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Cyber-Physical Systems Distributed Control: The Advanced Electric Power Grid

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University of Missouri-Rolla

Funded by the Energy Storage Systems Program of the U.S. Department Of Energy (DOE/ESS) through Sandia National Laboratories (SNL).

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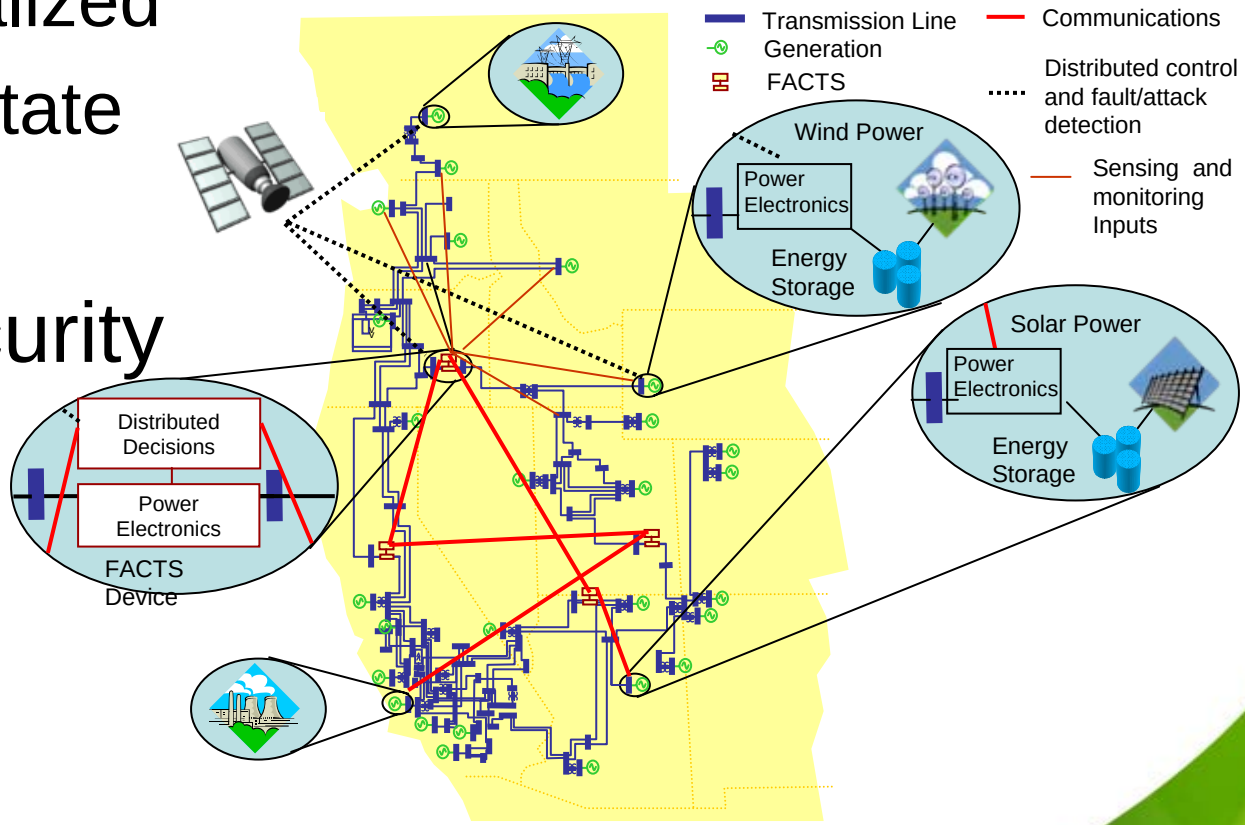
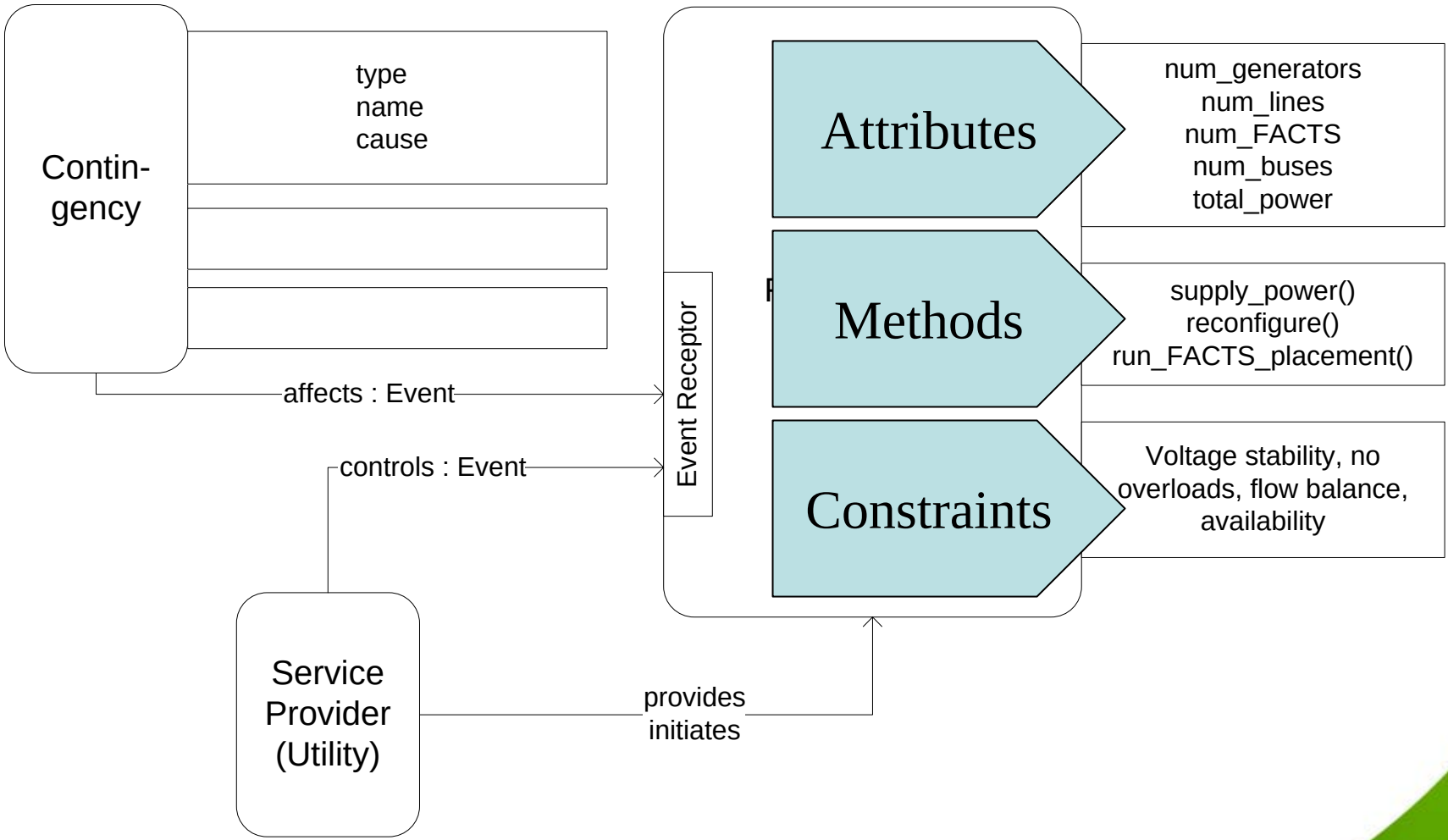
Issues

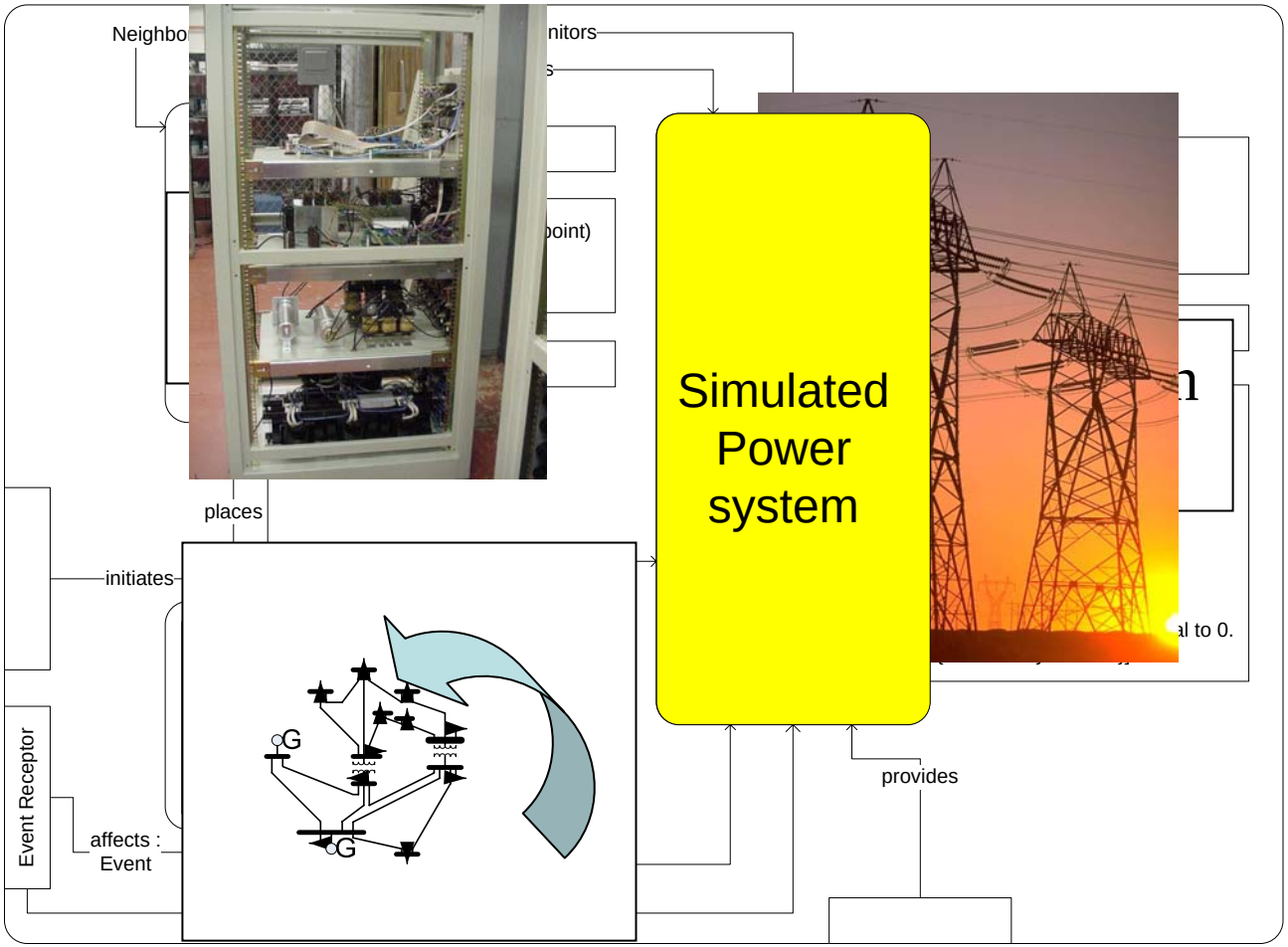
- Hardware-software co-design
- Device placement and control
  - Decentralized
  - Steady-state
  - Dynamic
- Cyber security
- Reliability



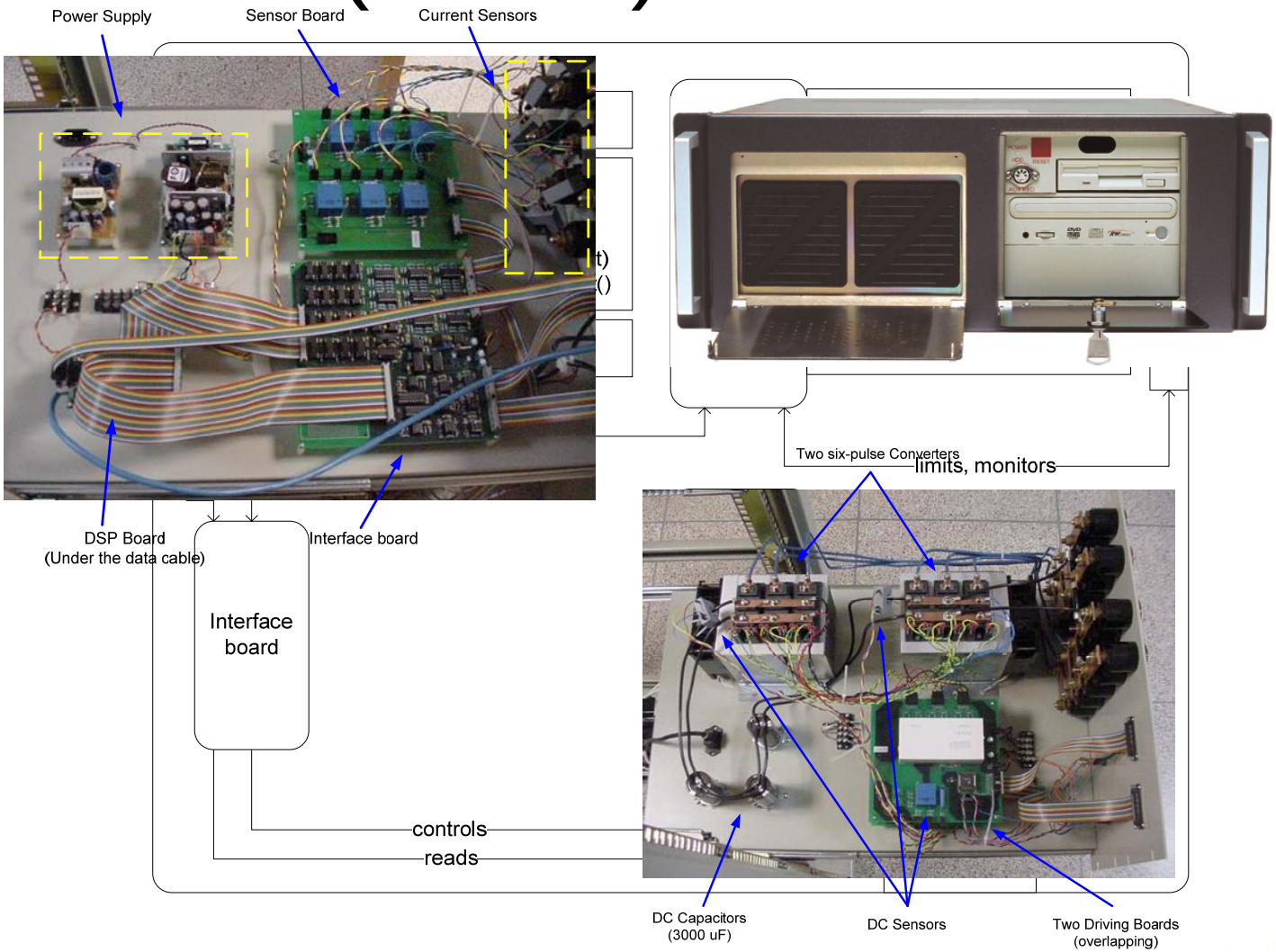
FACTS Power System Model



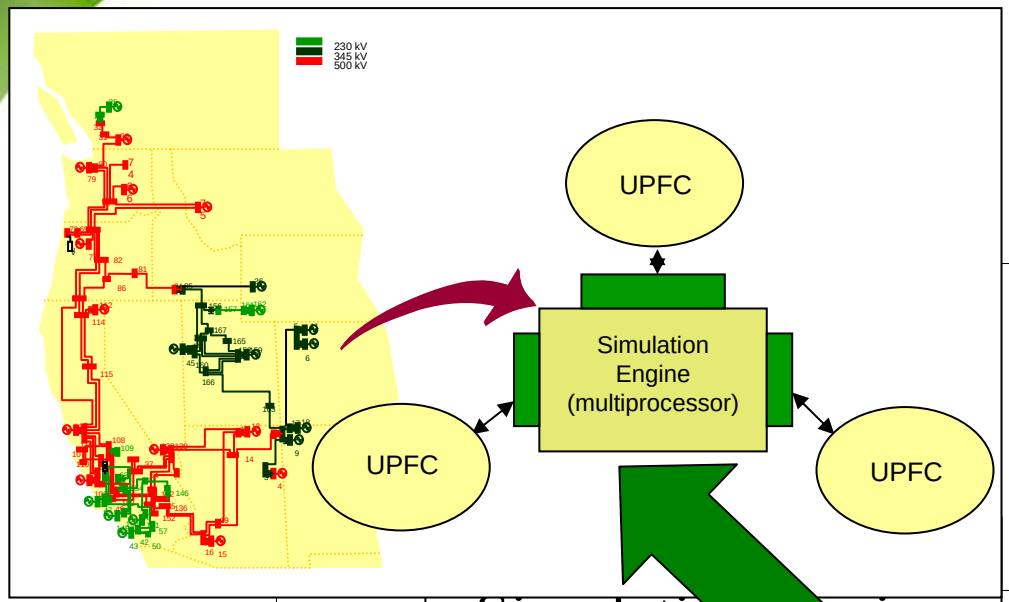
First Decomposition



Unified Power Flow Controller (UPFC) FACTS



Simulated Power Transmission System



UPFC

Simulation Engine (multiprocessor)

UPFC

UPFC

senses

generation_setpoint

Hardware in the Loop Line

Simulation Engine

limits, monitors

Power System Simulation Engine

Machine 1

D/A output

A/D input

UPFC 1

Programmable load

Machine 2

D/A output

A/D input

UPFC 2

Programmable load

Machine 3

D/A output

A/D input

UPFC 3

Programmable load

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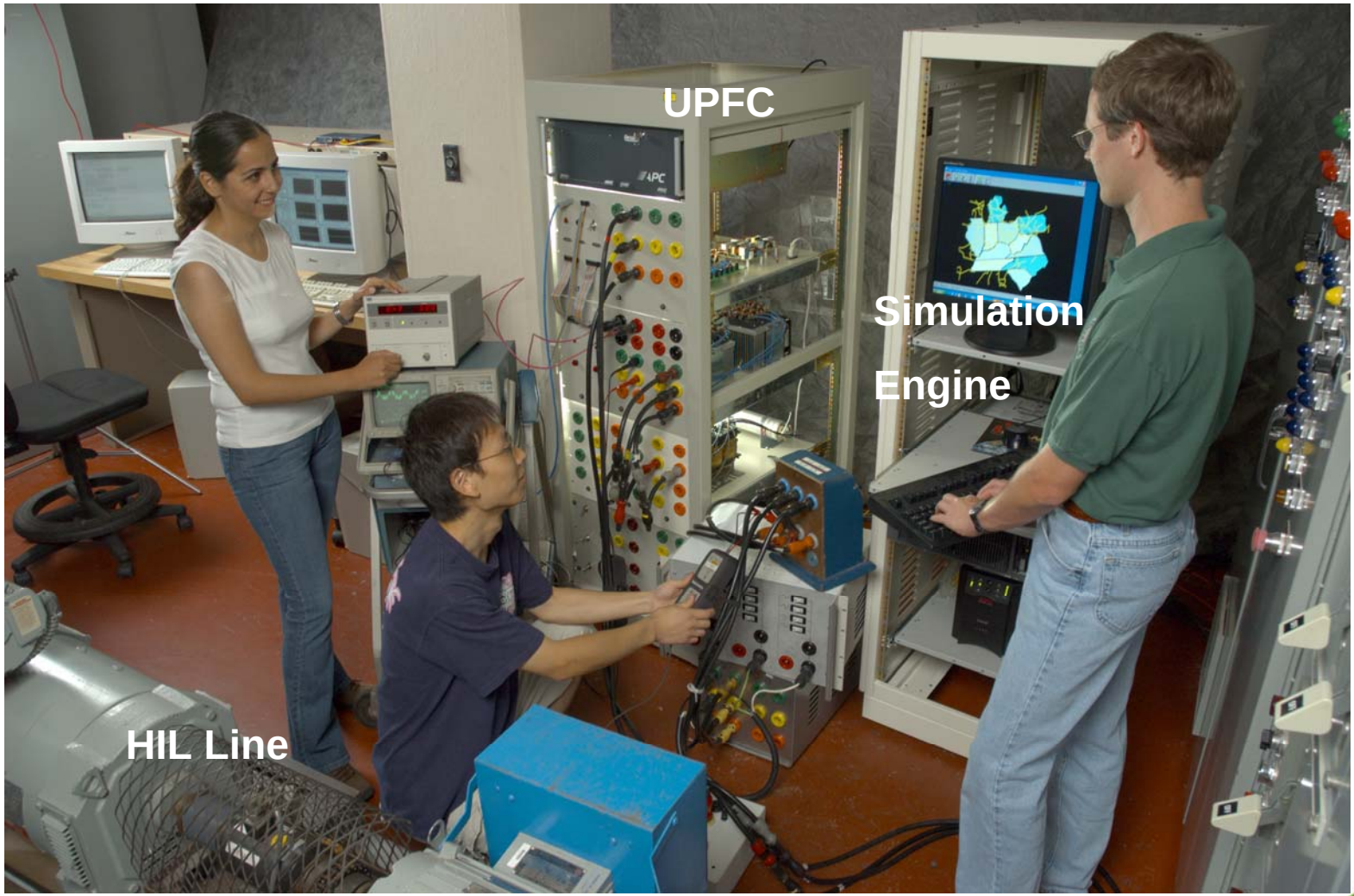
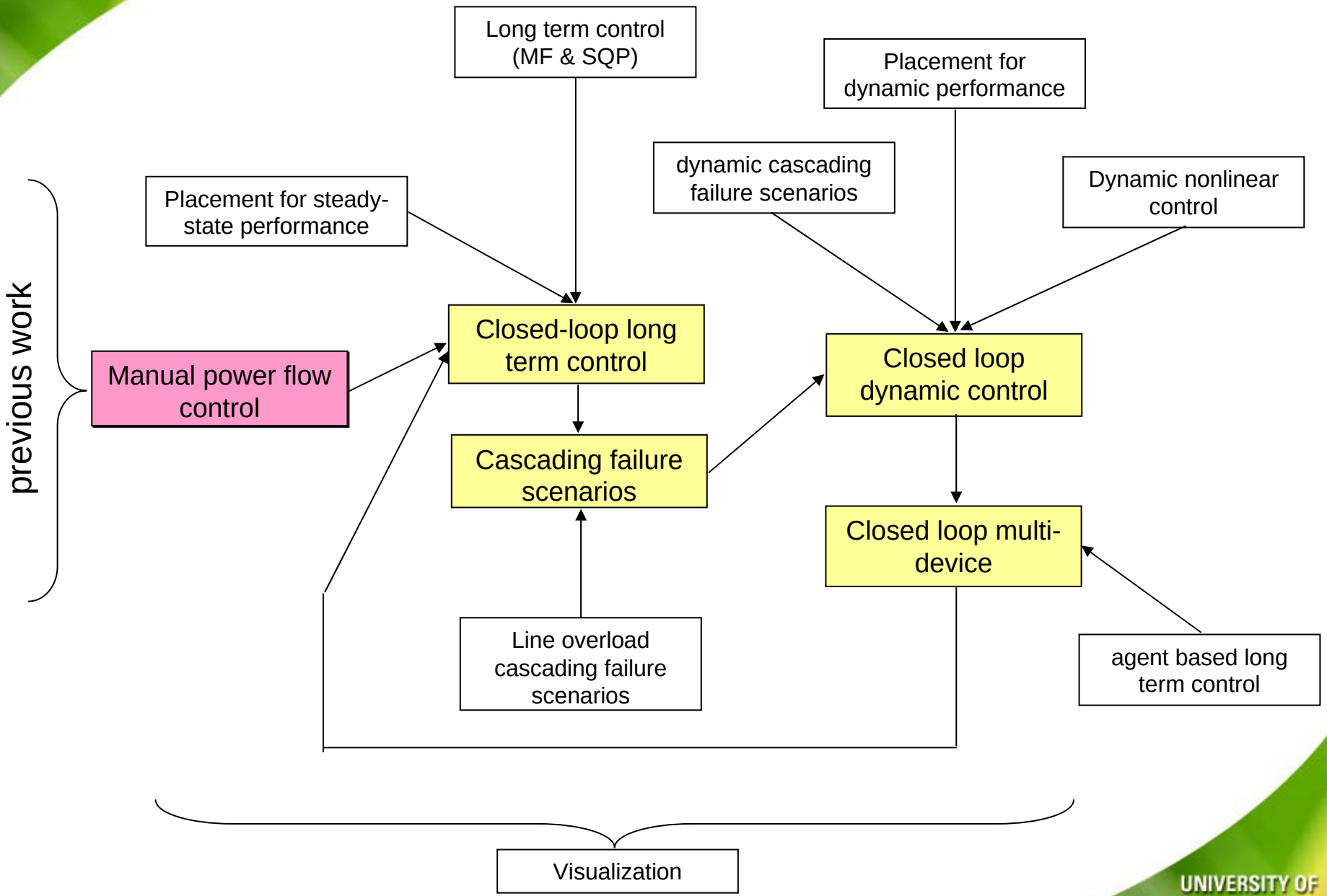
FACTS Interaction Laboratory




Long term control (MF & SQP)
Placement for dynamic performance
dynamic cascading failure scenarios
Dynamic nonlinear control
Placement for steady-state performance
previous work
Closed-loop long term control
Manual power flow control
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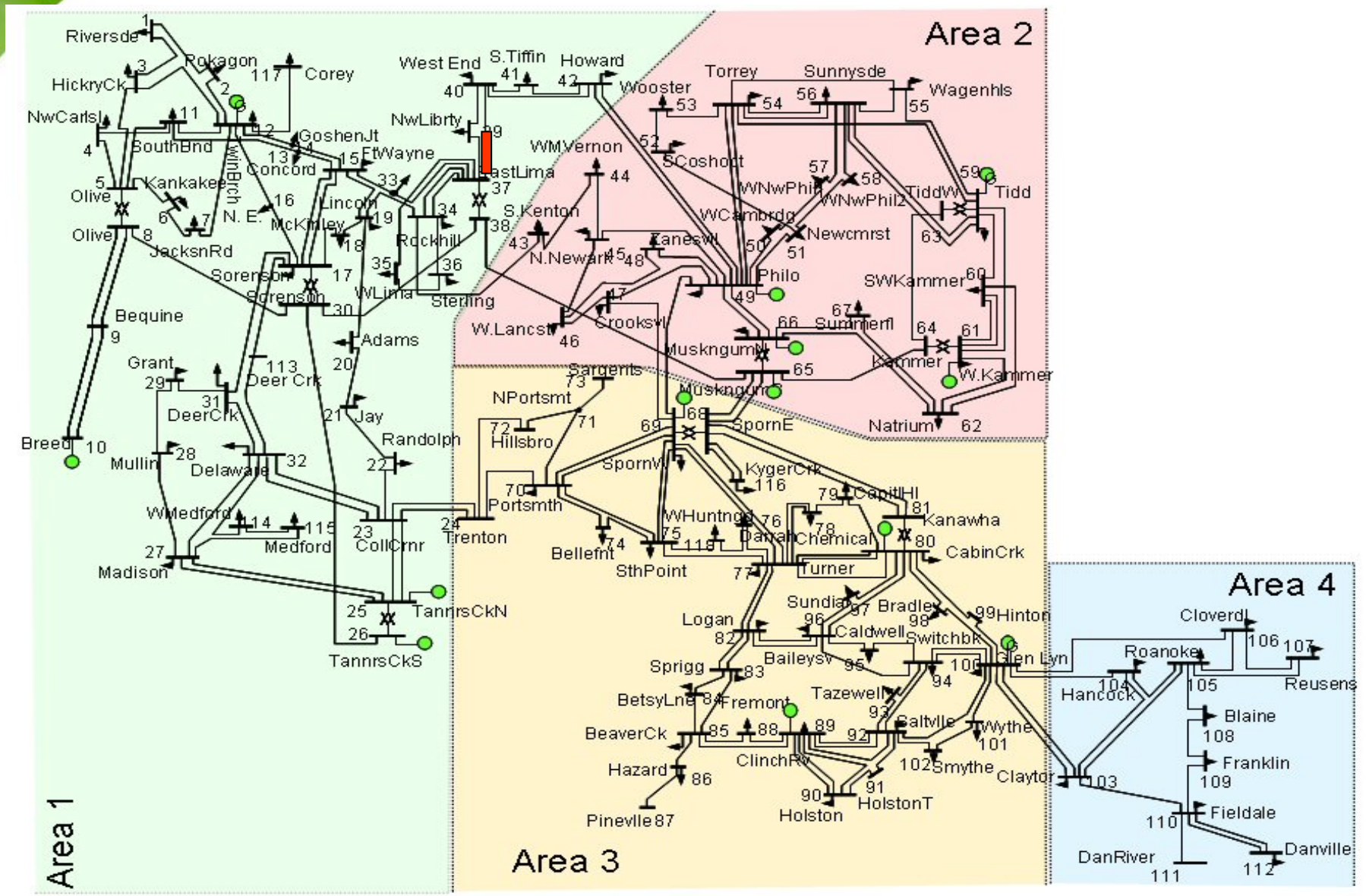
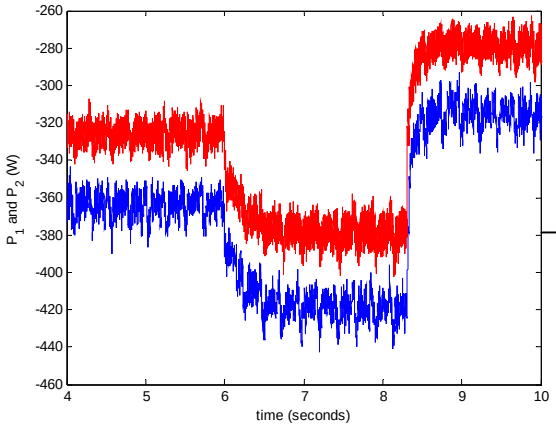
agent based long term control
Visualization

IEEE 118 Bus Test System

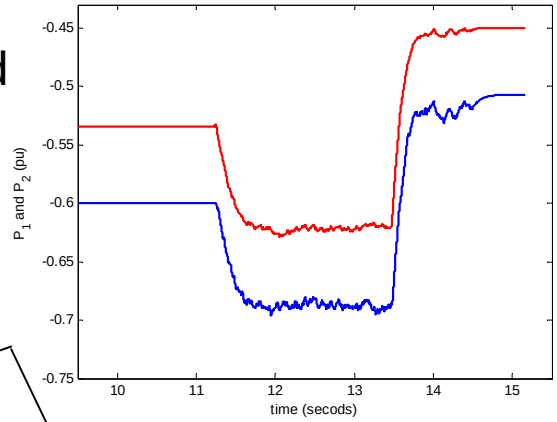


Manual Power Flow Control

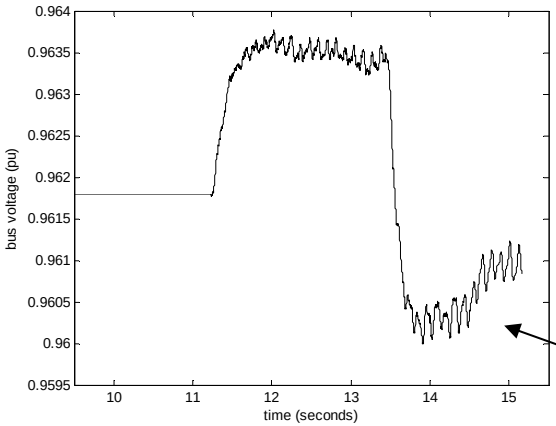
actual UPFC power flows

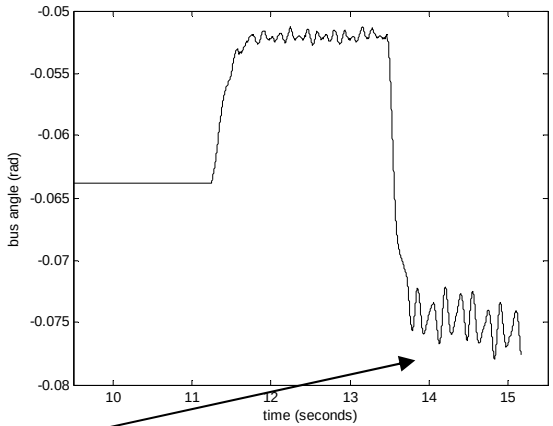


measured and filtered into simulation

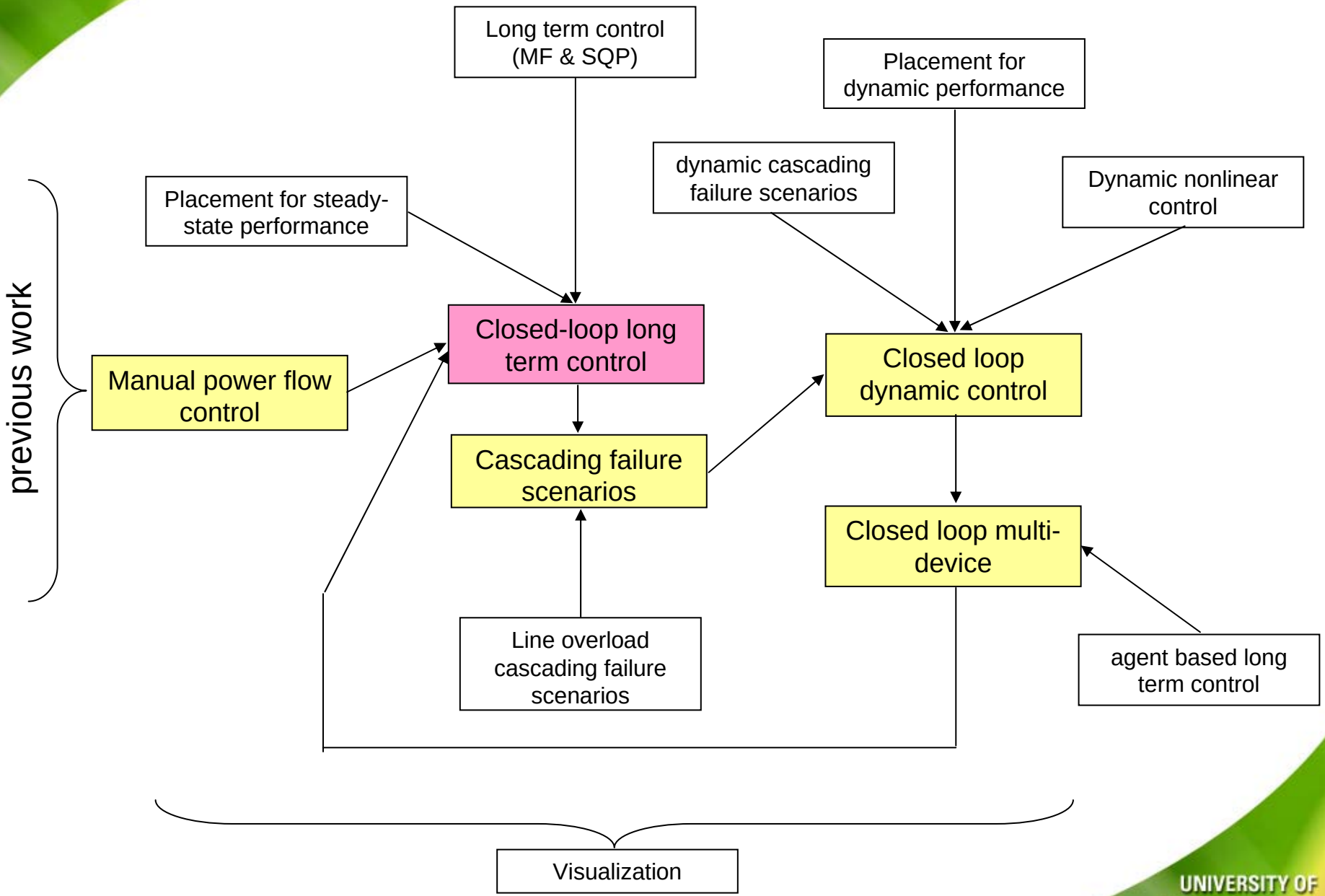


simulated bus voltages & angles





Note induced low frequency oscillations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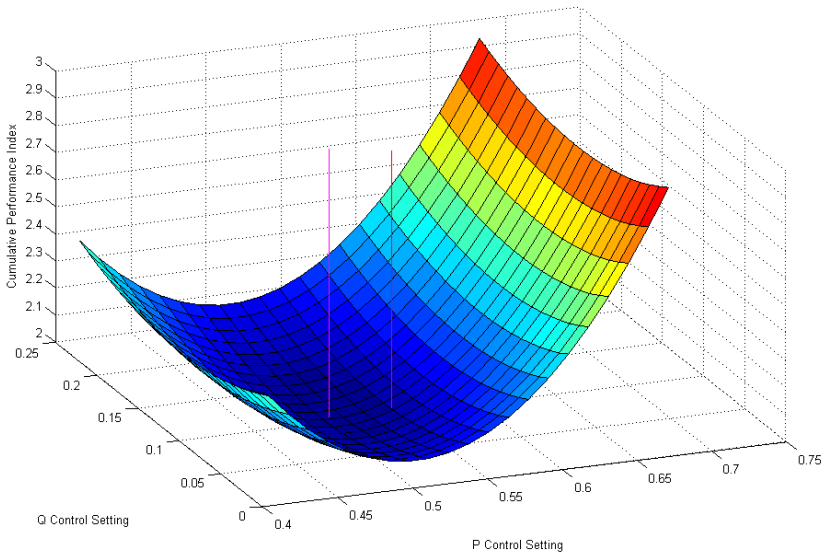
Closed-loop long term control

- Which setting yield the lowest PI over all possible contingencies?



Minimize

$$PI_{cum} = \sum_{all\ lines} \left(\frac{S_{ij}}{S_{ij}^{max}}\right)^2 + W_V \sum_{i=1}^{N} \left(\frac{V_i - V_i^{ss}}{\triangle V_i^{lim}}\right)^2$$

Subject to:

Equality constraints:

$$0 = \triangle P_i - \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_i - \theta_j - \phi_{ij})$$

$$0 = \triangle Q_i - \sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\theta_i - \theta_j - \phi_{ij})$$

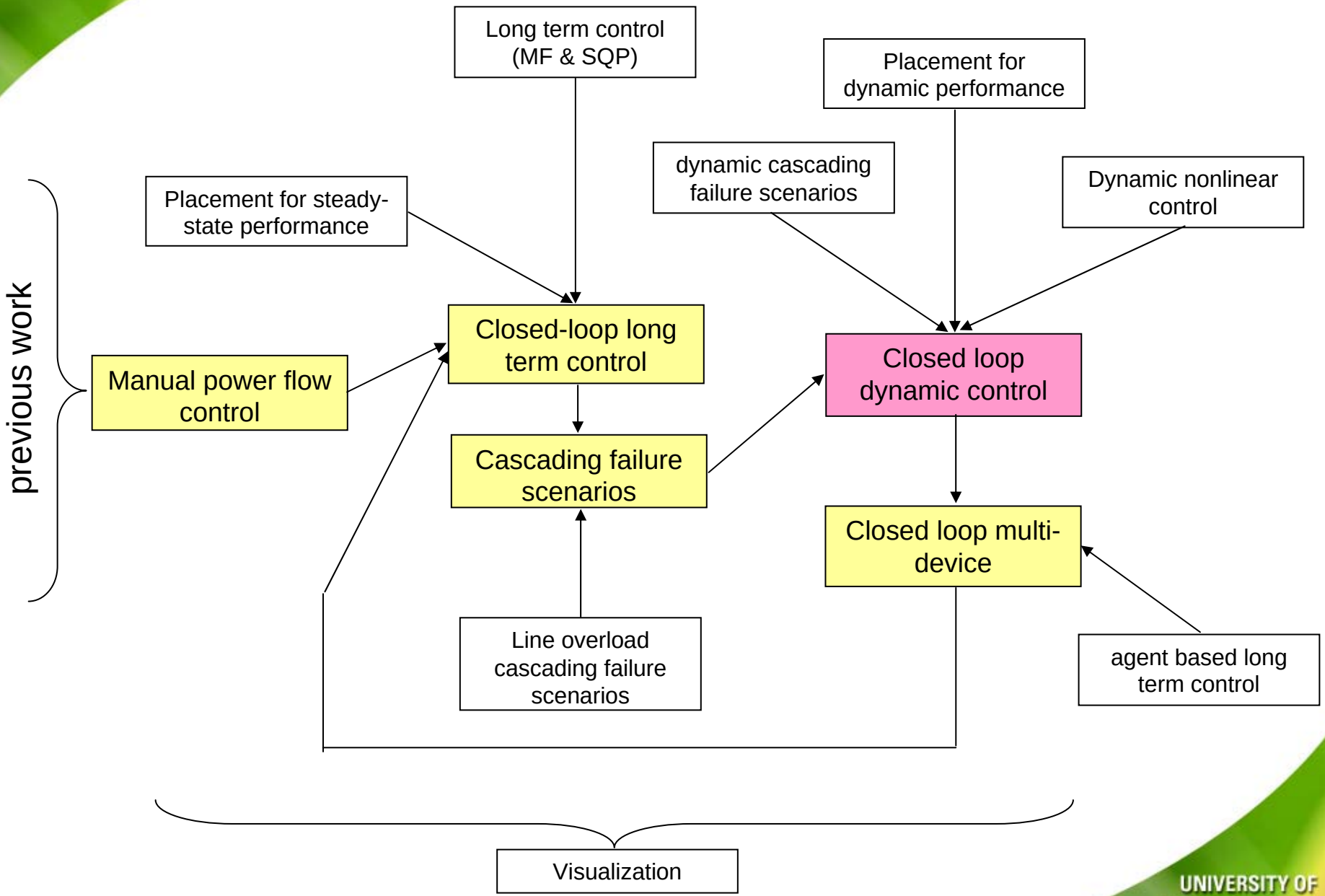
for $i=1,...,N$ and $j=1,...,N$

Inequality constraints:

$$P_i^{min} \le P_i \le P_i^{max}$$
$$Q_i^{min} \le Q_i \le Q_i^{max}$$
$$V_i^{min} \le V_i \le V_i^{max}$$

UPFC Constraints:

$$\sqrt{P_{SET}^2 + Q_{SET}^2} \le S_{ij}^{max}$$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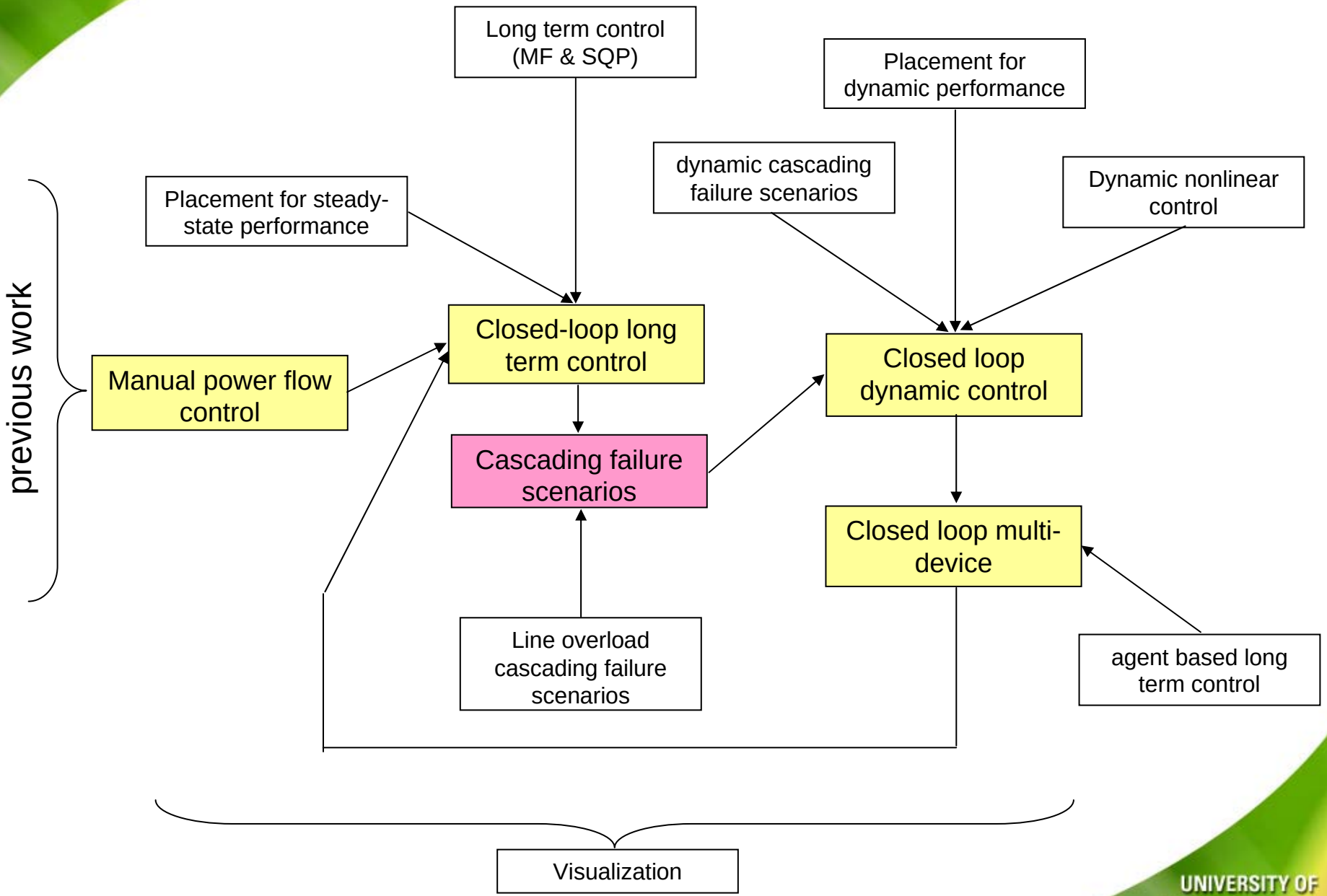
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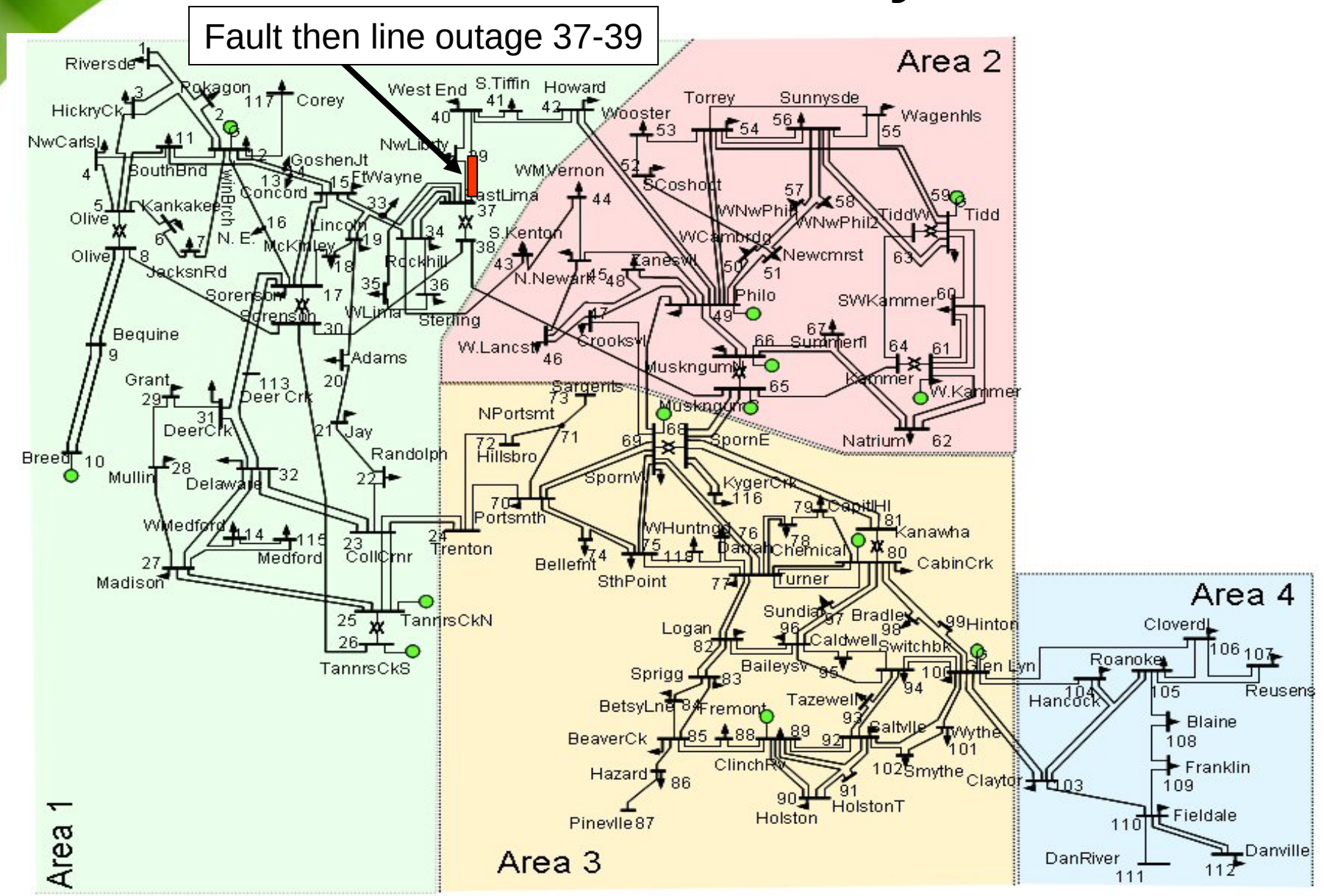

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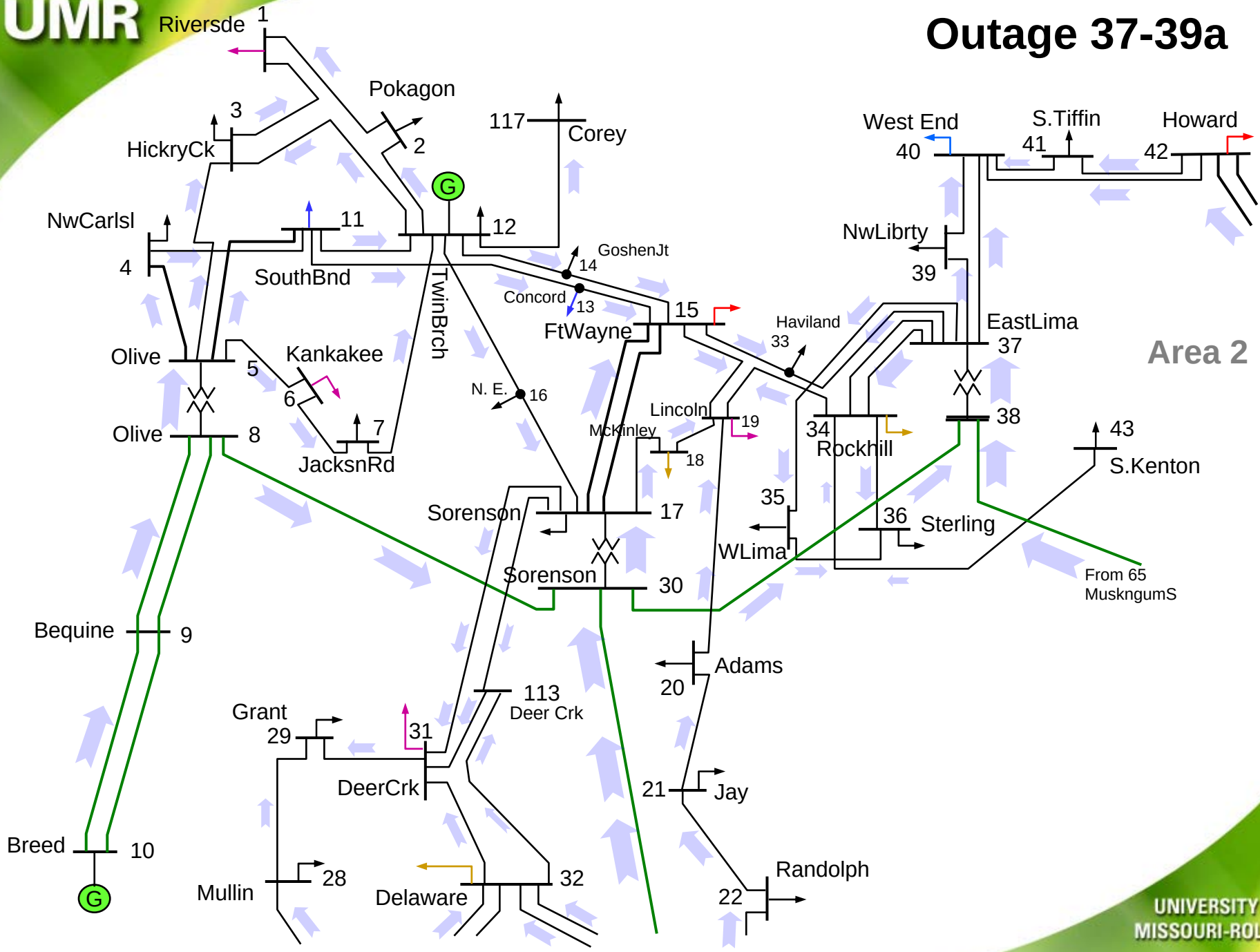
Outage 37-39a



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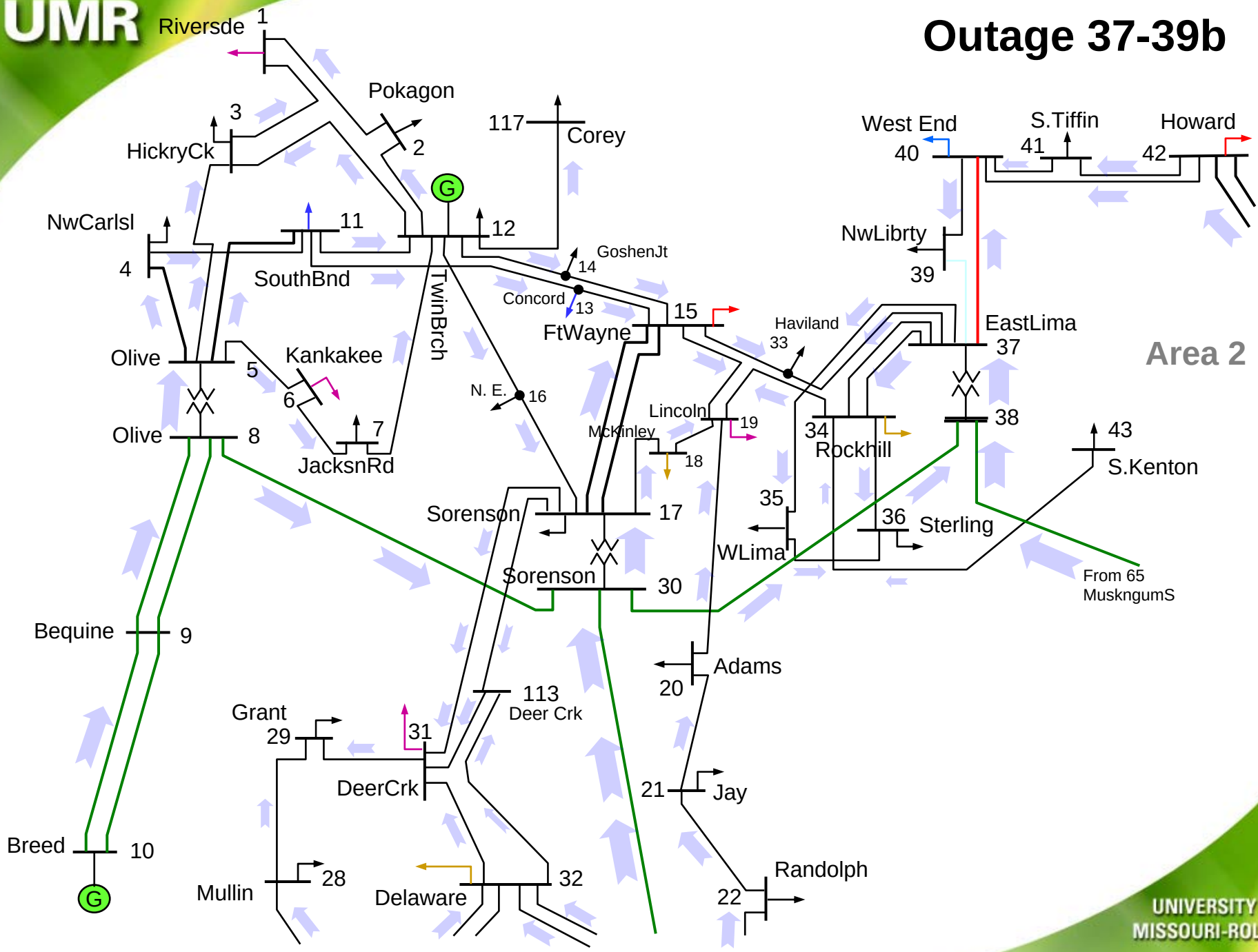
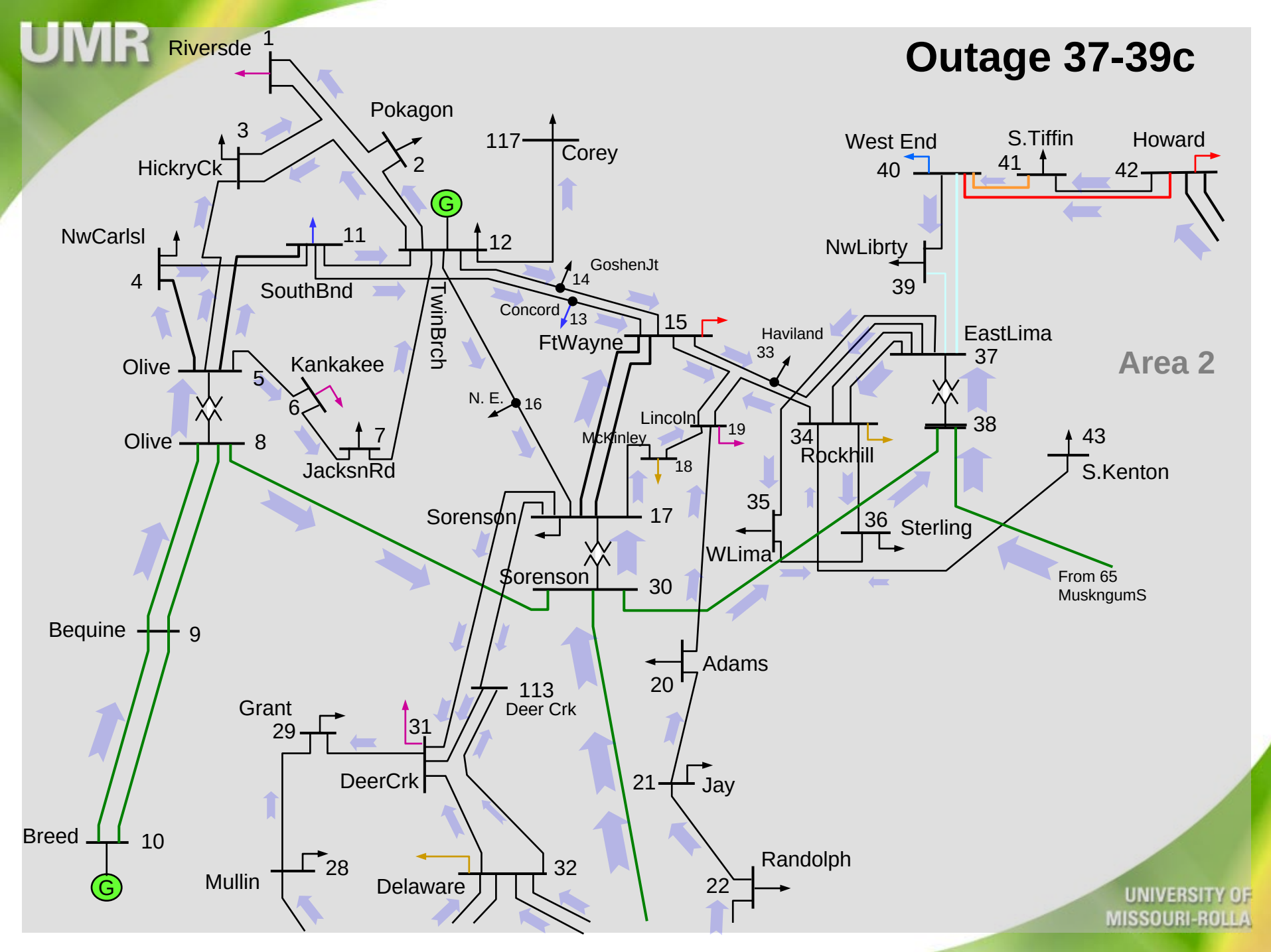
Outage 37-39b

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Outage 37-39c
Riversde
1
Pokagon
2
3
HickryCk
117
Corey
G
NwCarlsl
4
11
12
SouthBnd
TwinBrch
GoshenJt
14
Concord
13
15
FtWayne
West End
40
S.Tiffin
41
Howard
42
NwLibrty
39
Haviland
33
EastLima
37
Area 2
Olive
5
Kankakee
6
7
JacksnRd
Olive
8
N. E.
16
McKinley
Lincoln
19
18
34
Rockhill
38
43
S.Kenton
35
36
Sterling
WLima
Sorenson
17
Sorenson
30
From 65
MuskngumS
Bequine
9
Adams
20
113
Deer Crk
Grant
29
31
DeerCrk
21
Jay
Breed
10
G
Mullin
28
Delaware
32
Randolph
22
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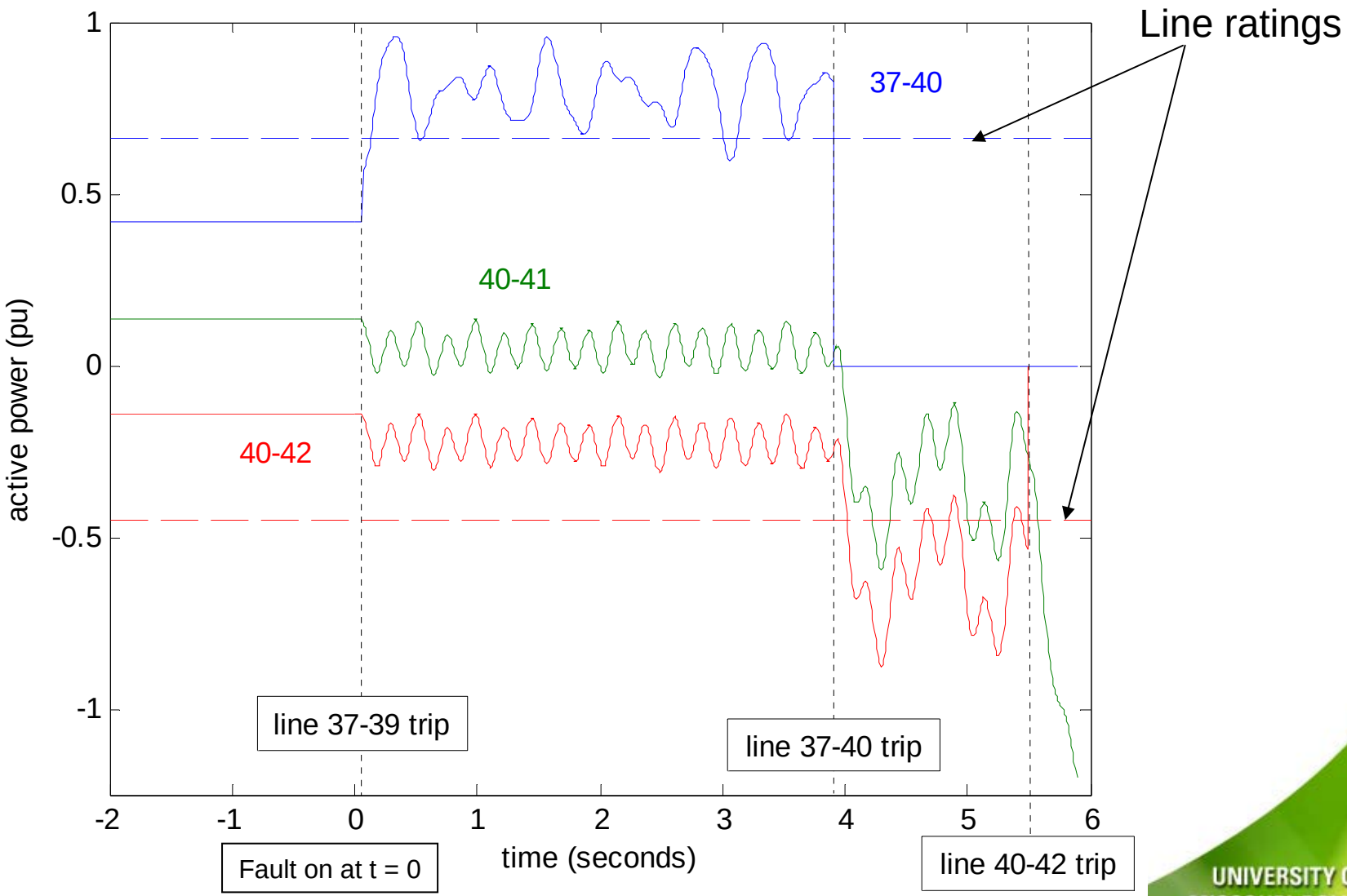
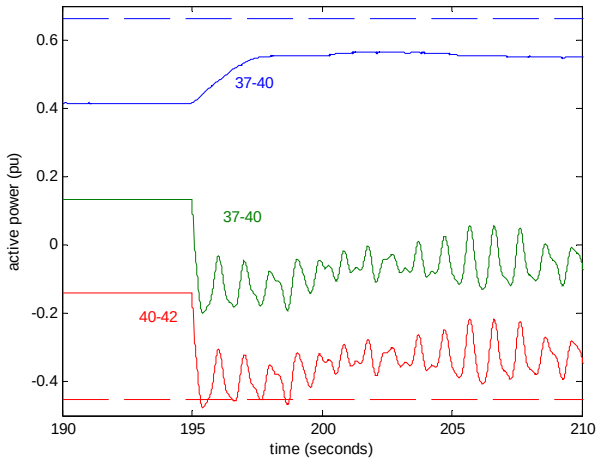
Simulation of cascading failure

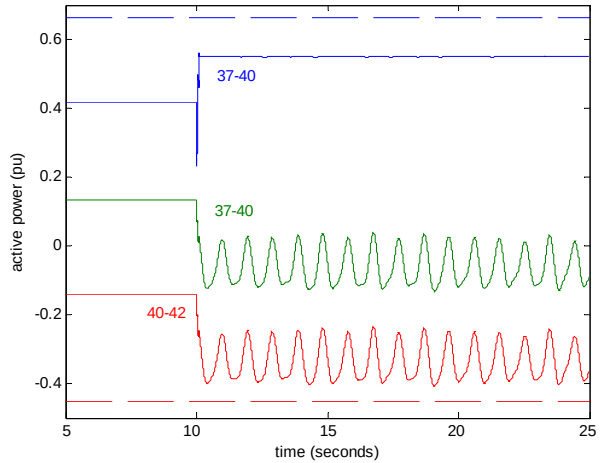


Comparison

experimental



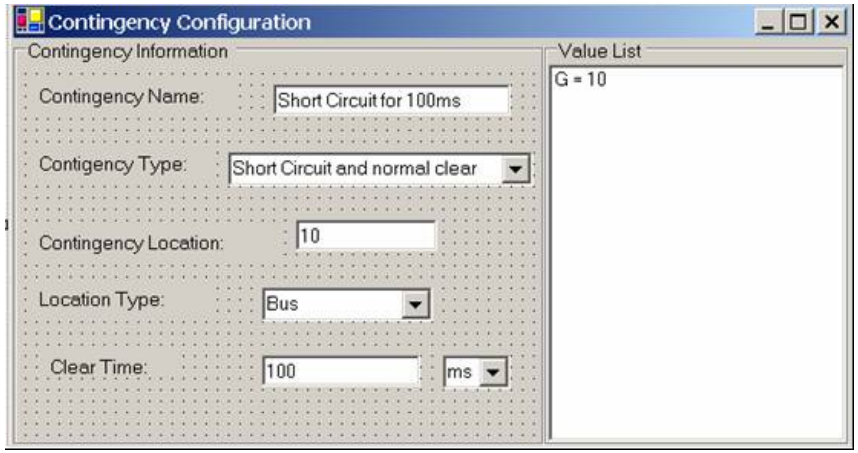
simulation

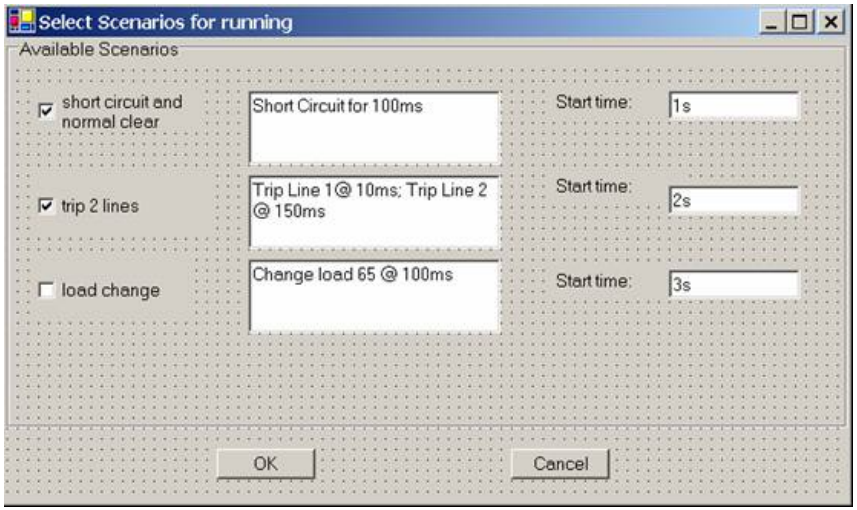


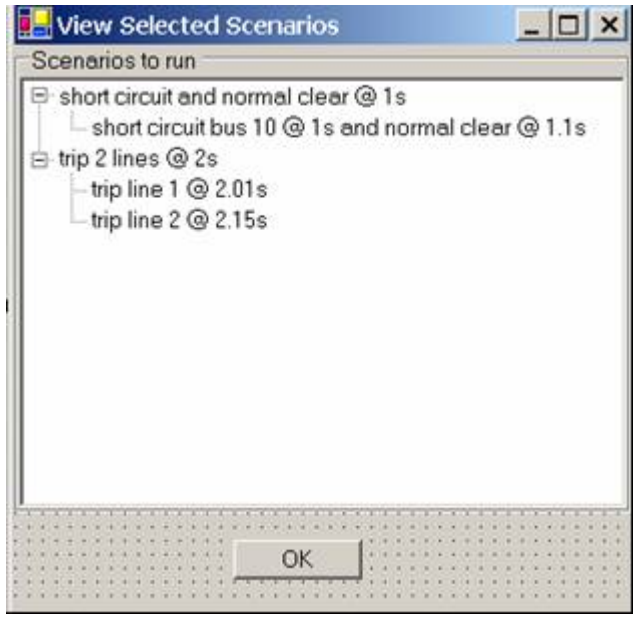
mode	*A(i)*	*B(i)*	*ω(i)*		mode	*A(i)*	*B(i)*	*ω(i)*
1	*0.02*	*0*	*13.05*		*1*	*0.02*	*0*	*13.04*
2	*0.05*	*0*	*6.55*		*2*	*0.07*	*0*	*6.54*
3	*0.02*	*-0.14*	*6.08*					
4	*0.04*	*0*	*6.1*					

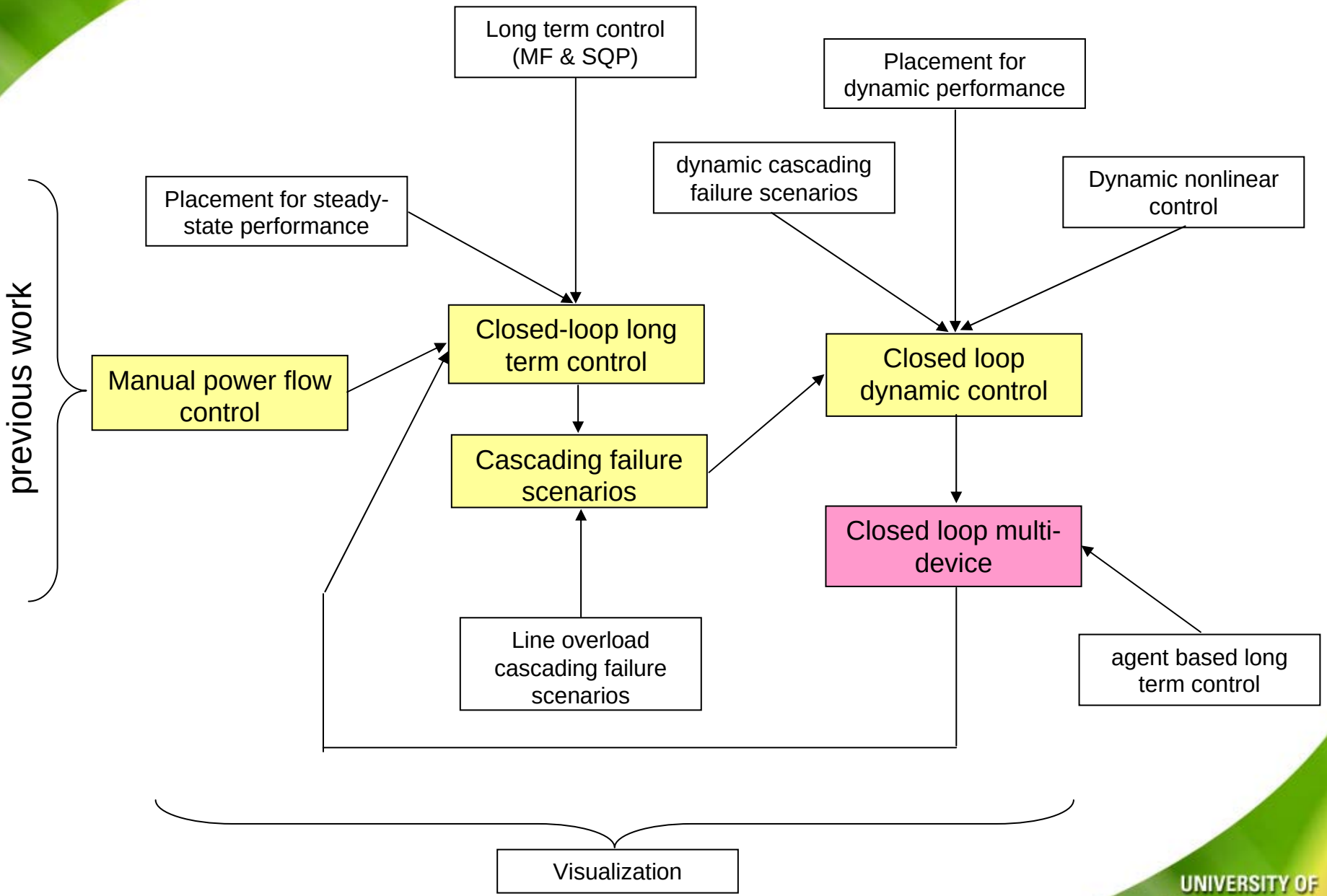
$$x(t) = \sum A_i e^{B_i t} \cos\left(\omega_i t + \theta_i\right)$$

GUIs for HIL


Contingency Configuration
Contingency Information
Contingency Name:
Short Circuit for 100ms
Contigency Type:
Short Circuit and normal clear
Contingency Location:
10
Location Type:
Bus
Clear Time:
100
ms
Value List
G = 10


Select Scenarios for running
Available Scenarios
short circuit and normal clear
Short Circuit for 100ms
Start time:
1s
trip 2 lines
Trip Line 1@ 10ms; Trip Line 2 @ 150ms
Start time:
2s
load change
Change load 65 @ 100ms
Start time:
3s
OK
Cancel


View Selected Scenarios
Scenarios to run
short circuit and normal clear @ 1s
short circuit bus 10 @ 1s and normal clear @ 1.1s
trip 2 lines @ 2s
trip line 1 @ 2.01s
trip line 2 @ 2.15s
OK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Special Thanks

- Imre Gyuk - DOE Energy Storage Program
- Stan Atcitty - Sandia National Laboratories
- John Boyes - Sandia National Laboratories

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UMR student team

Computer Science

- Gosnell, Michael
- Lininger, Adam
- Ryan, Matthew
- Service, Travis
- Siever, William
- Simsek, Sule
- Smorodkina, Ekaterina
- Su, Changyi
- Sun, Yan
- Tang, Han (Carol)
- Underwood, Ryan

Electrical Engineering

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- Li, Xiaomeng
- Ma, Hong Tao
- Mehraeen, Shahab
- Shi, Lisheng
- Wang, Keyou
- Yazdani, Atousa
- Zarghami, Mahyar