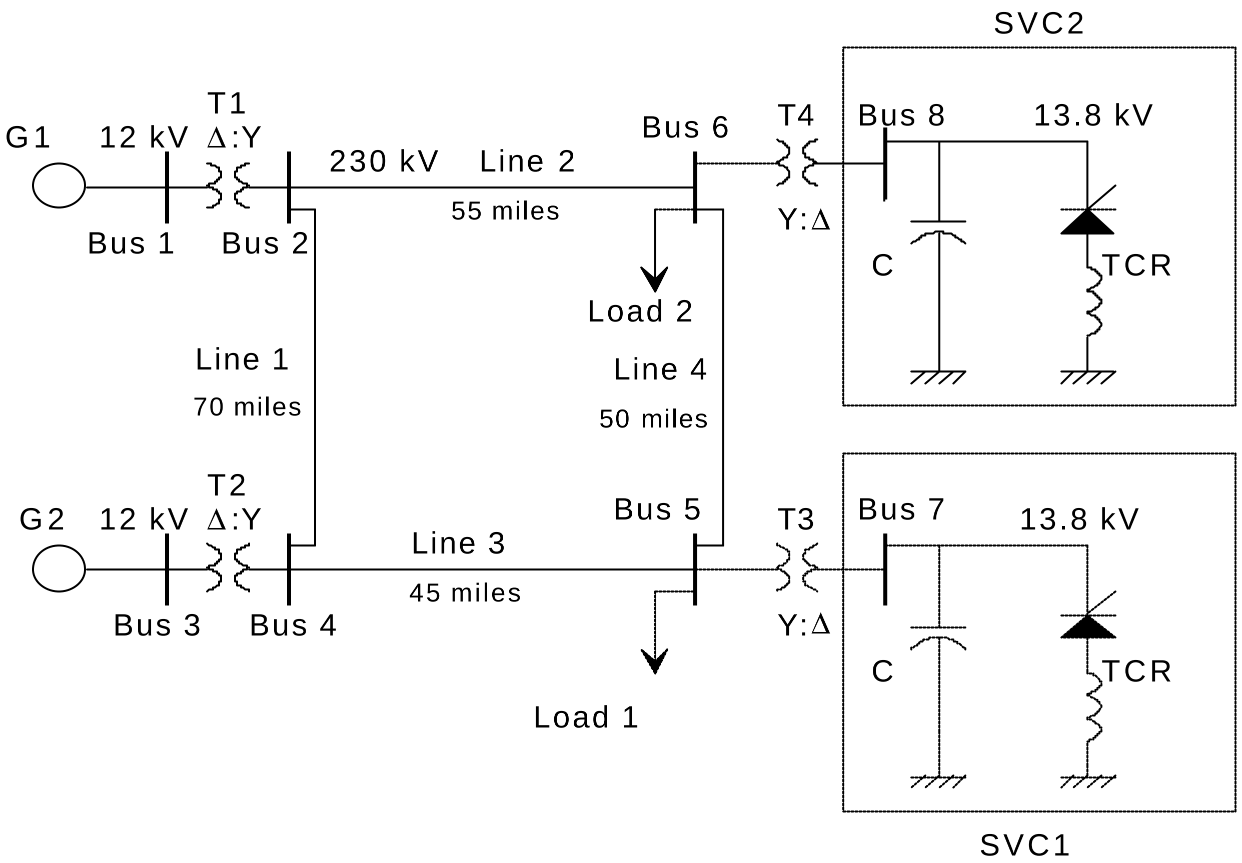
$$0 = Ax(t) + Bx(t-h) + Cu$$

$$x(t) = -A^{+}Bx(t-h) - A^{+}Cu$$

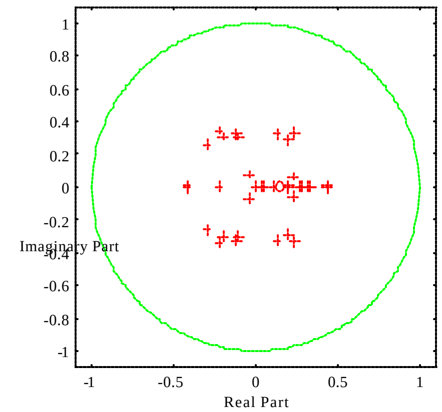
Important Issue:

Modeling of Feedback Control

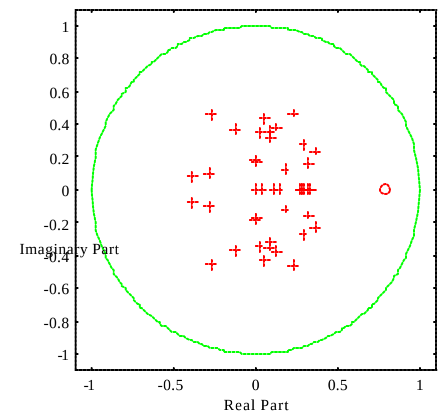
Small Signal Stability Analysis Example



SCV#1 On, SCV#2 Off



SCV#1 On, SCV#2 On



Summary

Physically Based Approach for Modeling and Analysis Provides Powerful Tools for Simulation, Control, Protection and Stability Analysis

Τελος