A Modeling Framework to Integrate Exogenous Tools for Identifying Critical Components in Power Systems

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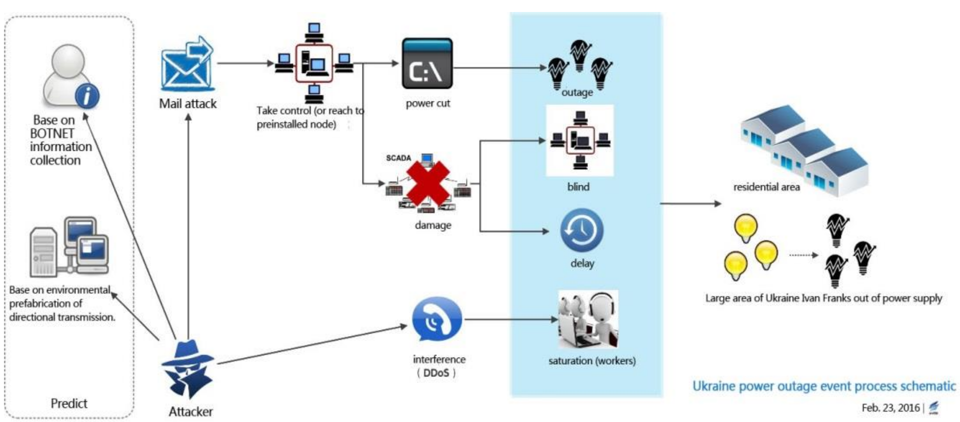
Cascading Failures: Power Transmission Systems

- Power systems are vulnerable to both **physical-attacks** and **cyber-attacks.**
- Dec 2015 **Ukraine** and July 2012 **India** are recent blackout cases.
- Need for detailed understanding of cascading failures to identify critical components for improving system reliability and resiliency.
- Simulation platforms including various aspects of the system either do not exist or are typically very expensive.



Cyber-Attack Example

Power System

Cascading Failures: Power Transmission and Distribution Systems

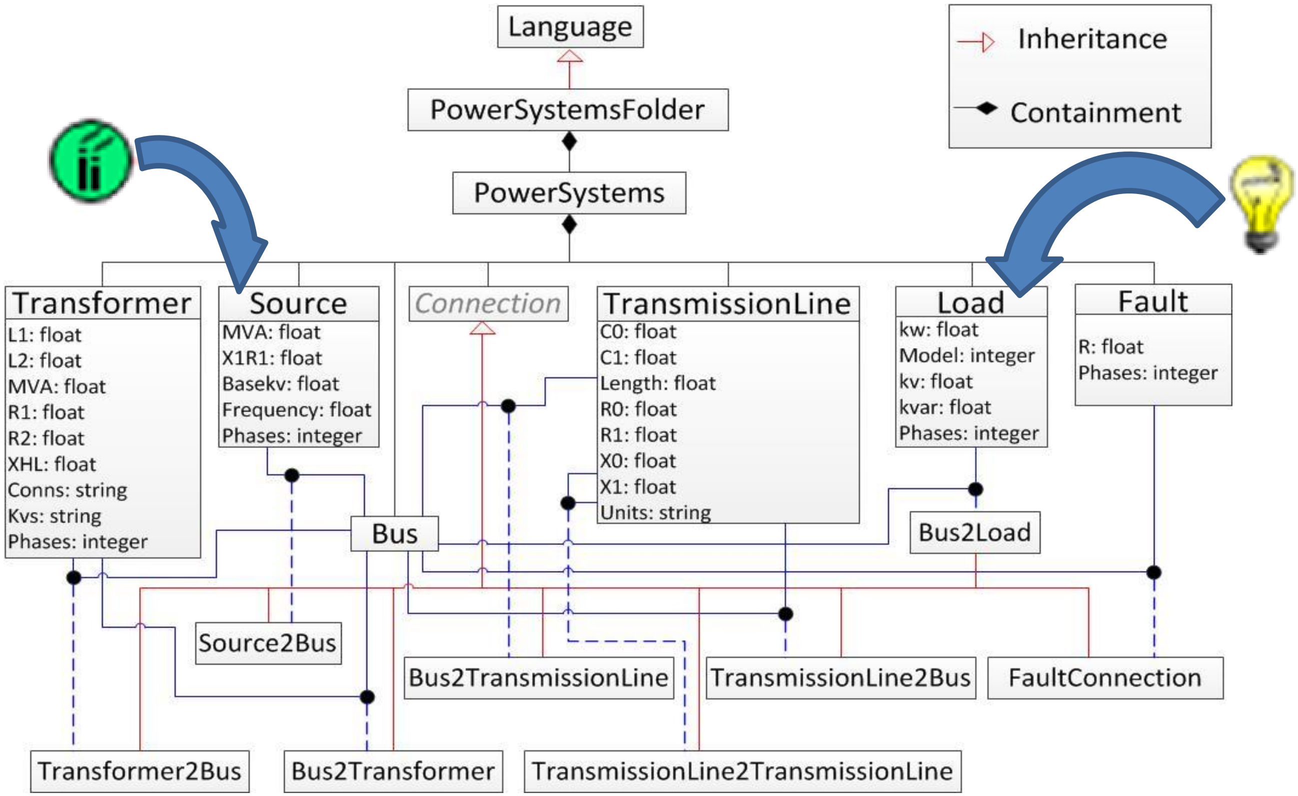
- Use of multiple simulation platforms (open source etc.)
- Tools have their own modeling semantics and specifications and are limited in their capabilities (GridLab-D, Modelica, PSCAD etc.).
- System modeling in multiple simulation platforms is error prone and time consuming.
- Need for a common Domain-Specific Modeling Language (DSML).
- Need for a System framework to integrate exogenous tools together.

Contributions

- Describes a **Domain-Specific Modeling Language (DSML) for power systems.**
- A **System framework** is proposed that **integrate exogenous tools** together.
  - ✓ System modeling using the developed DSML.
  - ✓ Identifying the type of analysis to be performed.
  - ✓ Model transformation based on the specifications of a particular tool.
  - ✓ Choosing the appropriate tool(s) and performing the analysis to identify critical components.

Modeling Language

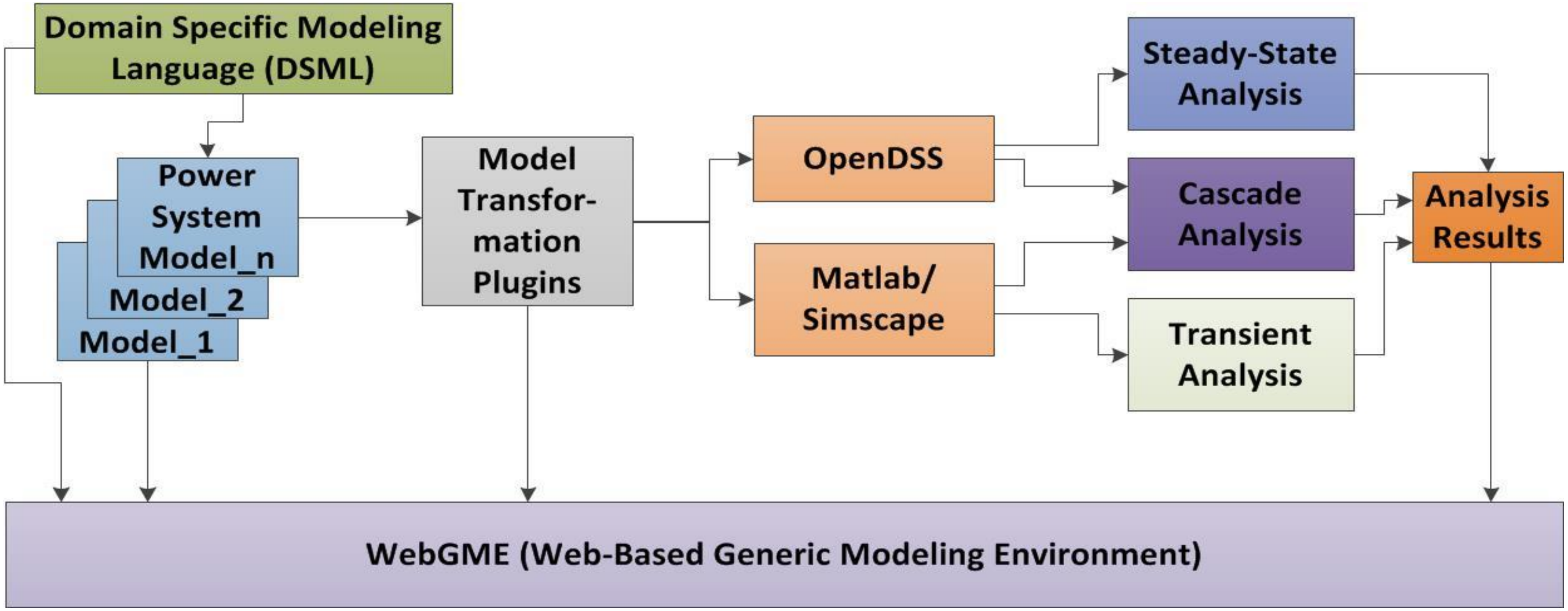
- Each **object** has a name and a **set of attributes** that define their **individual properties**.
- Objects are connected together using the **rules** defined by connection object.



Modeling Language- UML Class Diagram

System Framework

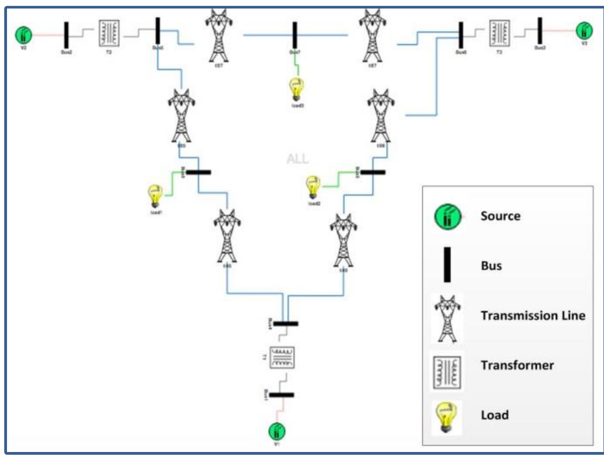
- Model development based on the semantics and rules defined in DSML.
- Model transformation considering object properties of individual simulation platforms.
- Reduces **system modeling time** and **error**.
- Modeler can select the appropriate simulation tool to perform the required analysis.



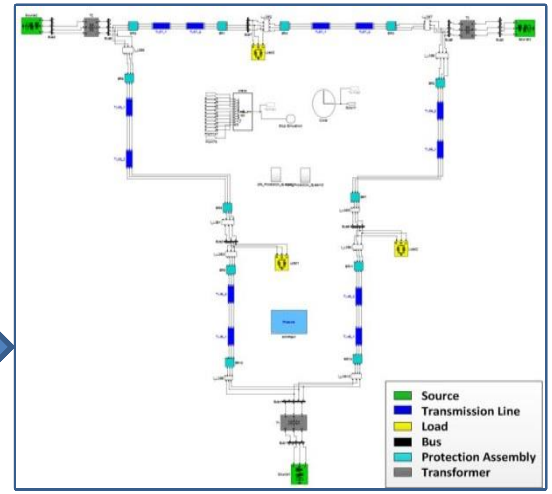
System Framework

Modeling and Model Transformation

Power system model (using DSML in WebGME):



Power system model (in SimScape):



Includes: Behavioral model of protection elements under cyber attack

Power system model (in OpenDSS):

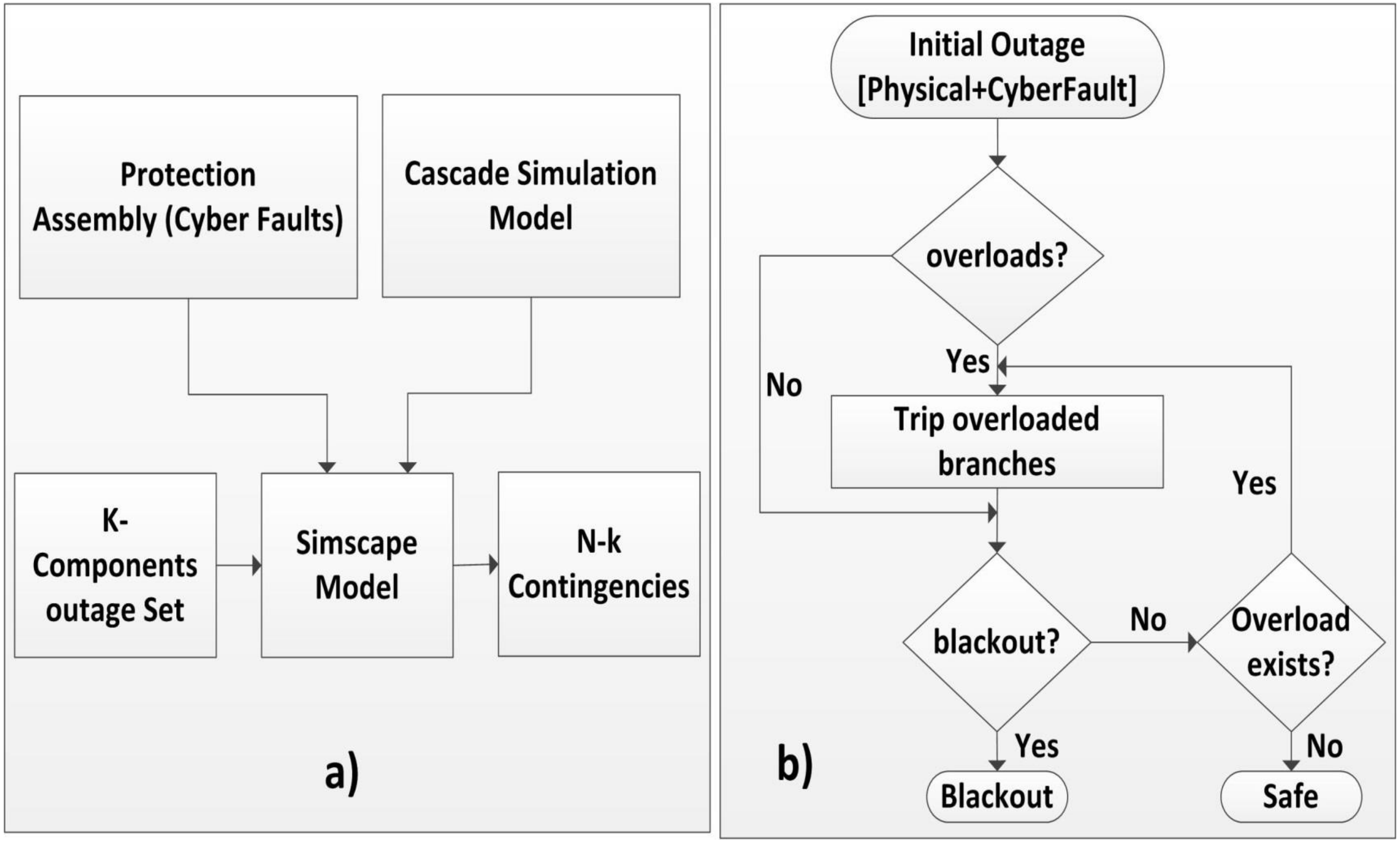
```
clear
New object=circuit.9bus
//Define Sources
New vsource.Source1 bus1=Bus1 phases=3 basekv=16.5 Mvasc3=247.5 r1=.0000001 x1=0.0000001
New vsource.Source2 bus1=Bus2 phases=3 basekv=18 Mvasc3=192 r1=.0000001 x1=.0000001
New vsource.Source3 bus1=Bus3 phases=3 basekv=13.8 Mvasc3=128 r1=.0000001 x1=.0000001
//Define the transmission lines and transformers
New Line.TL48 bus1=Bus4 bus2=Bus8 R1= 0.0529 R0=0.13225 X1=.4494 X0=.8972 C1=8.82  C0=5.188 length=62.1371 units=mi
New Line.TL49 bus1=Bus4 bus2=Bus9 R1=0.08993 R0=0.224825 X1=.4863 X0=1.2139 C1=7.922 C0=4.74 length=62.1371 units=mi
New Line.TL85 bus1=Bus8 bus2=Bus5 R1=0.16928 R0=0.4232 X1=.8516 X0=2.1262 C1=15.34 C0= 9.025 length=31.0686 units=mi
New Line.TL96 bus1=Bus9 bus2=Bus6 R1=0.20631 R0=0.5157 X1=.8972 X0=2.2959 C1=17.95 C0= 10.55 length=62.1371 units=mi
New Line.TL57 bus1=Bus5 bus2=Bus7 R1=0.044965 R0= 0.11241 X1=.3808 X0=.7615 C1=7.471 C0= 4.394 length=62.1371 units=mi
New Line.TL67 bus1=Bus6 bus2=Bus7 R1=0.062951 R0= 0.15737 X1=.5331 X0=1.3308 C1=10.47 C0= 6.15 length=62.1371 units=mi
New transformer.T1 phases= 3 buses= (Bus1 Bus4) Kvas=[100000 100000] conns= 'wye wye' kvs= "16.5 230" XHL=5.7147
New transformer.T2 phases= 3 buses= (Bus2 Bus5) Kvas=[100000 100000] conns= 'wye wye' kvs= "18 230" XHL=6.5619
New transformer.T3 phases= 3 buses= (Bus3 Bus6) Kvas=[100000 100000] conns= 'wye wye' kvs= "13.8 230" XHL=5.0917
//Define the loads
New Load.Load1 bus1=Bus8 phases=3 kVA=125000, 50000 Kv=230 conn= delta model=1
New Load.Load2 bus1=Bus9 phases=3 KVA=90000, 30000 Kv=230 conn= delta model=1
New Load.Load3 bus1=Bus7 phases=3 kVA=100000, 35000 Kv=230 conn= delta model=1
//Define the voltagebases
set voltagebases=[16.5, 18, 13.8, 230]
calcv
set freq=60
set mode=snapshot
solve
```

Why two models?

- ➢ *Simscape: fine grain time-domain analysis including discrete components (slow)*
- ➢ *OpenDSS: steady-state analysis (fast)*

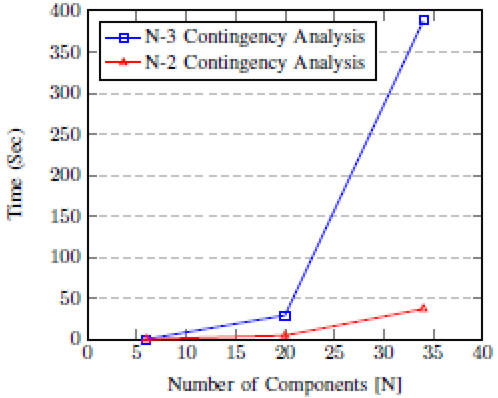
Cascade Algorithm Flowchart

- Based on initial outages (physical faults, cyber-faults or both) causing component(s) overloading.

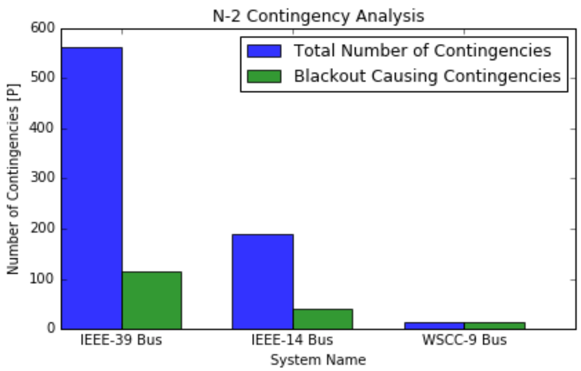


Case Study: Identification of Critical Components in Power Systems

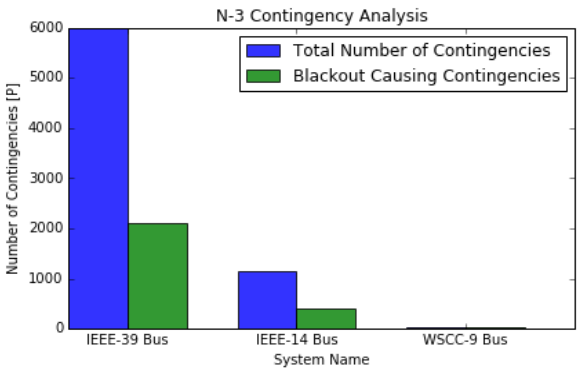
- Case study performed on:
  - WSCC-9 Bus System.
  - IEEE-14 Bus System.
  - IEEE-39 Bus System.
- OpenDSS Time-Independent Analysis.
  - Time Independent fast cascade analysis is performed using cascade framework.
  - Ideal for quickly identifying **critical transmission lines** based on **initial outages**.
  - Power Systems are usually N-1 tolerant (based on NERC).
  - N-2, N-3 contingency analysis is performed (168/901, 2515/7144).



Execution Time



N-2 Contingency Analysis



N-3 Contingency Analysis

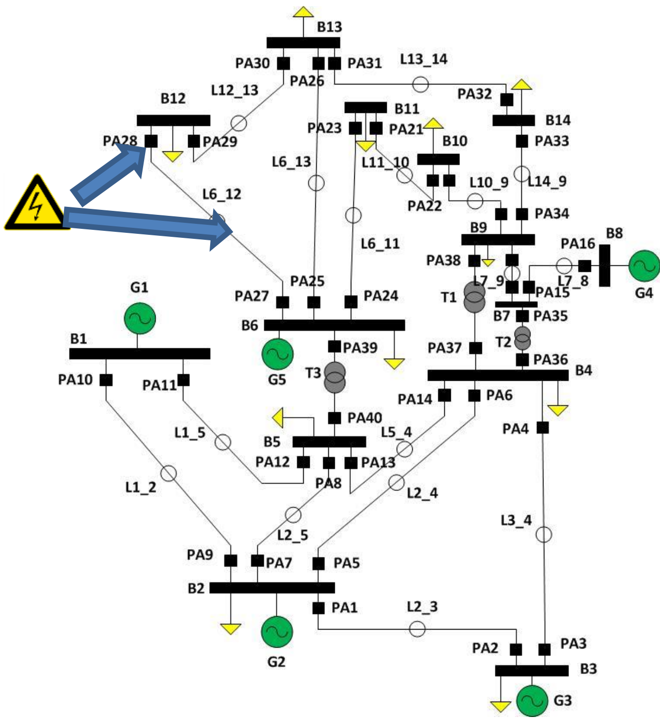
Case Study: Identification of Critical Components in Power Systems

❖ Matlab/Simscape Time-Based Analysis.

- Fine grain analysis (**Time domain analysis** and **cyber-faults injection** in protection assemblies).
- A **Physical fault** and a **cyber-fault** (*Stuck close breaker fault*).
- Identification of **critical protection assemblies** causing blackouts.

Critical Protection Assemblies Categorization

Category Name	Component Name	Load Loss
Category I	PA_BR4, PA_BR13, PA_BR14	Above 40%
Category II	PA_BR6, PA_BR7	Very close to 40% (39.22%)
Category III	PA_BR18, PA_BR22, PA_BR34	> 25% and < 35%



IEEE-14 Bus System

Conclusions

- A Domain-Specific Modeling Language is developed for power systems.
- A System framework is proposed that integrate exogenous tools and identify critical components in power systems.
- Identified critical components need to protected more for improving system resiliency.

Acknowledgements

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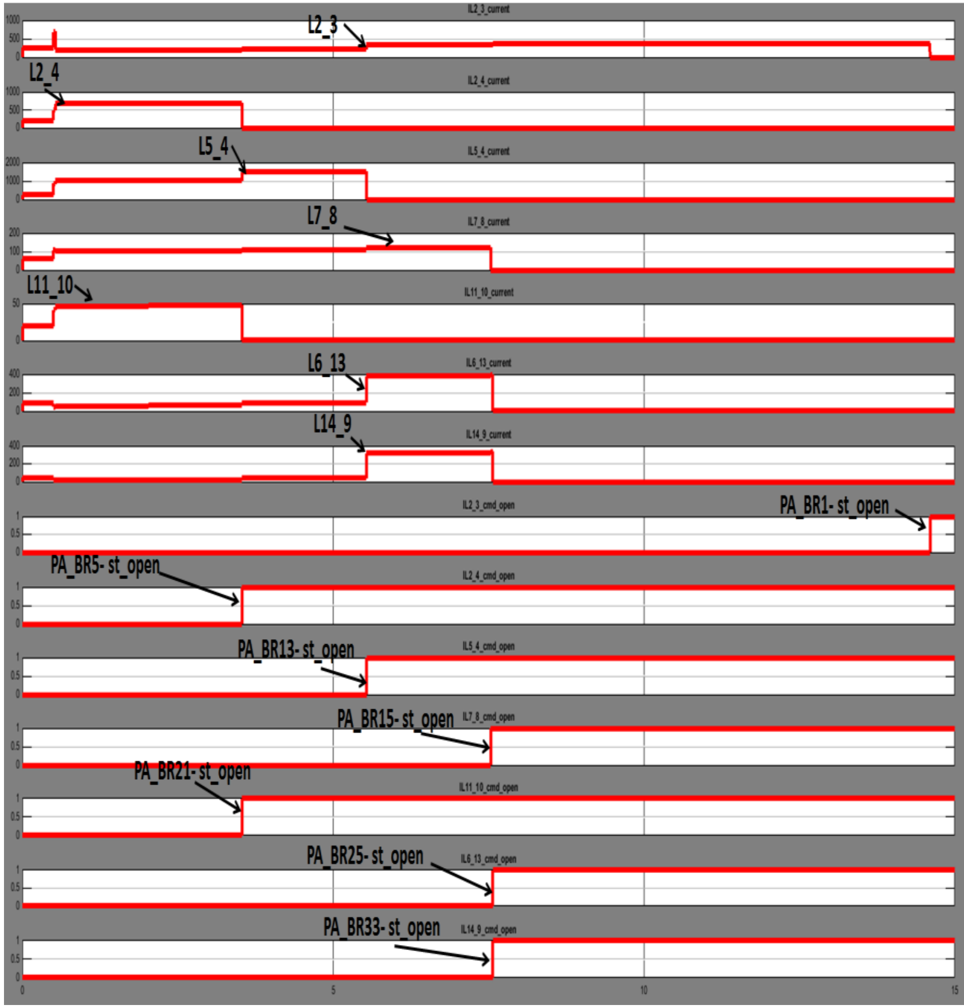
Thank You!

Cascade Scenario with Timing Details and Cyber-Faults in Protection Assemblies

TABLE II: Sequence of cascading events

Time(sec)	Event Description
0.500	**F:** 3ϕ-G fault- Line L3_4, Stuck close fault- PA_BR4.
0.501	**D:** Z1, Z3 in PA_DR{3,4}, PA_DR1, 'P1_OL' in PA_OR3, 'P2_OL' in PA_OR{5,1,13}, 'P3_OL' in PA_OR{9,15,21}. **CR:** 'cmd_open' in PA_BR3.
0.532	**S:** st_open-PA_BR3 is opened. **L:** Line L3_4 tripped partially.
2.000	**F:** Spurious detection fault in PA_DR27. **CS/CR:** 'cmd_open' in PA_DR27/PA_BR27.
2.031	**S:** 'st_open'-PA_BR27 is opened. **L:** Line L6_12 is removed.
3.503	**D:** 'P2_OL' in PA_OR13. **CS/CR:** 'cmd_open' in PA_OR{5,21}/PA_BR{5,21}.
3.534	**D:** 'P2_OL' in PA_OR31. **S:** 'st_open'- PA_BR{5,21} are opened. **L:** Lines L2_4, L11_10 removed.
5.505	**CS/CR:** 'cmd_open' in PA_OR13/PA_BR13.
5.536	**D:** 'P1_OL' in PA_OR{25,33}, 'P2_OL' in PA_OR {35,40}, 'P3_OL' in PA_OR{29,37}. **S:** 'st_open'-PA_BR13 is opened. **L:** Line L5_4 is disconnected.
6.536	**D:** 'P1_OL' in PA_OR31.
7.503	**CS/CR:** 'cmd_open' in PA_OR15/PA_BR15.
7.534	**S:** 'st_open'-PA_BR15 is opened. **L:** Line L7_8 is removed.
7.538	**CS/CR:** 'cmd_open' in PA_OR{25,33}/PA_BR{25,33}.
7.569	**D:** 'P3_OL' in PA_OR1. **S:** 'st_open'- PA_BR{25,33} are opened. **L:** Lines L6_13, L14_9 are removed.
14.571	**CS/CR:** 'cmd_open' in PA_OR1/PA_BR1.
14.602	**S:** 'st_open'- PA_BR1 is opened. **L:** Line L2_3 is tripped.

F: Occurrence of fault events, **D:** Detection of zone faults and overloads, **CS/CR:** Send/Receive commands from relays to circuit breakers, **S:** Status of the circuit breakers, **L:** Outage of lines.



Distance Relay Behavioral Model