Improving Power Transmission Efficiency and Reliability through Hardware/Software Co-Design

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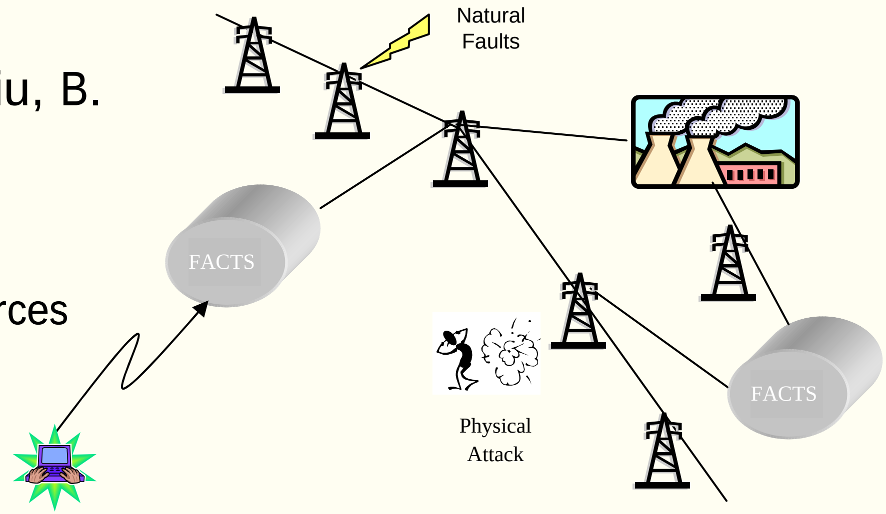

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The Name. The Degree. The Difference.

NSF MRI CNS-040869
Sandia National Lab

Problem Motivation

- Prevent Cascading failures:
  - 2003 Blackout
- Causes
  - Physical & Cyber contingencies
  - Deliberate disruption
    - Hackers
    - Terrorist Activity

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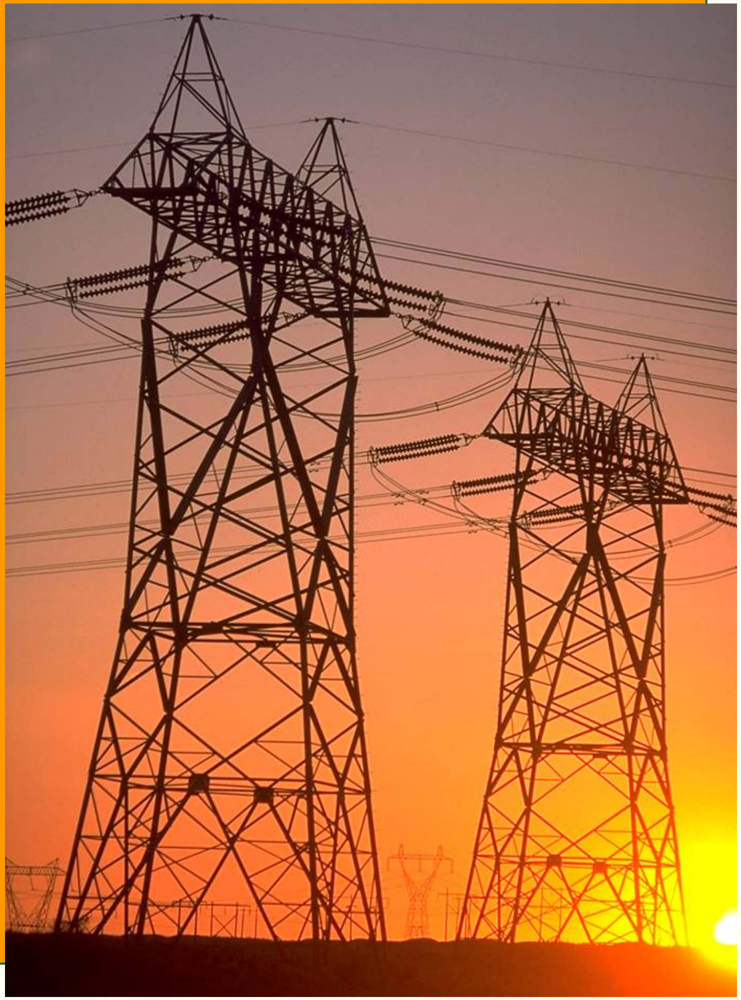
Proposed Solution

Flexible AC Transmission Systems (FACTS)

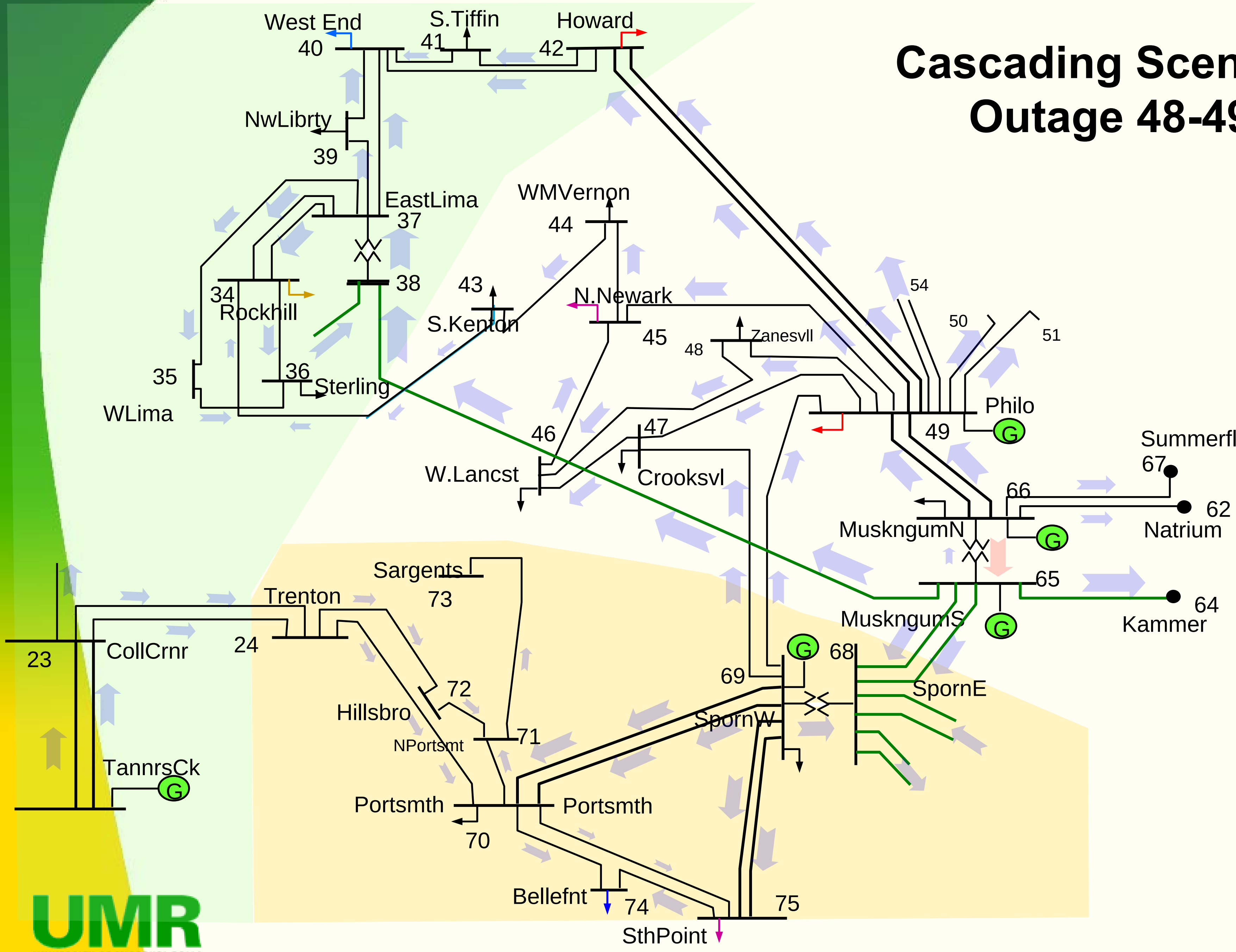
- Power Electronic Controllers
- Means to modify the power flow through a particular transmission corridor

Decentralized Infrastructures

- Communication and coordination
  - Operating - Distributed Long-Term control
  - Dynamic – Local Dynamic control
- Vulnerabilities of the combined physical/ cyber system
- Recovery and protection from physical faults and/or cyber attacks and/or human error



Cascading Scenario
Outage 48-49



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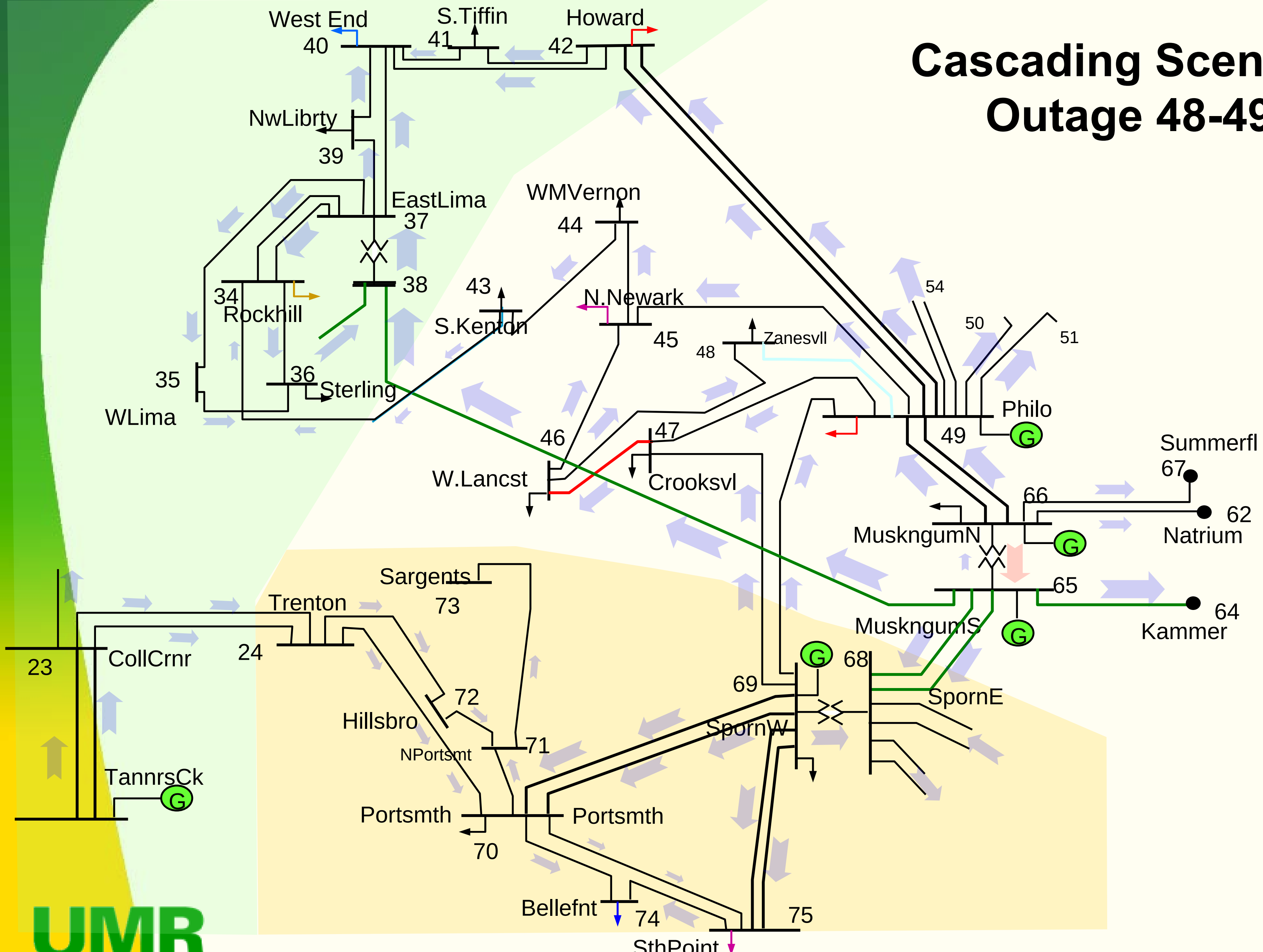

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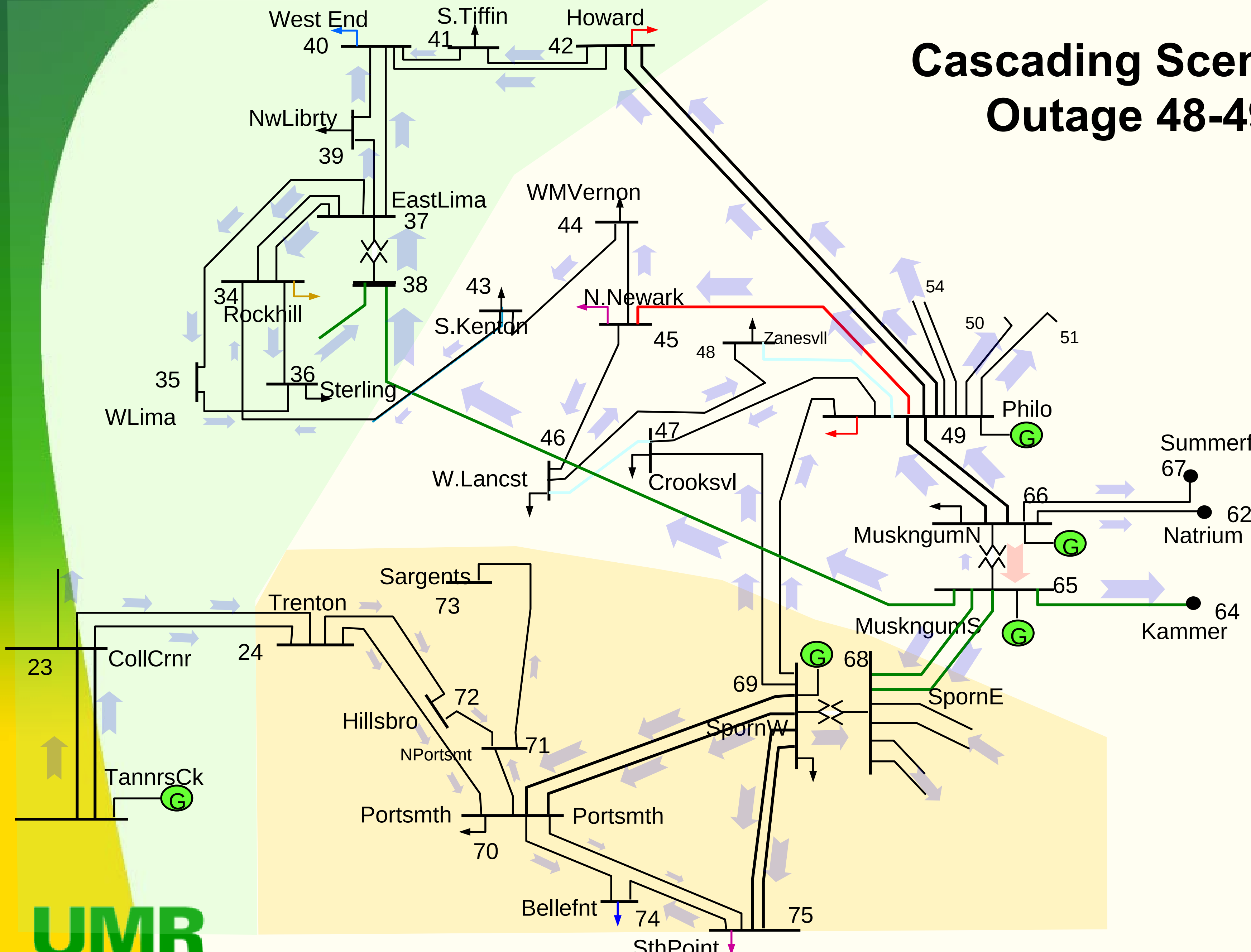

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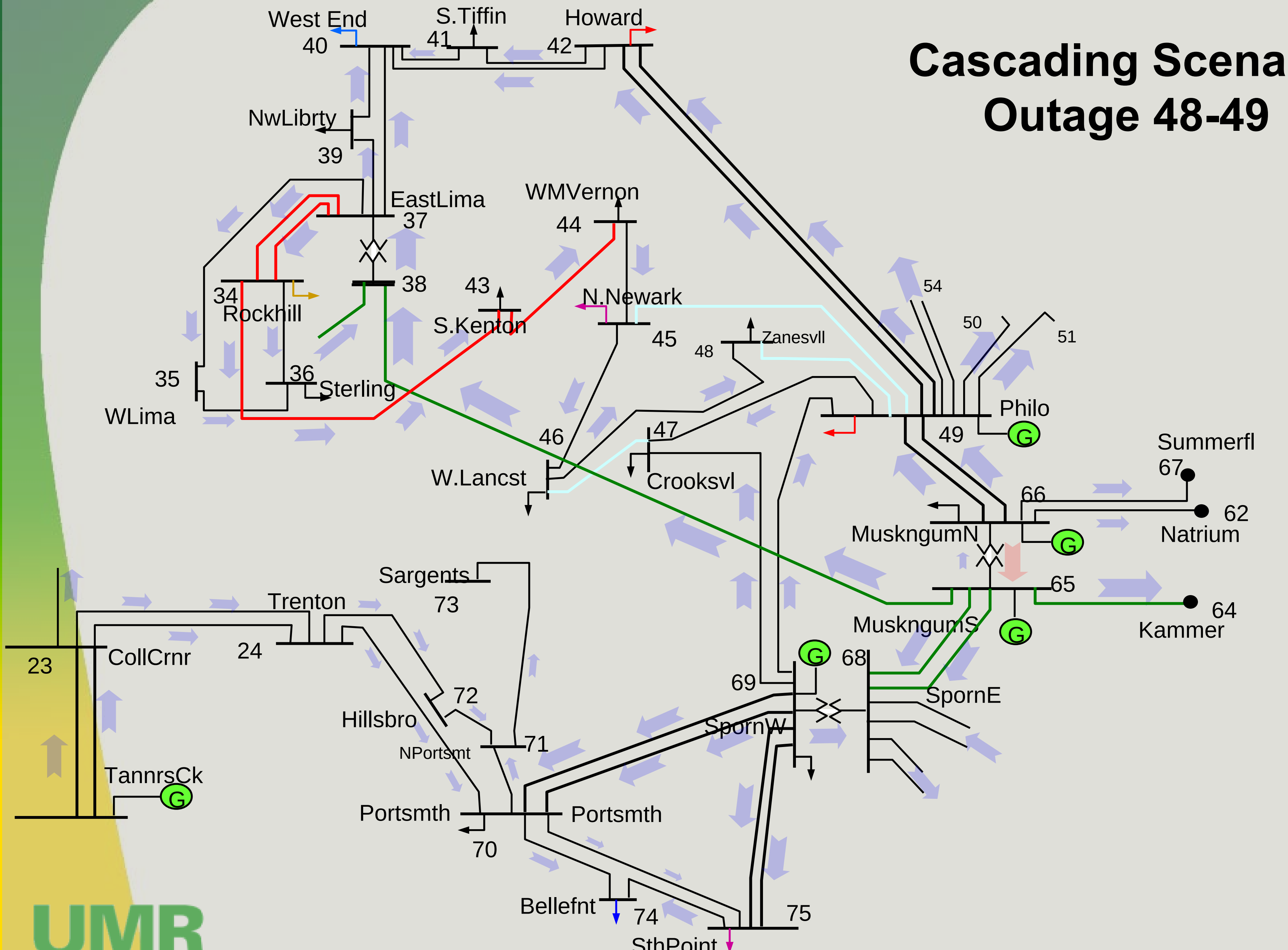
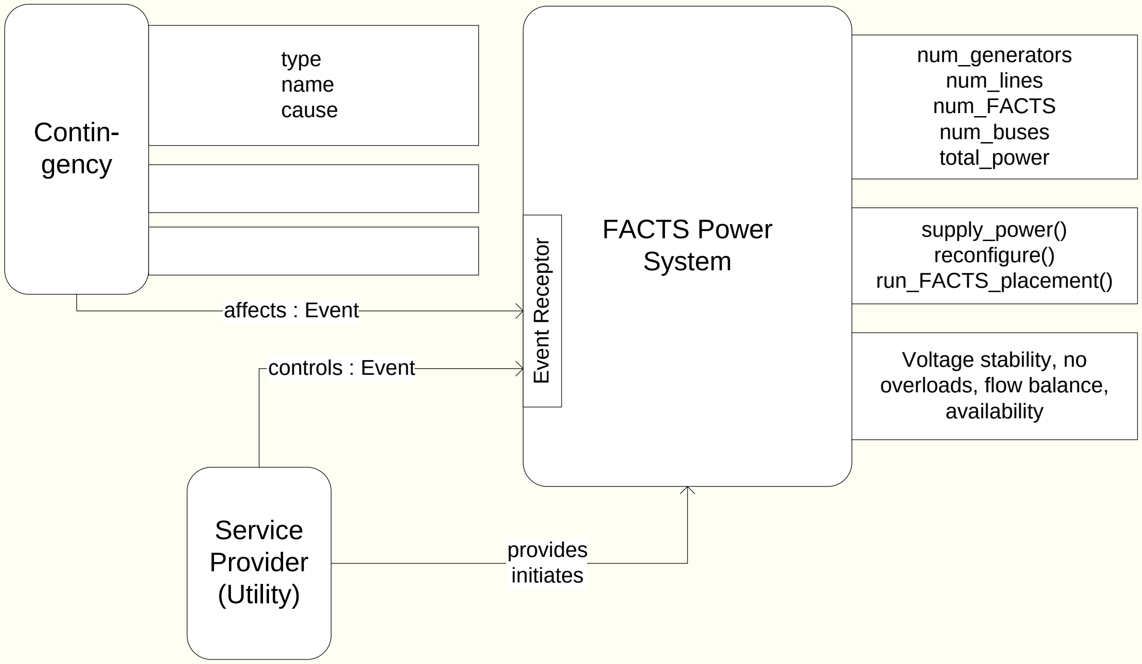


Context Object Diagram of FACTS Power System



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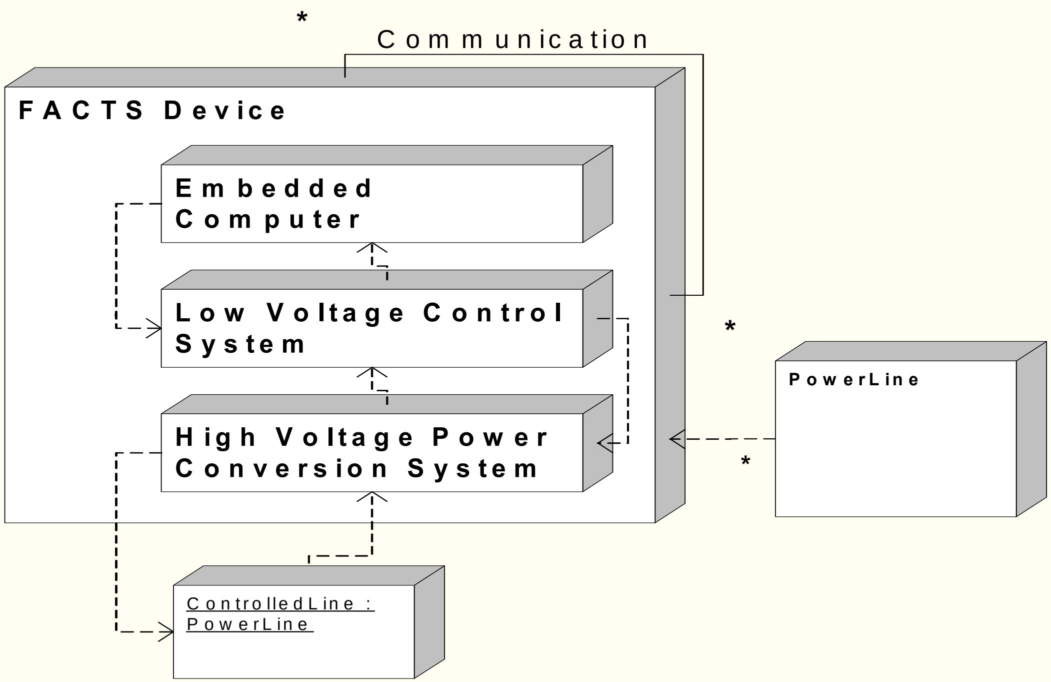
Redirect Power Away from Overloaded Lines

- **FACTS Device Controls Power Flow in an individual transmission line.**



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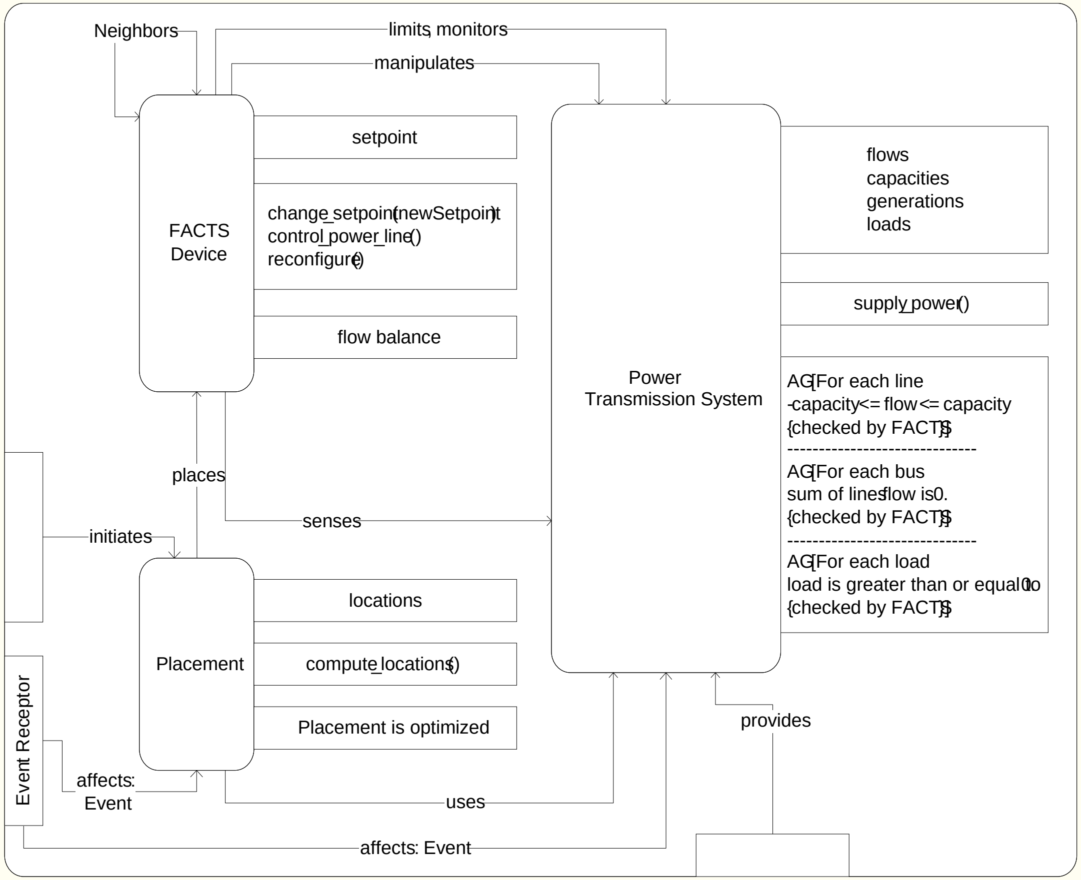
FACTS Power System Object Decomposition

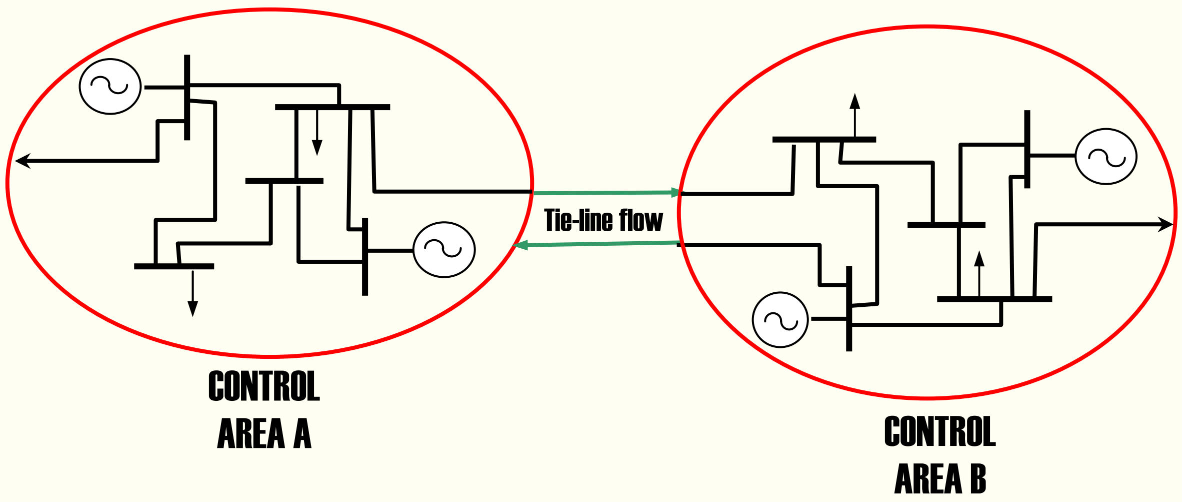


FACTS Control

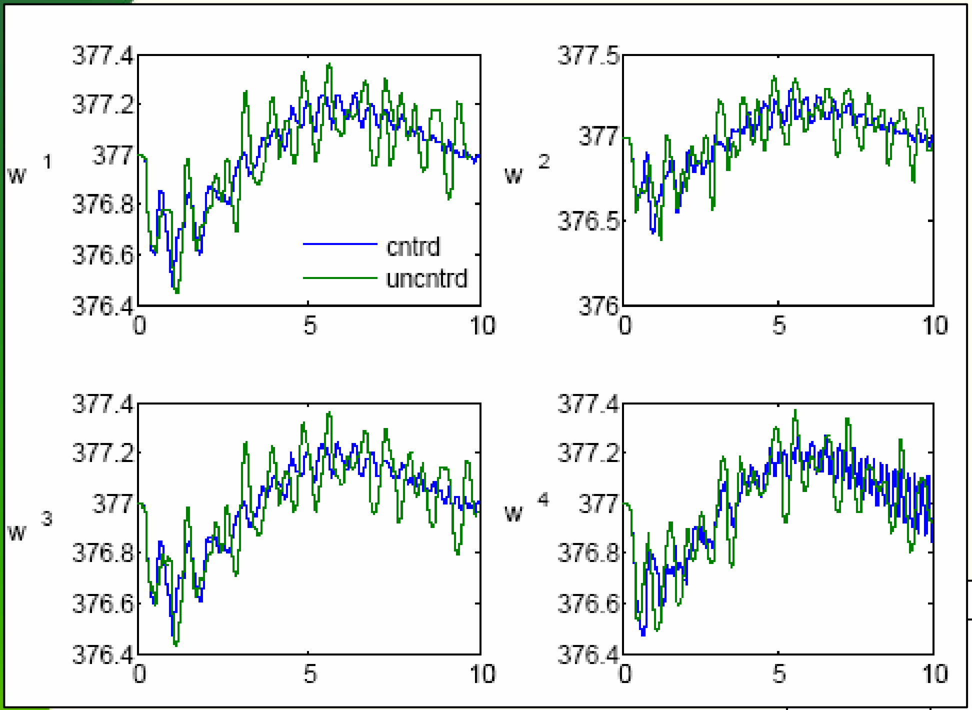
- **Distributed Long-Term control algorithms for FACTS settings**
  - **Run by each processor in each FACTS**
  - **Alternatives**
    - Max-flow algorithms
    - Local optimizations
    - Agent-based framework
  - **Assessment**
    - Reduction of Overloads
    - Computability

System Dynamic Control

Power Network Embedded With FACTS Devices

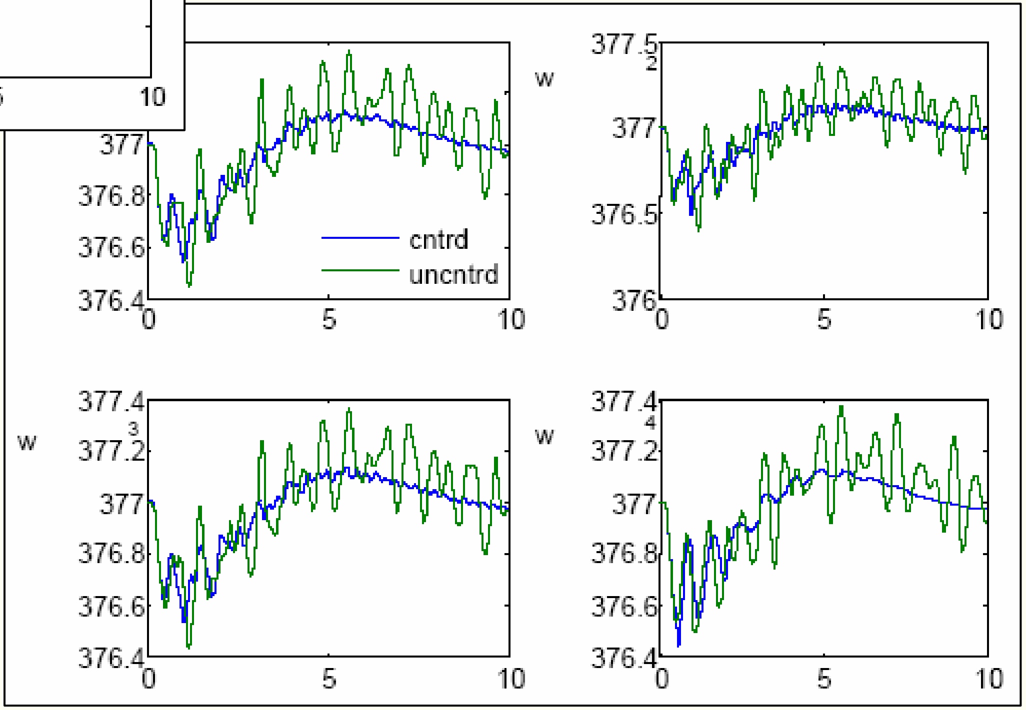


While the FACTS devices offer improved controllability, their actions in a decentralized power network can cause deleterious interactions among them.



Uncontrollable modes in generator speeds due to device interactions - Control based on local information only

Performance of FACTS controllers with ideal observability



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Control Issues

- Can we get global information?
  - Incomplete information
  - Time-delayed information
  - Opens the potential for increased security issues

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FACTS Interaction Laboratory (FIL)

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FIL Overview

- Construct a Laboratory System to Study and Mitigate
  - Cascading Failures
  - Deleterious effects of interacting power control devices
  - Cyber Vulnerabilities
- Hardware in the Loop (HIL)
  - Real-time Simulation Engine
    - Simulate Existing Power Systems
    - Inject Simulated Faults
  - Interconnected laboratory-scale UPFC FACTS Device
    - Measure actual device interaction

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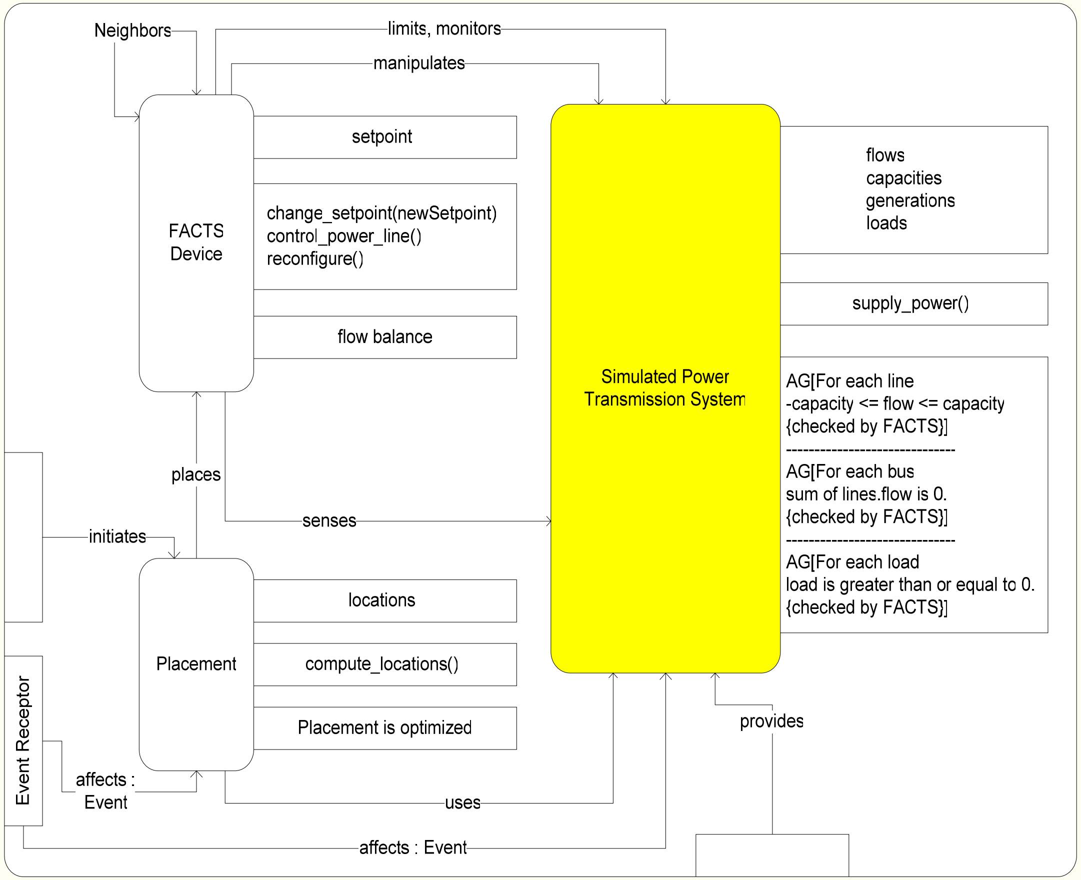

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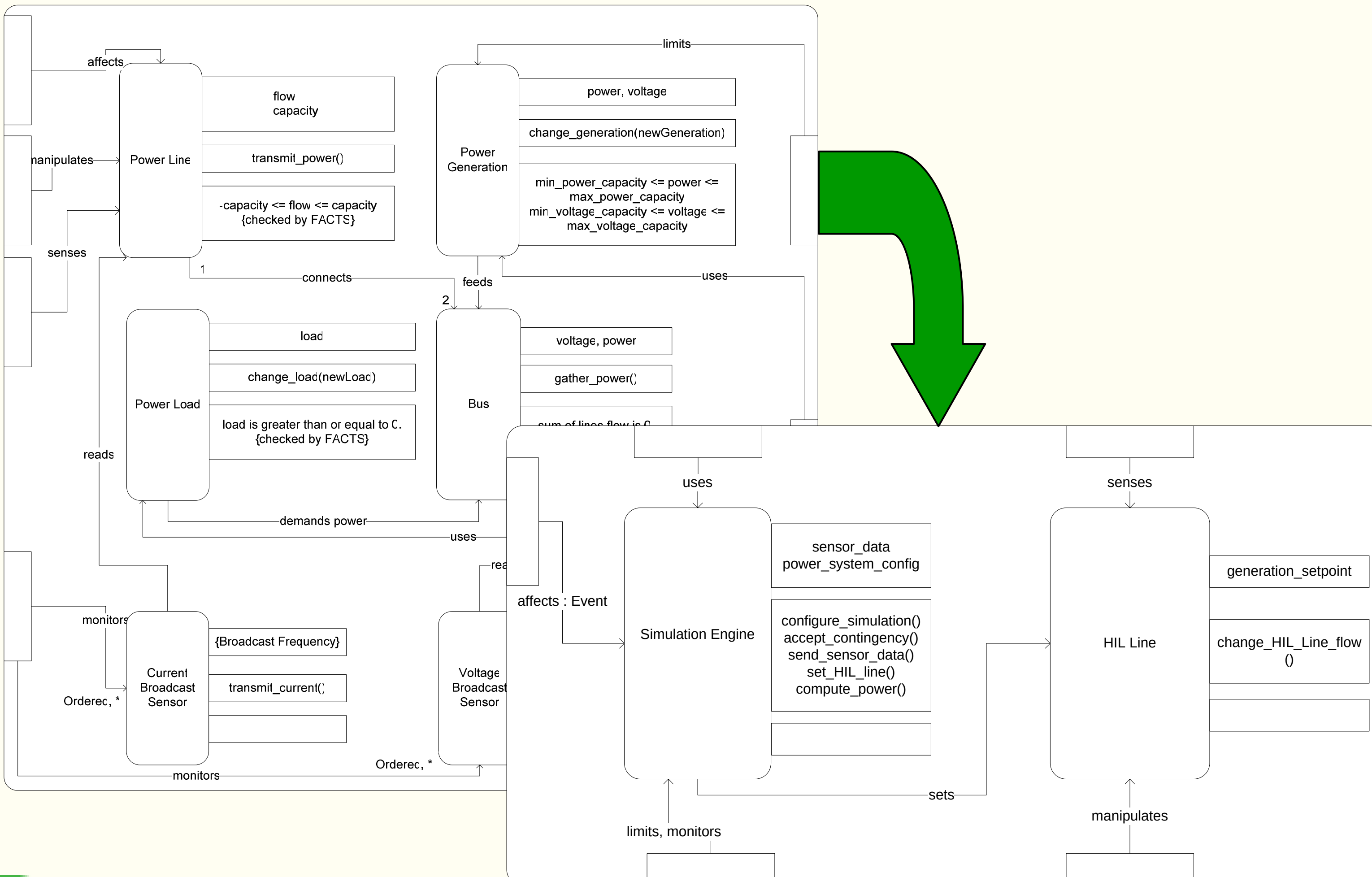
Hardware/Software FACTS Interaction Laboratory

POWER TRANSMISSION SYSTEM



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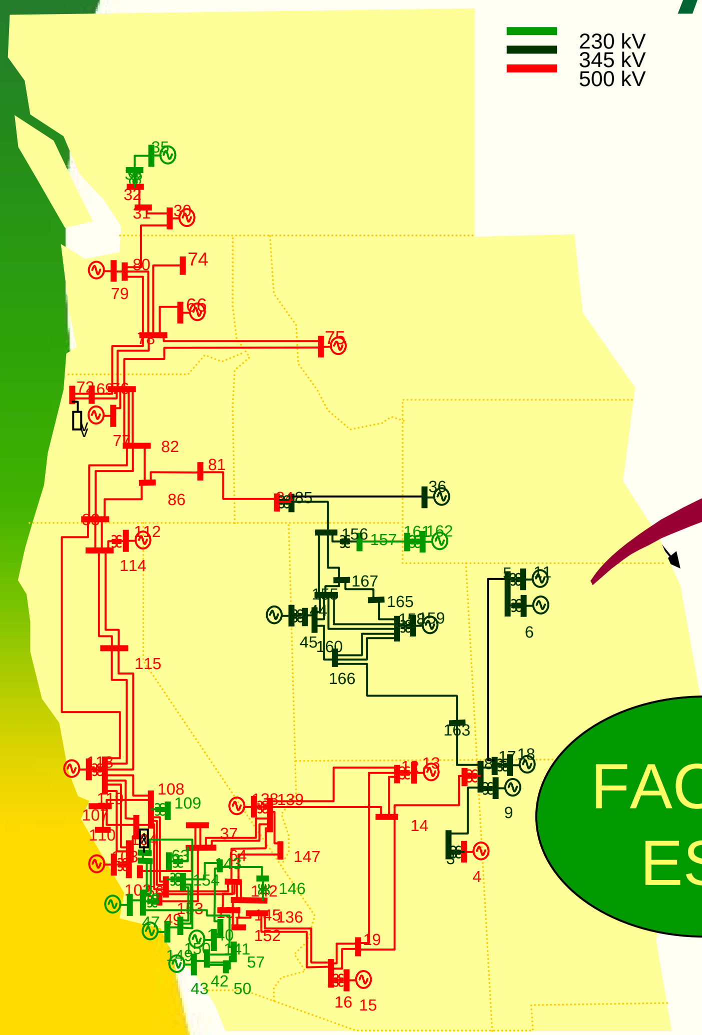
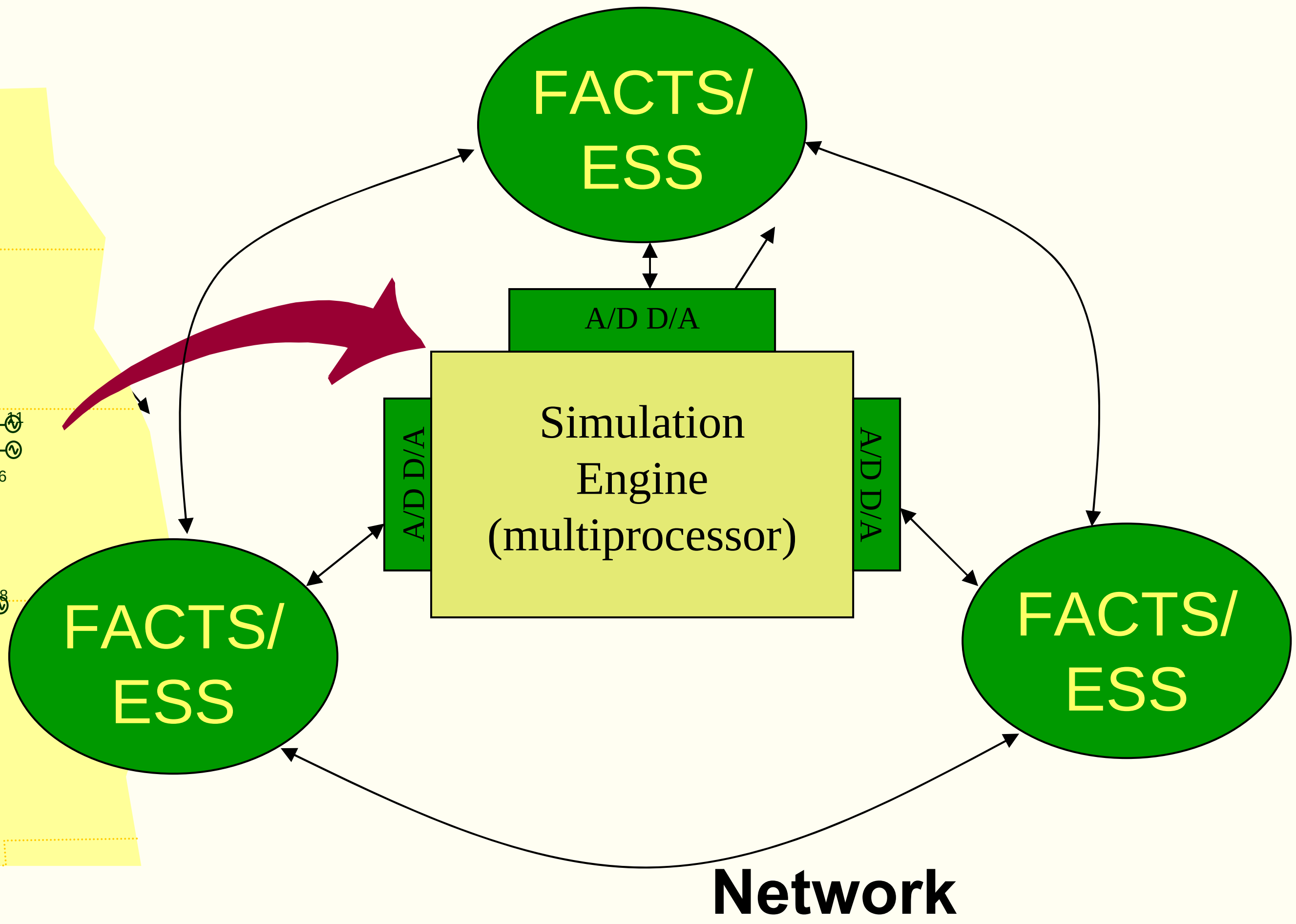
FACTS Interaction Laboratory Architecture





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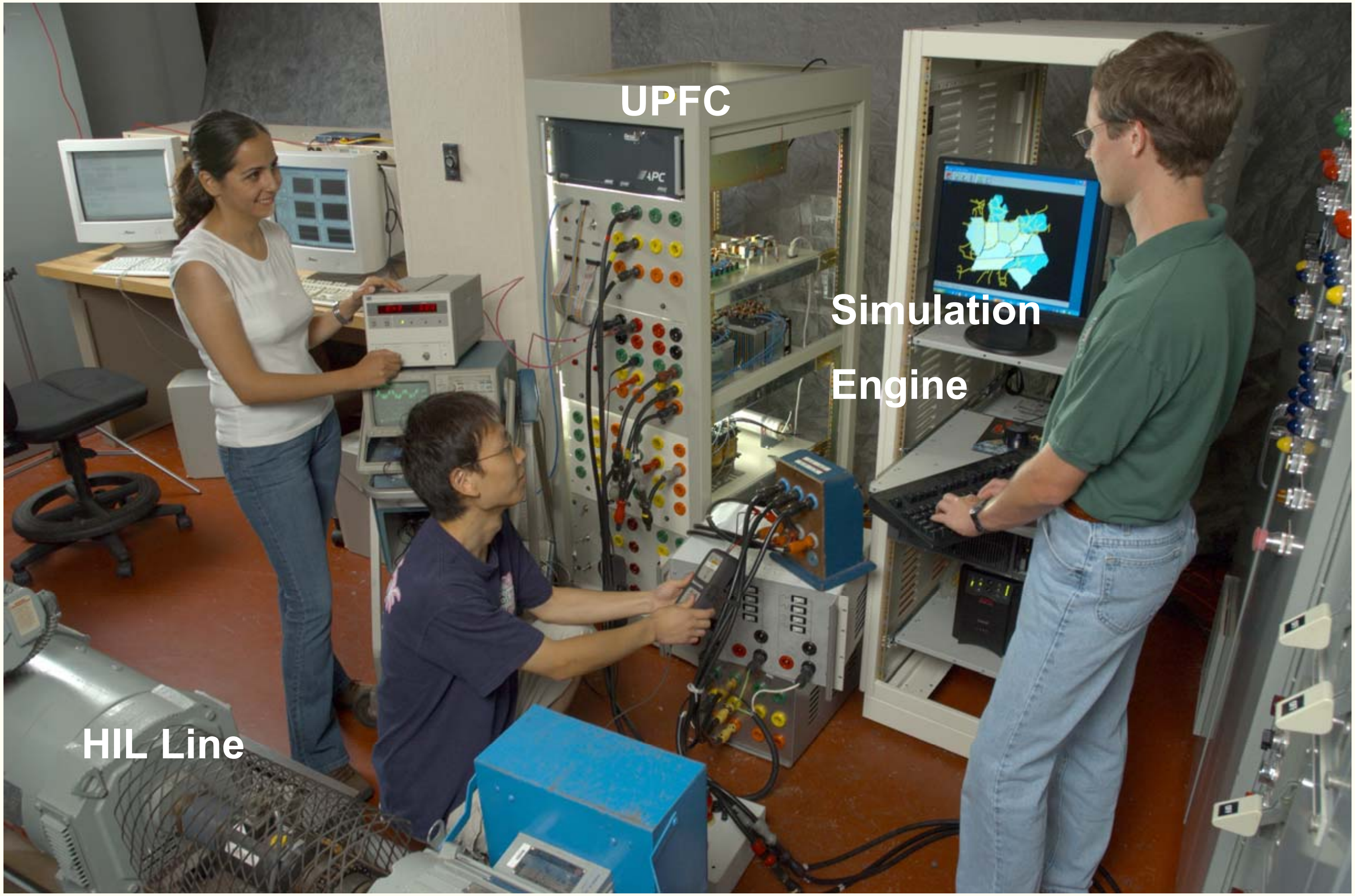
FACTS Interaction Laboratory



Cyber Fault Detection

Fault Tolerance

- Define correct operation of the power system with FACTS
- Embed as executable constraints into each FACTS computer
- FACTS check each other during operation of distributed control algorithms – State Dissemination

Some Basic Constraints

- Constraint 1
  - Power flow into a bus = power flow out of a bus
- Constraint 2
  - Line Power Flow ≤ Maximum Line capacity.

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Cyber Fault Injection

- Attempt to confuse the FACTS embedded computers
- Attempt to disrupt the communication between FACTS embedded computers
- Confuse the power system's operation

Error Coverage of Distributed Executable Correctness Constraints (Maximum Flow Algorithm)

Error Type	Errors Detected By			Unreported Errors	Coverage of Errors Detection	Average Time (sec)
	Program	Timeout	Connection Termination			
Edge Error (over all edges)	117 (100%)	0 (0%)	0 (0%)	0 (0%)	100%	3.437
Vertex Error (over all vertices)	115 (98.3%)	0 (0%)	2 (1.7%)	0 (0%)	98.3%	1.181
Lose All Flow Messages	0 (0%)	100 (100%)	0 (0%)	0 (0%)	100%	NA
Randomly Lose Flow Messages	0 (0%)	131 (97.0%)	0 (0%)	4 (3.0%)	97.0%	NA
Alter All Flow Messages	50 (100%)	0 (0%)	0 (0%)	0 (0%)	100%	0.454
Randomly Alter Flow Messages	50 (100%)	0 (0%)	0 (0%)	0 (0%)	100%	0.452
Invert All Accept/ Reject Messages	100 (100%)	0 (0%)	0 (0%)	0 (0%)	100%	11.803
Randomly Invert Accept/Reject	50 (100%)	0 (0%)	0 (0%)	0 (0%)	100%	6.852

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Project Benchmarks

- Construction of FIL
- Demonstration of Cascading Failures
- Placement and Control
- Hardware/Software Architecture
- Cyber Fault Detection
- Dynamic Control
- Visualization

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