A Simulation Testbed for Cascade Analysis

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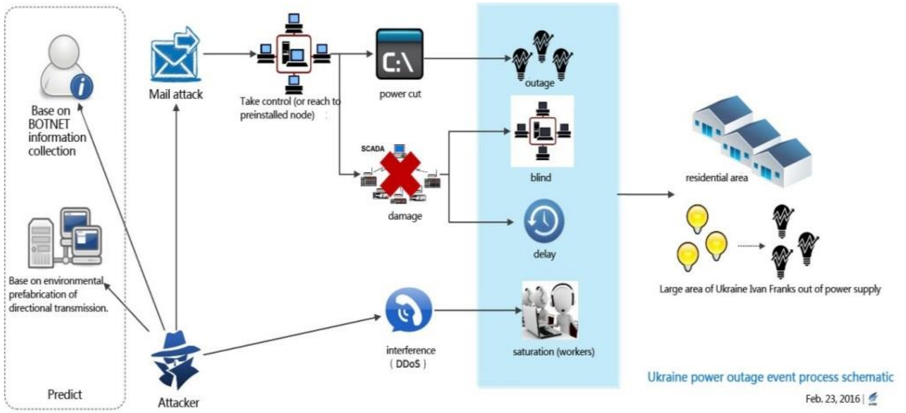
Cascading Failures: Power Transmission Systems

- Power systems are vulnerable to both **physical Faults** and **cyber Faults.**
- Cyber Faults in protection assembly can lead to severe cascading failures.
- **Dec 2015 Ukraine** and **Aug 2003 USA** are recent blackout cases.
- Diagnosing and predicting cascading failures effectively requires the consideration of behavioral models of these protection assembly.
- Behavioral models can introduce cyber-faults and produce new cascading trajectories.


Base on BOTNET information collection
Base on environmental prefabrication of directional transmission.
Predict
Mail attack
Attacker
Take control (or reach to preinstalled node)
power cut
SCADA
damage
interference (DDoS)
outage
blind
delay
saturation (workers)
residential area
Large area of Ukraine Ivan Franks out of power supply
Ukraine power outage event process schematic
Feb. 23, 2016 |

Cyber-Fault Example

Power System

Contributions

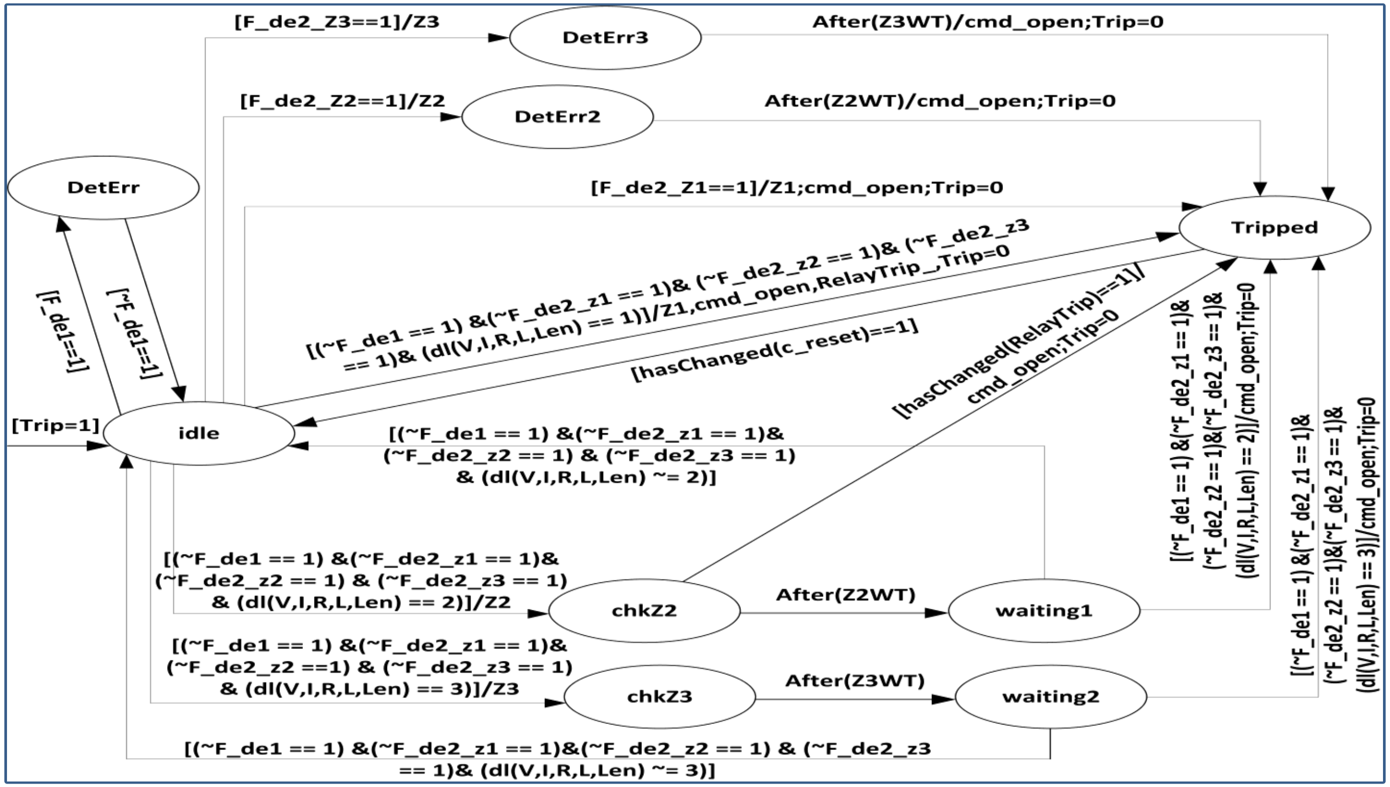
- Detailed behavioral models of protection Assembly are developed.
  - **Nominal** and **faulty modes** of operation.
  - For simulation based evaluation **Cyber-Faults** introduction at **specific time**.
  - **Ordering** of events are taken into account.
- A contingency analysis framework is proposed.
  - To study the **evolution of cascades** in the **presence of cyber-faults**.
  - Analysis provides **new cascade evolution trajectories** not obvious otherwise.
  - Case study performed on **IEEE-14 Bus System**.

Protection Assembly and Cyber-Faults

- Protection Assembly
  - **Distance Relay** Behavioral Model.
  - **Over-Current Relay** Behavioral Model.
  - **Circuit Breaker** Behavioral Model.
- Cyber-Faults
  - **Missed Detection Faults:** Relay fails to detect the anomaly.
  - **Spurious Detection Faults:** Relay incorrectly detects the anomaly.
  - **Stuck breaker Faults:** Breaker does not operate as commanded.

Distance Relay Behavioral Model

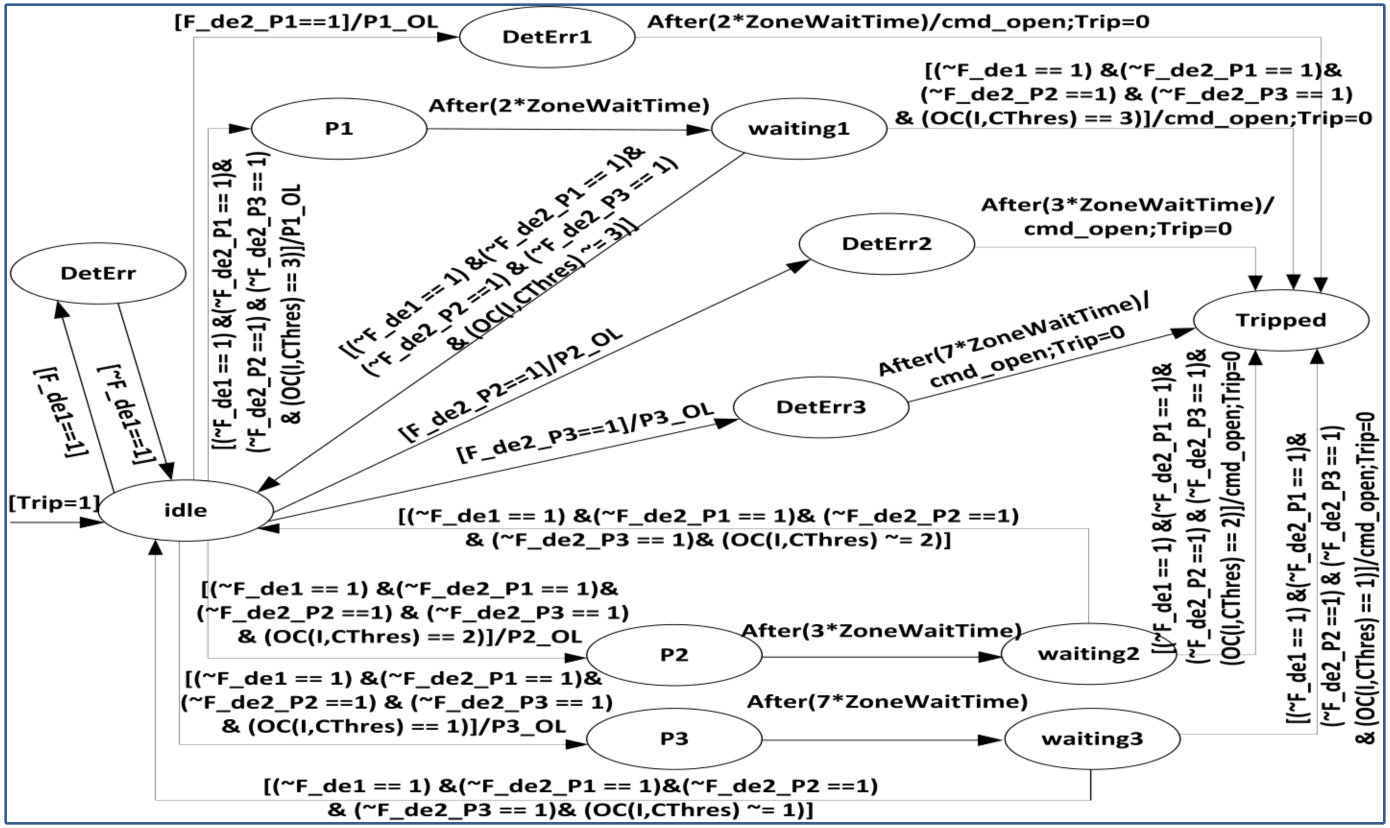
- **Primary protection** in electrical power systems.
- Three zone reaches (**Zone1, Zone2 and Zone3**).
- Normal mode operation and operation under cyber-faults.


[F_de2_Z3==1]/Z3
DetErr3
After(Z3WT)/cmd_open;Trip=0
[F_de2_Z2==1]/Z2
DetErr2
After(Z2WT)/cmd_open;Trip=0
DetErr
[F_de2_Z1==1]/Z1;cmd_open;Trip=0
Tripped
[F_de1=1]
[~F_de1=1]
[(~F_de1 == 1) &(~F_de2_z1 == 1)& (~F_de2_z2 == 1)& (~F_de2_z3 == 1)& (dl(V,I,R,L,Len) == 1)]/Z1,cmd_open,RelayTrip_Trip=0
[hasChanged(c_reset)==1]
[hasChanged(RelayTrip)==1]/ cmd_open;Trip=0
[Trip=1]
idle
[(~F_de1 == 1) &(~F_de2_z1 == 1)& (~F_de2_z2 == 1) & (~F_de2_z3 == 1) & (dl(V,I,R,L,Len) ~= 2)]
[(~F_de1 == 1) &(~F_de2_z1 == 1)& (~F_de2_z2 == 1)&(~F_de2_z3 == 1)& (dl(V,I,R,L,Len) == 2)]/cmd_open;Trip=0
[(~F_de1 == 1) &(~F_de2_z1 == 1)& (~F_de2_z2 == 1)&(~F_de2_z3 == 1)& (dl(V,I,R,L,Len) == 3)]/cmd_open;Trip=0
[(~F_de1 == 1) &(~F_de2_z1 == 1)& (~F_de2_z2 == 1) & (~F_de2_z3 == 1) & (dl(V,I,R,L,Len) == 2)]/Z2
chkZ2
After(Z2WT)
waiting1
[(~F_de1 == 1) &(~F_de2_z1 == 1)& (~F_de2_z2 ==1) & (~F_de2_z3 == 1) & (dl(V,I,R,L,Len) == 3)]/Z3
chkZ3
After(Z3WT)
waiting2
[(~F_de1 == 1) &(~F_de2_z1 == 1)&(~F_de2_z2 == 1) & (~F_de2_z3 == 1)& (dl(V,I,R,L,Len) ~= 3)]

Distance Relay Behavioral Model

Over-Current Relay Behavioral Model

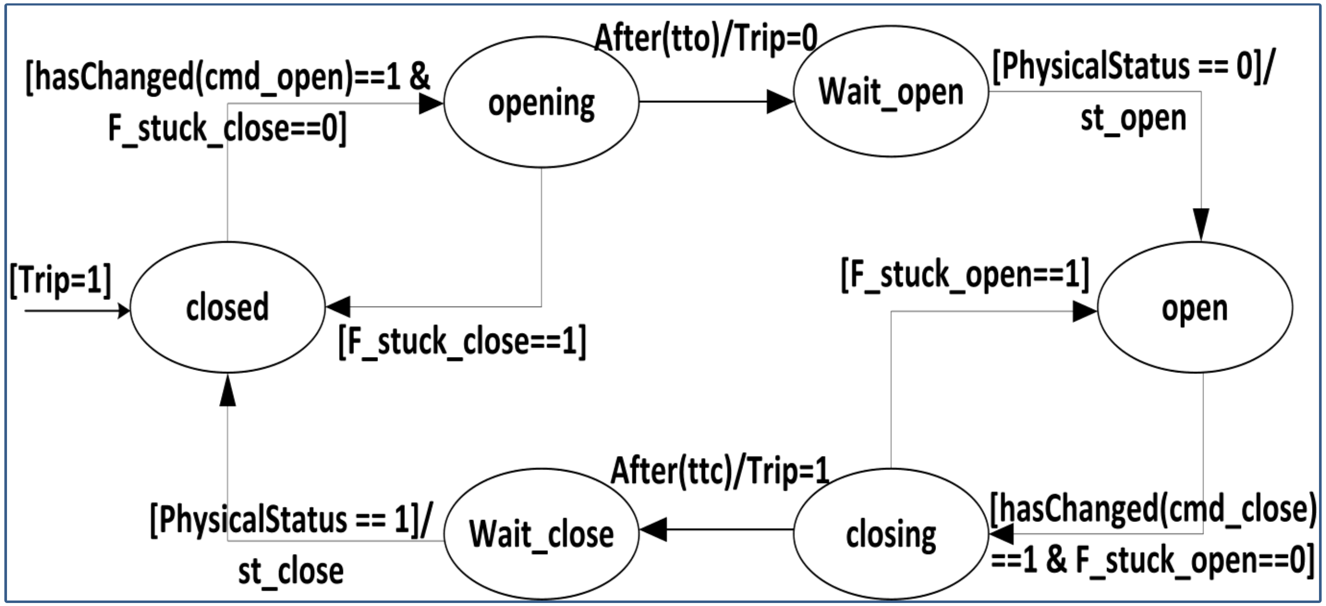
- Used as a **back-up protection** in electrical power systems.
- Normal mode operation and operation under cyber-faults.


[F_de2_P1==1]/P1_OL
DetErr1
After(2*ZoneWaitTime)/cmd_open;Trip=0
P1
After(2*ZoneWaitTime)
waiting1
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1) & (OC(I,CThres) == 3)]/cmd_open;Trip=0
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1) & (OC(I,CThres) == 3)]/P1_OL
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1) & (OC(I,CThres) ~= 3)]
DetErr2
After(3*ZoneWaitTime)/ cmd_open;Trip=0
DetErr
[F_de1=1]
[~F_de1=1]
Tripped
After(7*ZoneWaitTime)/ cmd_open;Trip=0
[F_de2_P2==1]/P2_OL
DetErr3
[F_de2_P3==1]/P3_OL
[Trip=1]
idle
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1)& (OC(I,CThres) ~= 2)]
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1) & (OC(I,CThres) == 2)]/P2_OL
P2
After(3*ZoneWaitTime)
waiting2
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1)& (OC(I,CThres) == 2)]/cmd_open;Trip=0
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1) & (OC(I,CThres) == 1)]/P3_OL
P3
After(7*ZoneWaitTime)
waiting3
[(~F_de1 == 1) &(~F_de2_P1 == 1)& (~F_de2_P2 ==1) & (~F_de2_P3 == 1)]& (OC(I,CThres) == 1)]/cmd_open;Trip=0
[(~F_de1 == 1) &(~F_de2_P1 == 1)&(~F_de2_P2 ==1) & (~F_de2_P3 == 1)& (OC(I,CThres) ~= 1)]

Over-Current Relay Behavioral Model

Circuit Breaker Behavioral Model

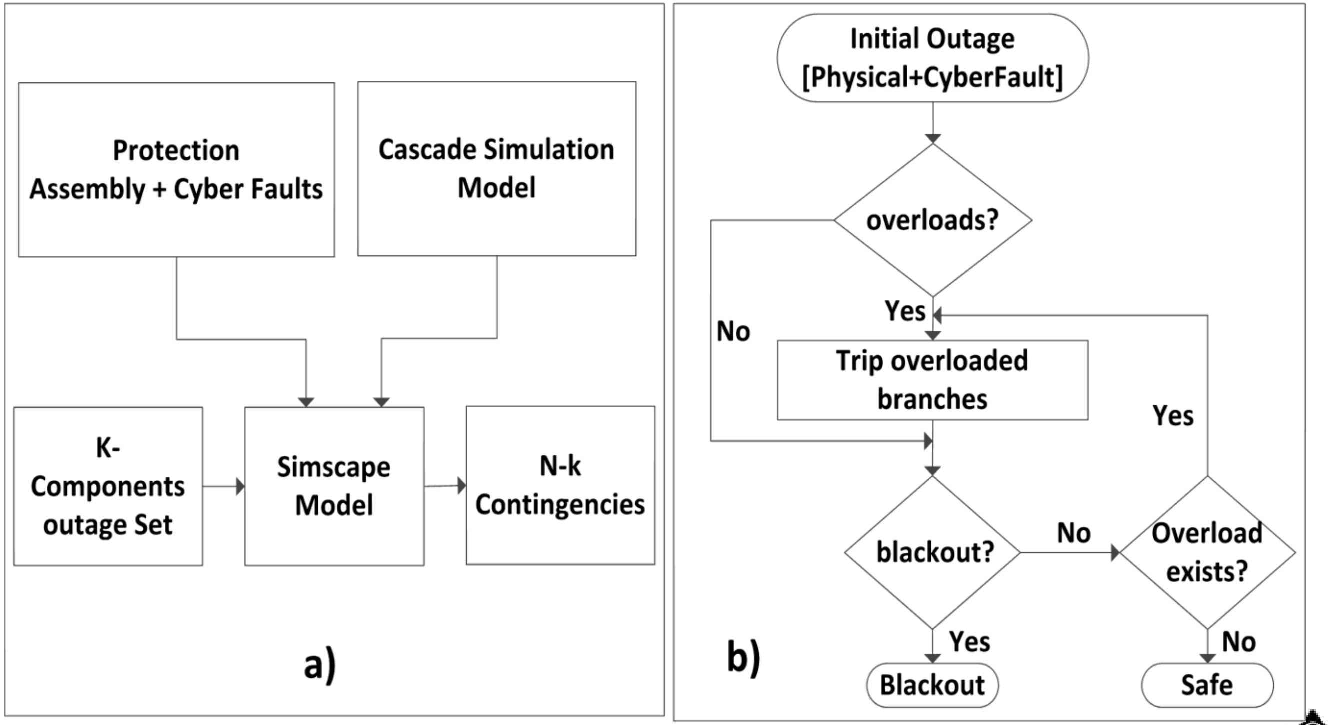
- **Physically connects or disconnects** the components in electrical power systems.
- Normal mode operation and operation under cyber-faults.



Circuit Breaker Behavioral Model

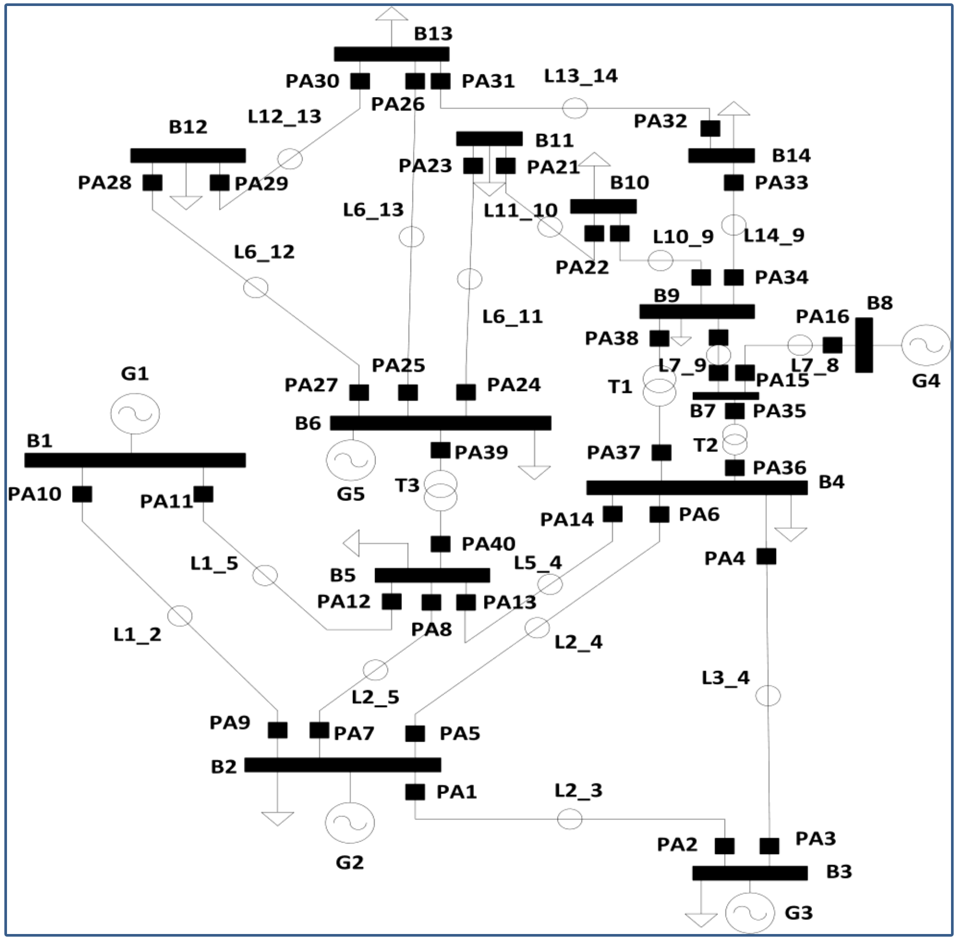
Towards Contingency Analysis

- **Identify critical sets** causing cascading failures leading to blackouts.
- **Integration of protection assembly** behavioral models.
- **Captures time between events** and **trigger cyber-faults** at specific instants.
- **Arbitrary cyber-faults** can be introduced at **any time instant** during the simulation.



System Under Test

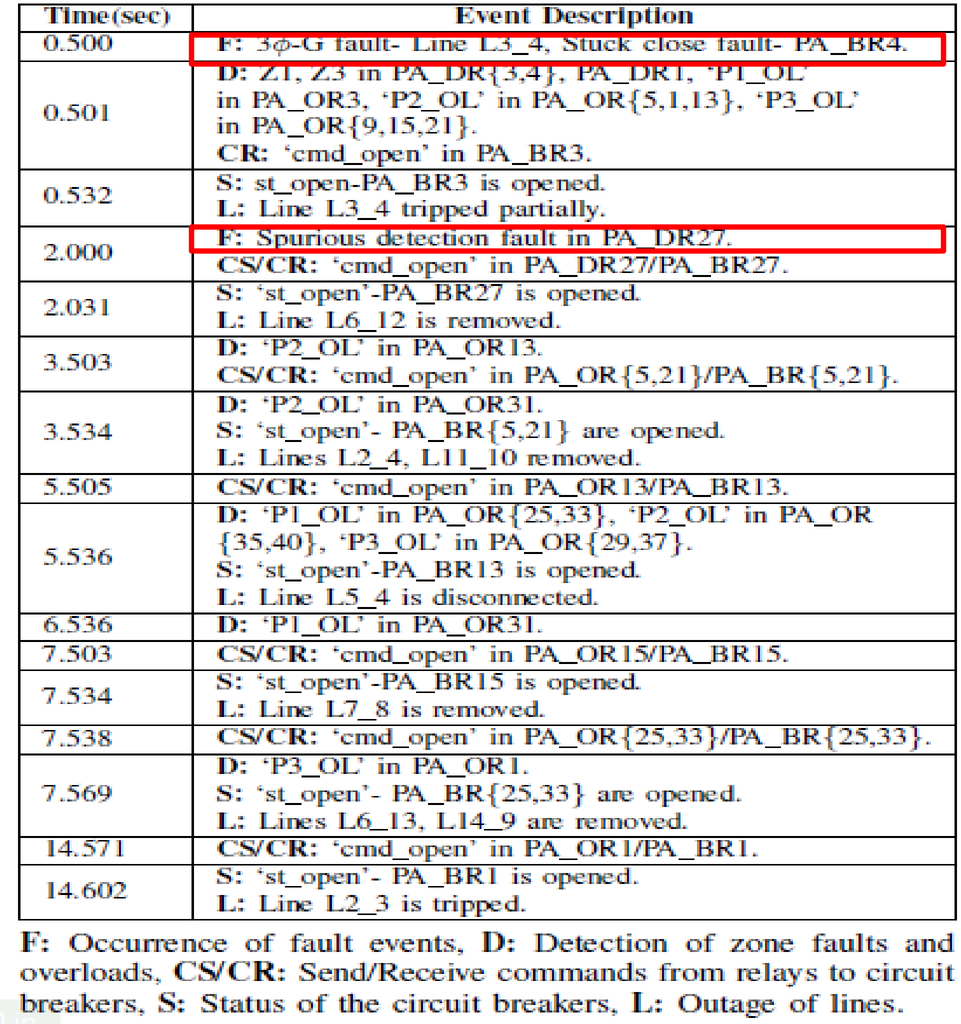
- IEEE-14 bus system is used for analysis.
- Each transmission line is protected by a pair of protection assembly.



Analysis Results

- How cyber-faults leads to severe cascading failures causing blackouts?
- How the proposed framework can be used for identifying new blackout causing contingencies?
- Case 1
  - **Physical fault** in **transmission line ‘L3_4’** at **t= 0.5 sec**.
  - **No cascading failure**.
- Case 2
  - **Physical fault** in **transmission line ‘L3_4’** at **t= 0.5 sec**.
  - **Cyber-fault** in **circuit breaker ‘PA_BR4’** at **t= 0.5 sec**.
  - **Cyber-fault** in **distance relay ‘PA_DR27’** at **t= 2.0 sec**.
  - **Cascading failure resulting in blackout**.

Analysis Results- 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.

Conclusion and Future Work

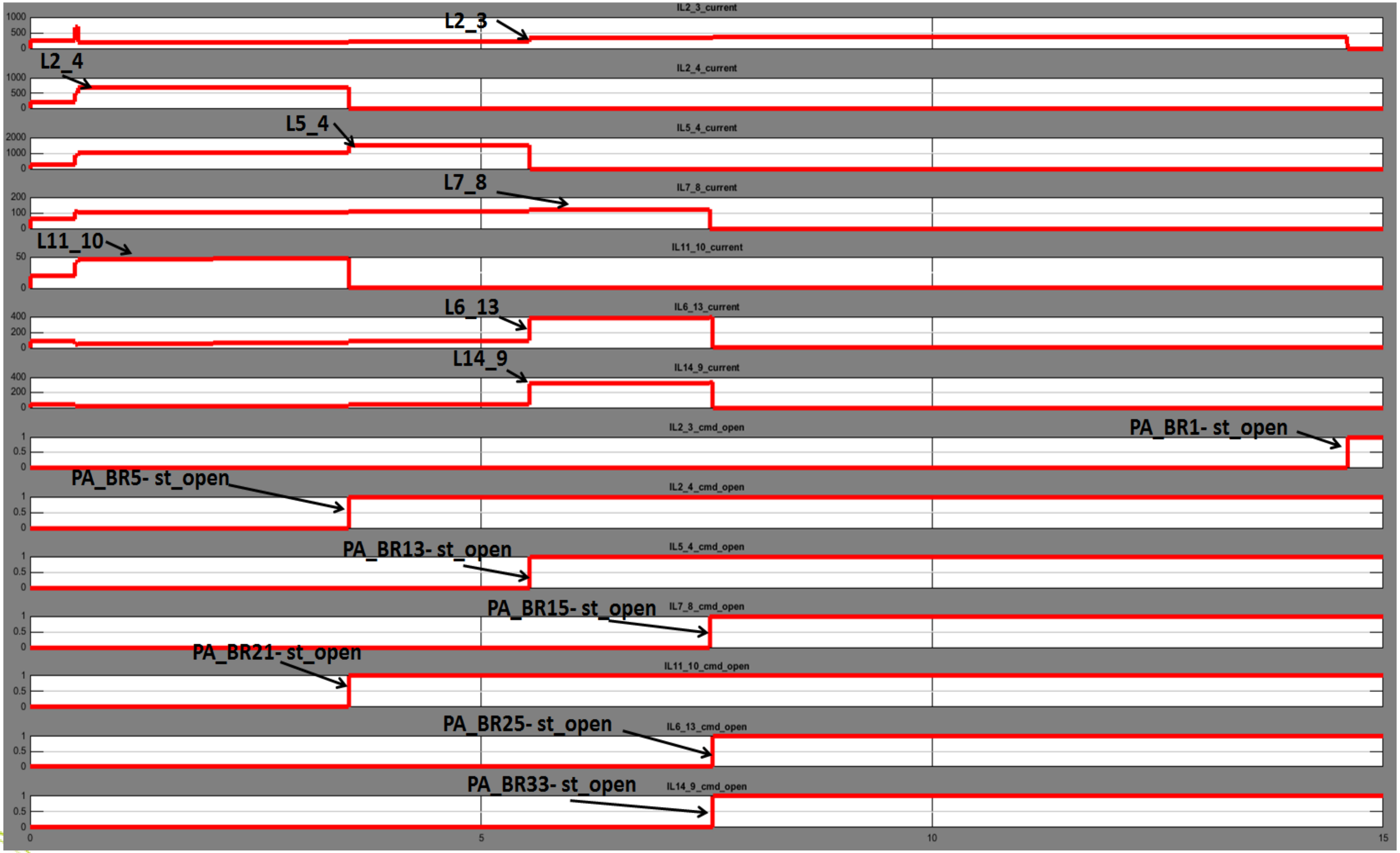
- Detailed behavioral models of protection assembly are presented.
- Capability to introduce cyber-faults at specific instants.
- A contingency analysis framework is proposed.
- Case study is presented to identify severe cascading causing contingencies resulting in blackout.
- As part of the future work, we will look at the scalability of the approach.

Acknowledgements

- National Science Foundation (NSF).

THANK YOU!

Analysis Results- Sequence of Cascading Events Waveforms


IL2_3_current
L2_3
L2_4
IL2_4_current
L5_4
IL5_4_current
L7_8
IL7_8_current
L11_10
IL11_10_current
L6_13
IL6_13_current
L14_9
IL14_9_current
IL2_3_cmd_open
PA_BR1- st_open
PA_BR5- st_open
IL2_4_cmd_open
PA_BR13- st_open
IL5_4_cmd_open
PA_BR15- st_open
IL7_8_cmd_open
PA_BR21- st_open
IL11_10_cmd_open
PA_BR25- st_open
IL6_13_cmd_open
PA_BR33- st_open
IL14_9_cmd_open