DIAGNOSTICS AND PROGNOSTICS USING TEMPORAL CAUSAL MODELS FOR CYBER PHYSICAL SYSTEMS - A CASE OF SMART ELECTRIC GRID

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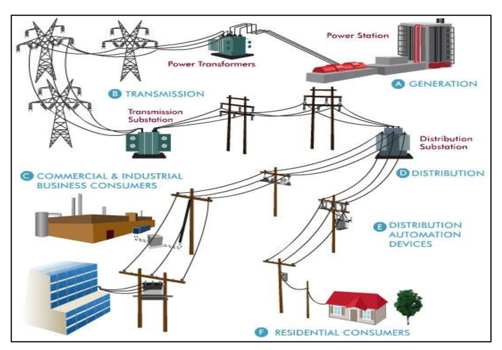
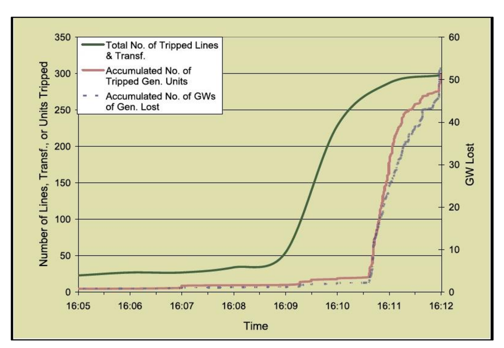
Motivation

- Cyber Physical Systems are integrating computation, networking and physical processes where interactions among discrete and continuous subsystems play an important role.
Fault diagnosis becomes challenging as these interactions cause failure cascades. For instance, in power systems, protection system mis-operations often lead to cascading effects and system wide failures.

- Fault diagnosis and prognosis needs reasoning about these interactions, allowing for control actions that effect the cascades.



- Our approach is based on constructing a system-level discrete event model that captures the causal and temporal relationships between failure modes (causes) and discrepancies (effects) in a system, thus modeling the failure cascades while taking into account propagation constraints imposed by operating modes, protection elements, and timing delays. Another characteristics is tha hierarchical reasoning that can use external reasoners or simulators to refine system level fault hypotheses.



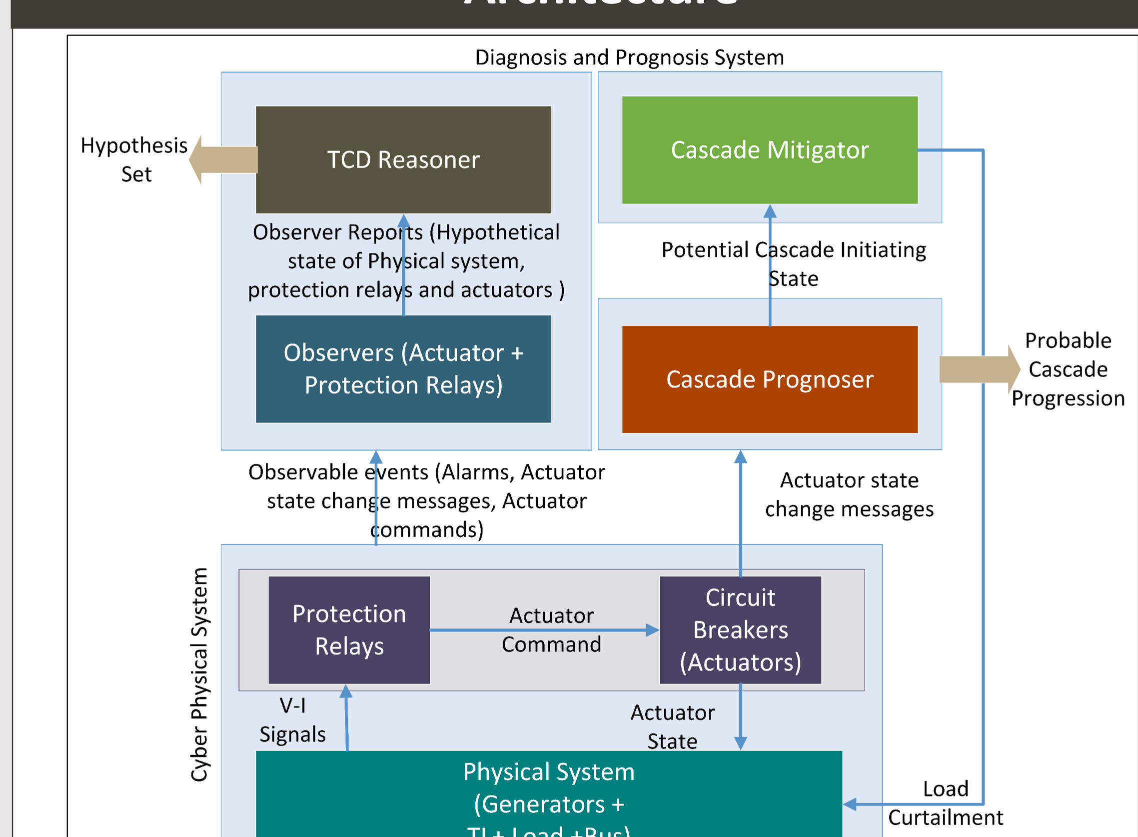
Progression of events in the 2003 blackout.

Project Achievements

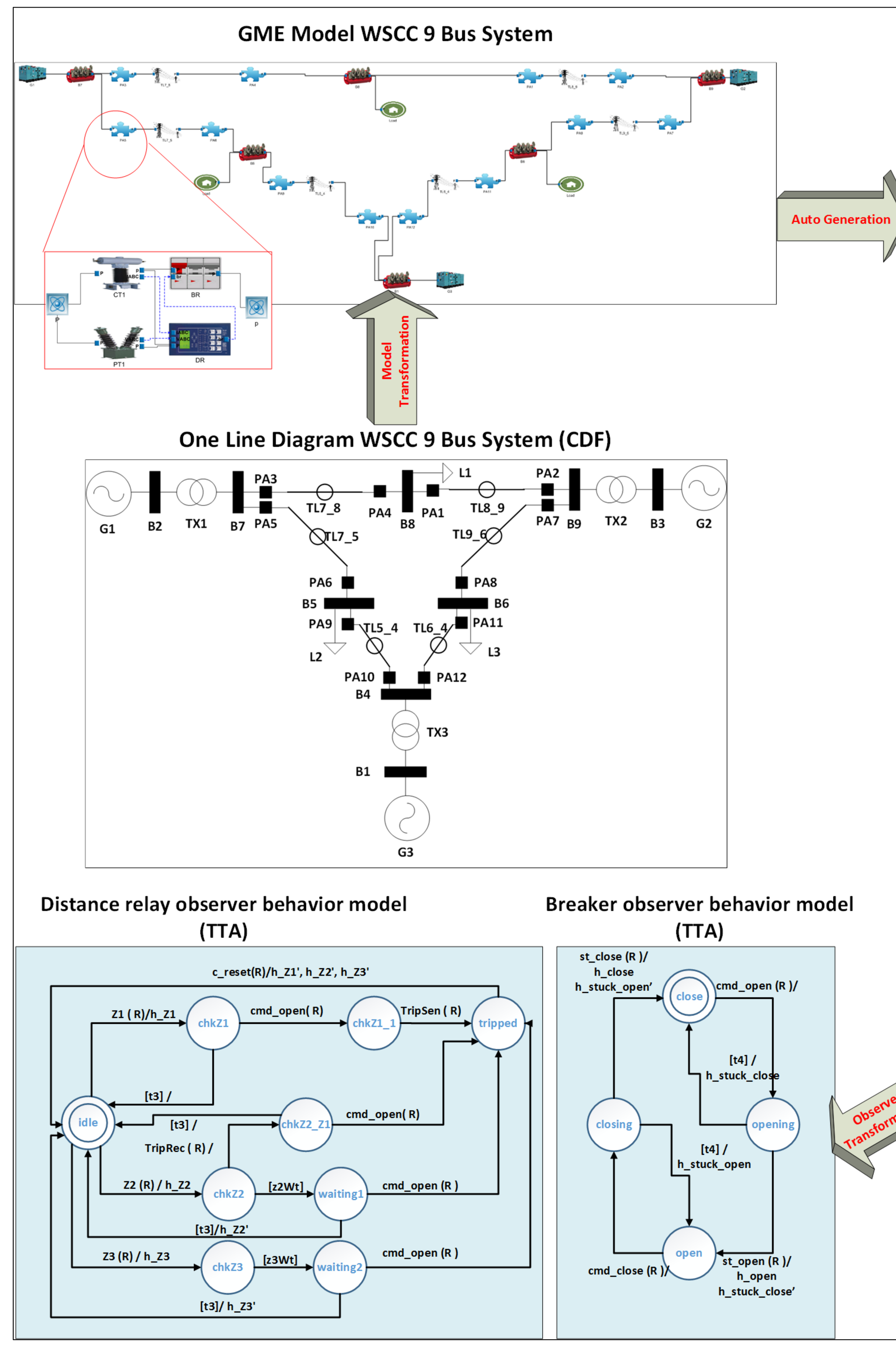
In order to devise a systematic approach to understand and improve the resilience of cyber physical energy systems through automated generation of failure graphs, simulation models, failure cascade sequences and minimal reconfiguration actions, we

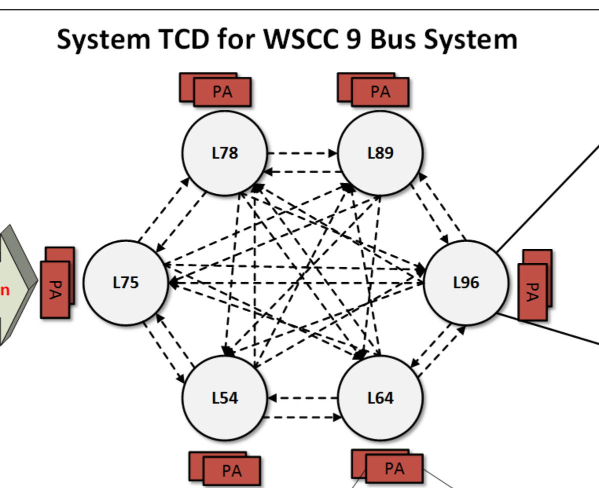
1) Developed a new modeling formalism, Temporal Causal Diagrams, to capture the interplay between failure progression and component behaviors.
2) Extended the Modeling formalism of Temporal Failure Propagation Graphs, to include effect nodes and uncertainty in failure propagation.
3) Extended a Time-Triggered Automata (TTA) model to include constraints imposed by faults.
4) Developed a domain specific modeling language to represent the component behavior and fault propagation across component interactions in cyber physical energy systems.
5) Proposed a novel approach of encoding failure cascade progressions using binary decision diagrams (BDDs)
6) Formulated a nonlinear optimization problem for identifying minimalistic reconfiguration strategies to arrest failure cascades.

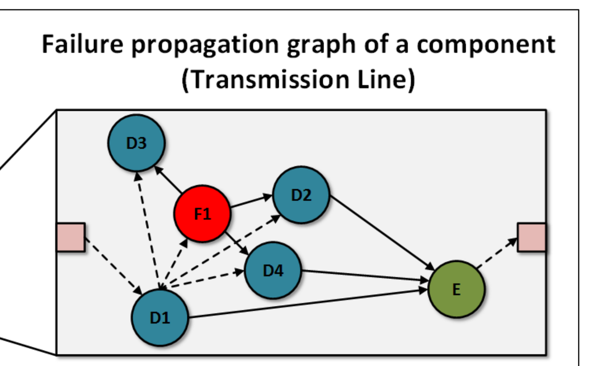
Architecture



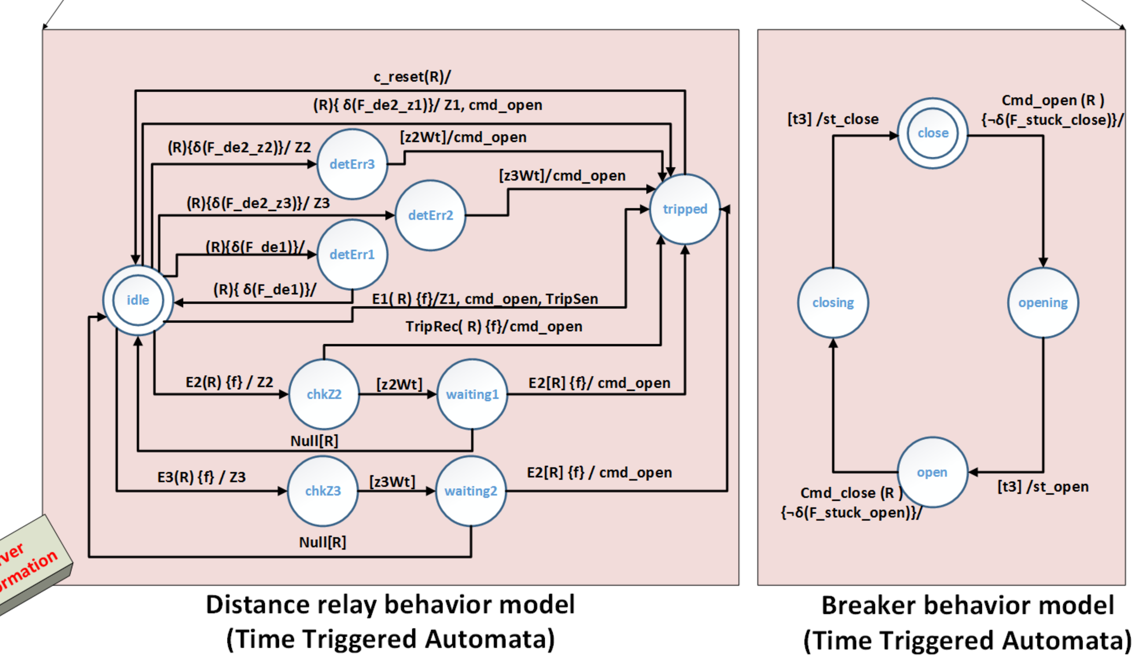
Cascade Diagnosis







F1: This failure mode represents internal faults like phase-to-ground and or phase-to-phase faults.
E: These are the set of effect nodes, which implies the change in the state of the breaker assemblies attached to the physical component.
D2(D4): These are the set of discrepancies that represent the failure effects of F1 signaled by primary protection elements.
D3: These are the set of discrepancies that represent the failure effects of F1 captured by the protection elements associated to the neighboring elements.
D1: These are the set of observable discrepancies that are associated to the secondary protection element associated with the physical component.



Distance relay behavior model (Time Triggered Automata)

Breaker behavior model (Time Triggered Automata)

Cascade Prognostics

Industry practice is to identify the set of initial outages that can lead to cascading outages and ultimately blackouts.

The set of contingencies $T \in S$ can be encoded using binary decision diagram [1] B_T, where S is the set of all possible states. The progression of the cascade is stored as a set of transitions, $TR \in S \times S$ using BDD B_{T_R}.

The state of a system can be defined by a boolean vector, $(v_1, v_2, \ldots, v_n)$ where n is the number of branches in the system.

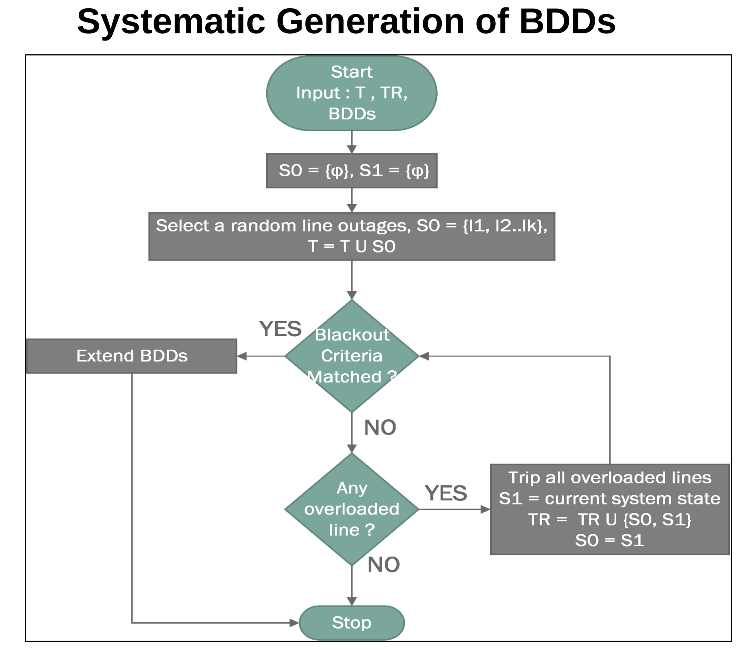
A labeling function L is defined over set of state S, $L(S): S \rightarrow P(Branch)$, where $Branch$ is the set of branch labels. The boolean encoding of state s is given as $(v_1, v_2, \ldots, v_n)$ where $v_i = 1$ if $Branch_i \notin L(s)$.

The characteristic function $f_T: \{0,1\}^n \rightarrow \{0,1\}$ for set member ship can be defined as $(l_{11} \cdot l_{12} \ldots \cdot l_{1n}) + (l_{21} \cdot l_{22} \ldots \cdot l_{2n}) + \cdots + (l_{k1} \cdot l_{k2} \ldots \cdot l_{kn})$ where the Boolean function $(l_{j1} \cdot l_{j2} \ldots \cdot l_{jn})$ represents the state s_j.

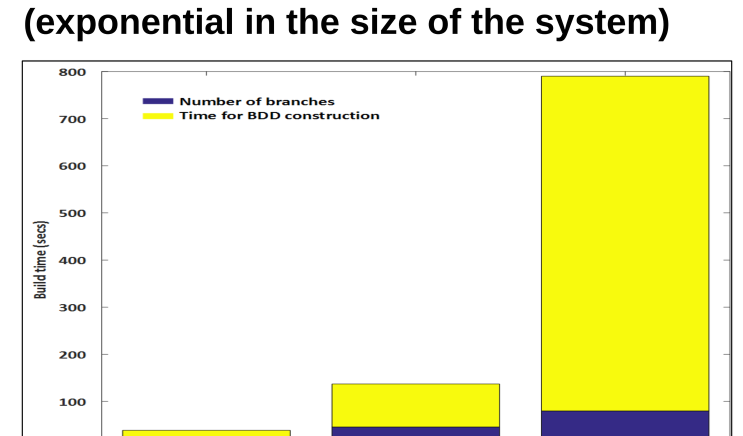
Similarly, the characteristic function can be calculated as the boolean product of two states.

[1] E. M. Clarke, O. Grumberg, and D. Peled, Model checking. MIT press, 1999

Systematic Generation of BDDs

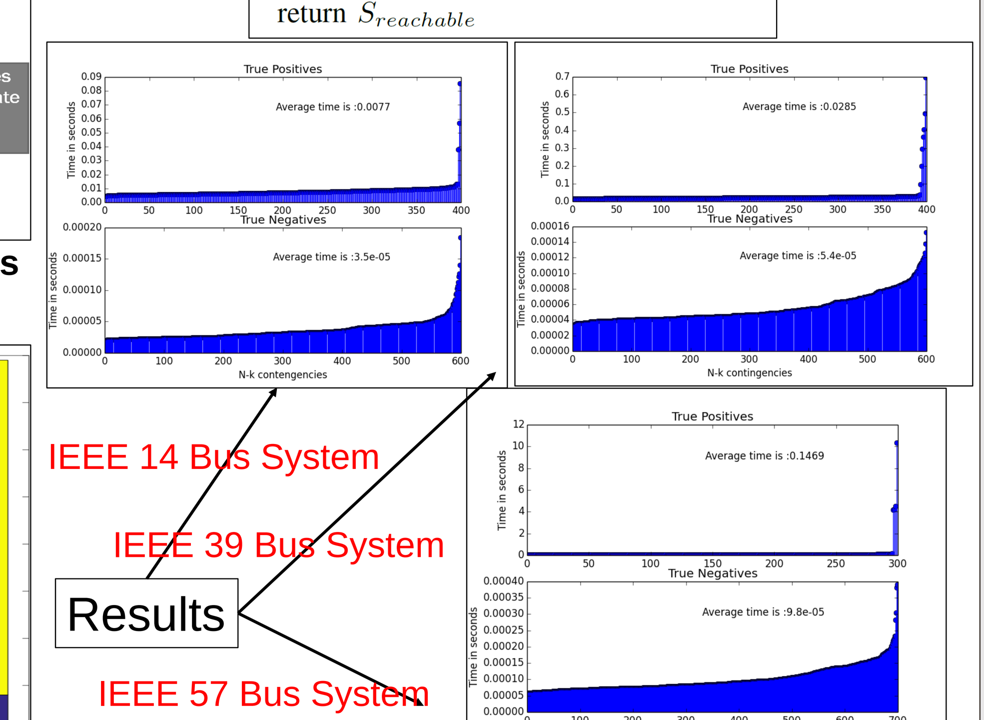


Time taken by building BDDs (exponential in the size of the system)



Cascade prognostics algorithm

Input: $S_0 = (v_1, v_2, \ldots, v_n)$; B_T ; B_{T_R}
Output: $S_{reachable} = \phi$
if Evaluate(B_T, S_0) == True **then**
  i = 0
  $S_{reachable} = \phi$
  while $S_i != \phi$ **do**
    $S_{reachable} = S_{reachable} \cup S_i$
    $S_{i+1} = Image(B_{T_R}, S_i) \setminus S_{reachable}$
    i = i+1
  end while
end if
return $S_{reachable}$

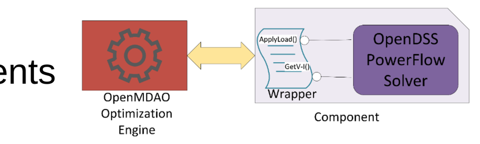


Cascade Mitigation

- In order to prevent cascades from spreading load(s) have to be curtailed such that secondary and tertiary overloads disappear.
- We use a component-based approach by using OpenMDAO as the optimization framework that acts an orchestrator for finding optimal values. OpenDSS is used for solving the AC load flow for different load profiles.

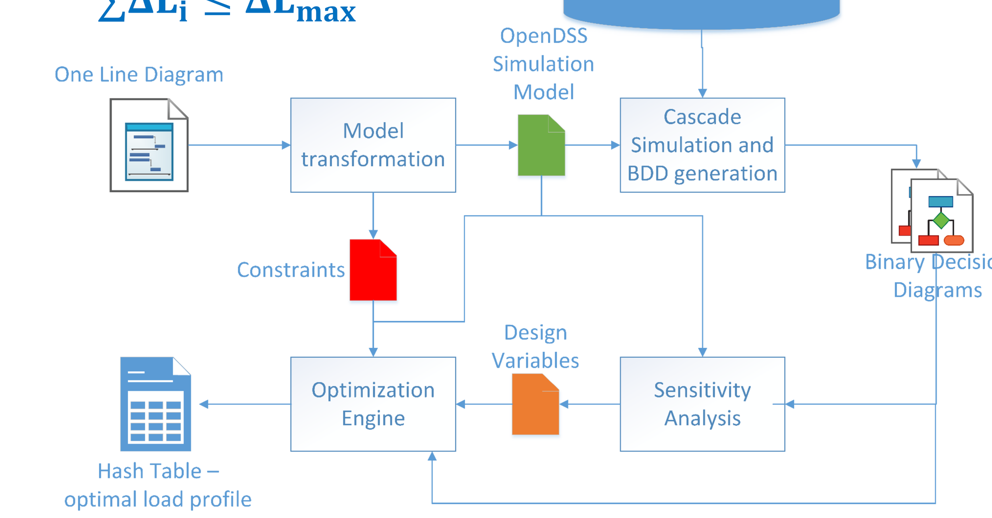
Optimization problem

$L = \{L_1, L_2, \ldots, L_n\}$ is the vector of n loads where $n \in Z$.
$\Delta L = \{\Delta L_1, \Delta L_2, \ldots, \Delta L_n\}$ is a vector of n independent variables where ΔL_i represents the change in load L_i.



$I = \{I_1, I_2, \ldots, I_m\}$ is a vector of magnitude of currents flowing through all m branches of the system. I_k^{Max} is the maximum current flowing through branch k.
ΔL_{max} is the maximum load that can be shed from the system.

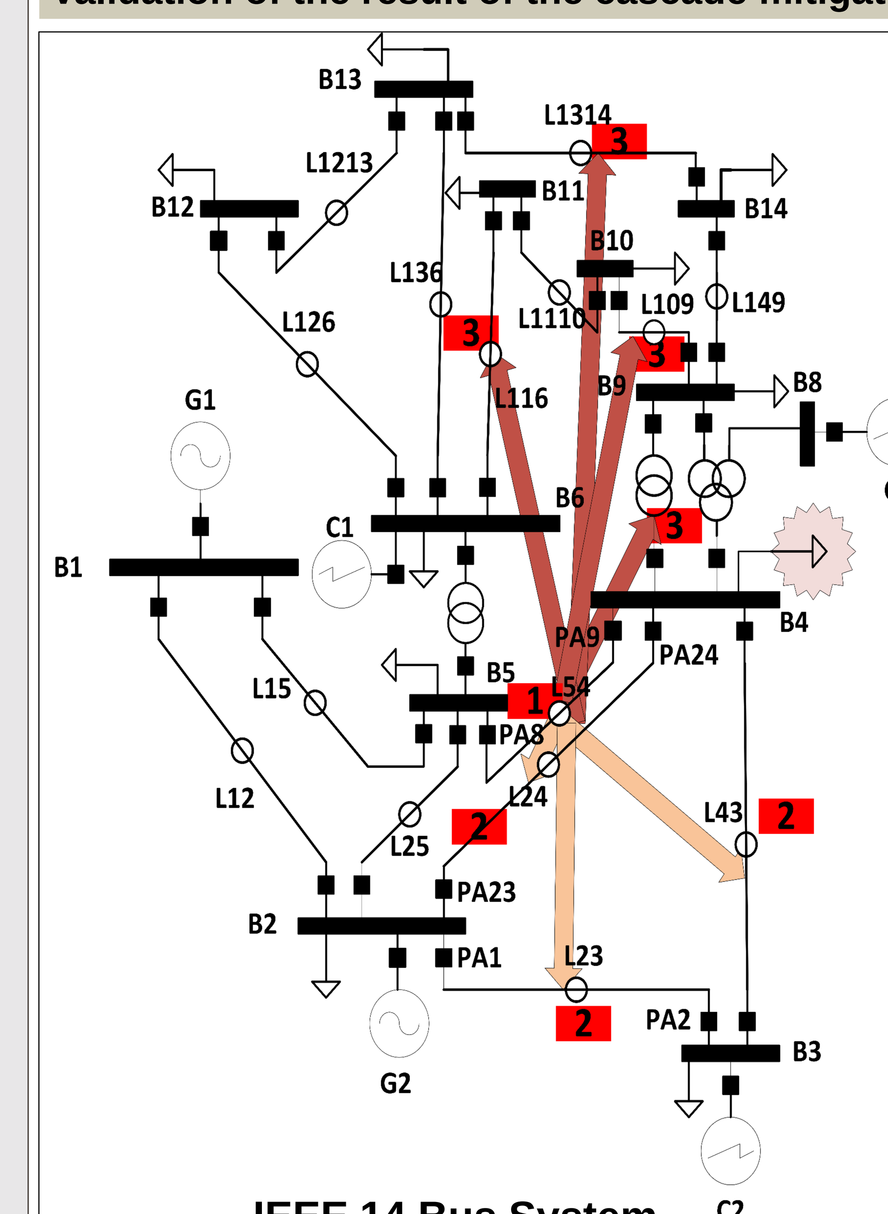
$$\text{minimize } \sum \Delta L_i$$
$$\text{subject to: } \forall I_k, 0 \le I_k \le I_k^{Max}$$
$$\forall \Delta L_k, 0 \le \Delta L_k \le L_k$$
$$\sum \Delta L_i \le \Delta L_{max}$$



End-to-end toolchain for Cascade prognostics and Mitigation

Case Study

Validation of the result of the cascade mitigation calculations



- A 3 phase to ground fault in introduced in line L54
- Distance relays PA8 and PA9 detect the fault and send trip signals
- Breakers open and overload lines L24, L34, L23
- Overload protection elements trip lines L24, L34, L23
- Breakers open and overload lines L116, L109, L1314, L49
- Overload protection elements trip lines L116, L109, L1314, L49
- BLACKOUT

System Evolution with mitigation actions applied

A 3 phase to ground fault in introduced in line L54 → Distance relays PA8 and PA9 detect the fault and send trip signals → Breakers open and overload lines L24, L34, L23 → Shed Load attached to Bus by 10%. → SAFE