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A Co-Evolutionary Armsrace Methodology for Improving Cyber-Physical System Robustness – Distributed Power Electronics Devices

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Fourth Annual Carnegie Mellon Conference on the Electricity Industry

Motivation

- Cyber-Physical Systems (CPS) are ubiquitous and their reliability critical, but ensuring their robust operation is very difficult
- CPS robustness can be improved through hardening

CPS Hardening

- System hardening examples
  - Hardening individual components
  - Increasing redundancy
  - Improving controllability
- Measuring hardening performance
  - Taking hardening cost into account, evaluate the hardening over all scenarios

CPS Hardening Search Space

- Characteristics of CPS hardening search spaces:
  - Combinatorial in complexity
  - Contain non-linear dependencies
- Traditional search algorithms fail to perform well under such conditions

Evolutionary Algorithms 101

- Type of Generate-and-Test algorithm which exploit solution quality gradient
- Population-based, stochastic search algorithms inspired by Evolution Theory
- Bias search towards optimum by stochastically combining features of high quality solutions to create new solutions and use randomized perturbations to explore new features

Measuring hardening performance - revisited

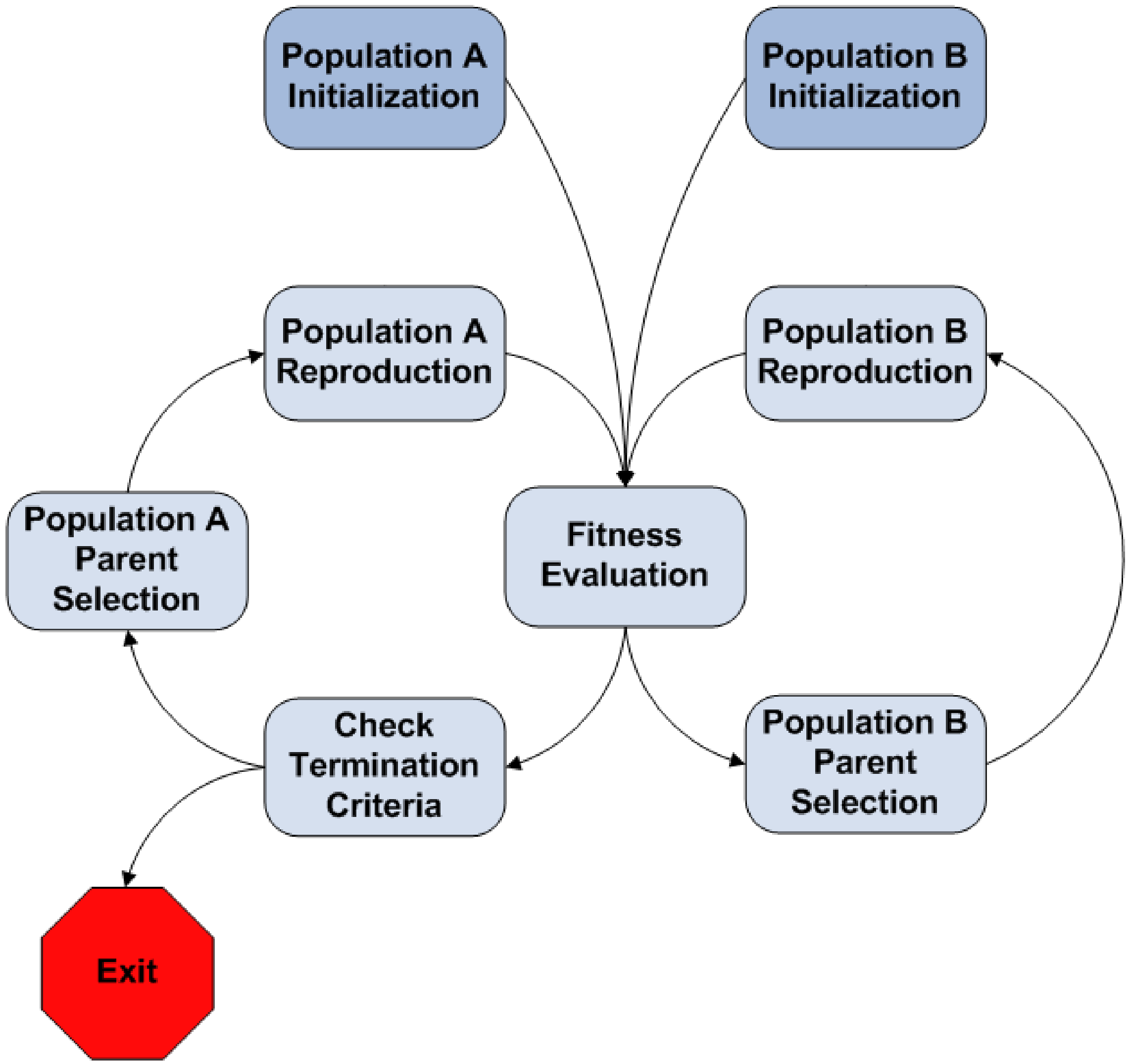
- In practice: evaluate over a representative sampling of scenarios
- Sampling approaches
  - Pruned Exhaustive (e.g., *n-1* security index in power systems)
  - Monte Carlo
  - Intelligent adversary

Intelligent Adversary

- Game Theoretic: Two-player game of defenders & attackers
- Dependent search spaces: CPS hardening space (defenders) & scenario space (attackers)
- Computational methods for dependent search:
  - Iterative approach [1]
  - Competitive Coevolution approach [3,4]
  - Generalized Co-Optimization approach [5]

Competitive Coevolution

- Type of Evolutionary Algorithm where solution quality is dependent on other solutions
- For two-player games an armsrace is created by having two opposing populations of solutions where solution quality is inversely dependent on solutions in the opposing population


Population A Initialization
Population B Initialization
Population A Reproduction
Population B Reproduction
Population A Parent Selection
Fitness Evaluation
Check Termination Criteria
Population B Parent Selection
Exit

Co-Optimization

- Generalization of Coevolution
- Evolutionary principles are replaced by arbitrary black-box optimization techniques
- Allows matching of interactive problem domains to optimization techniques

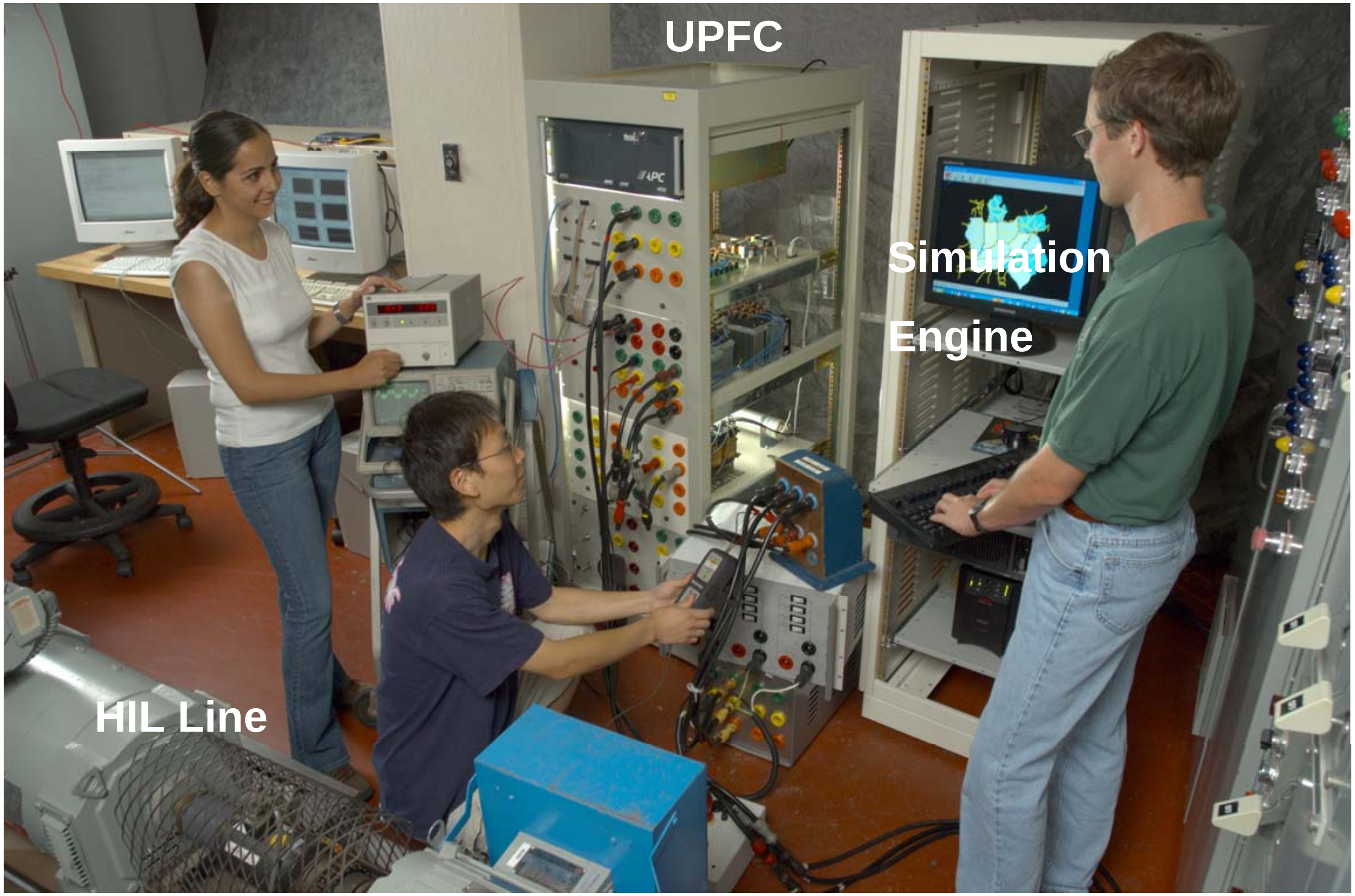
Summary of methodology

- Improve CPS robustness by creating an armsrace between hardenings (defenders) and fault scenarios (attackers) through the use of Co-Optimization
- Hardenings are evolved to minimize economic loss
- Fault scenarios are evolved to maximize economic loss
- Stair stepping of ability

Advanced Power Transmission System with Distributed Power Electronics Devices - Case Study

- Hardenings: Unified Power Flow Controller (UPFC) placements
  - Control power flow through transmission lines
  - UPFCs are a powerful type of Flexible AC Transmission System (FACTS) device
- Fault scenarios: line outages

FACTS Interaction Laboratory

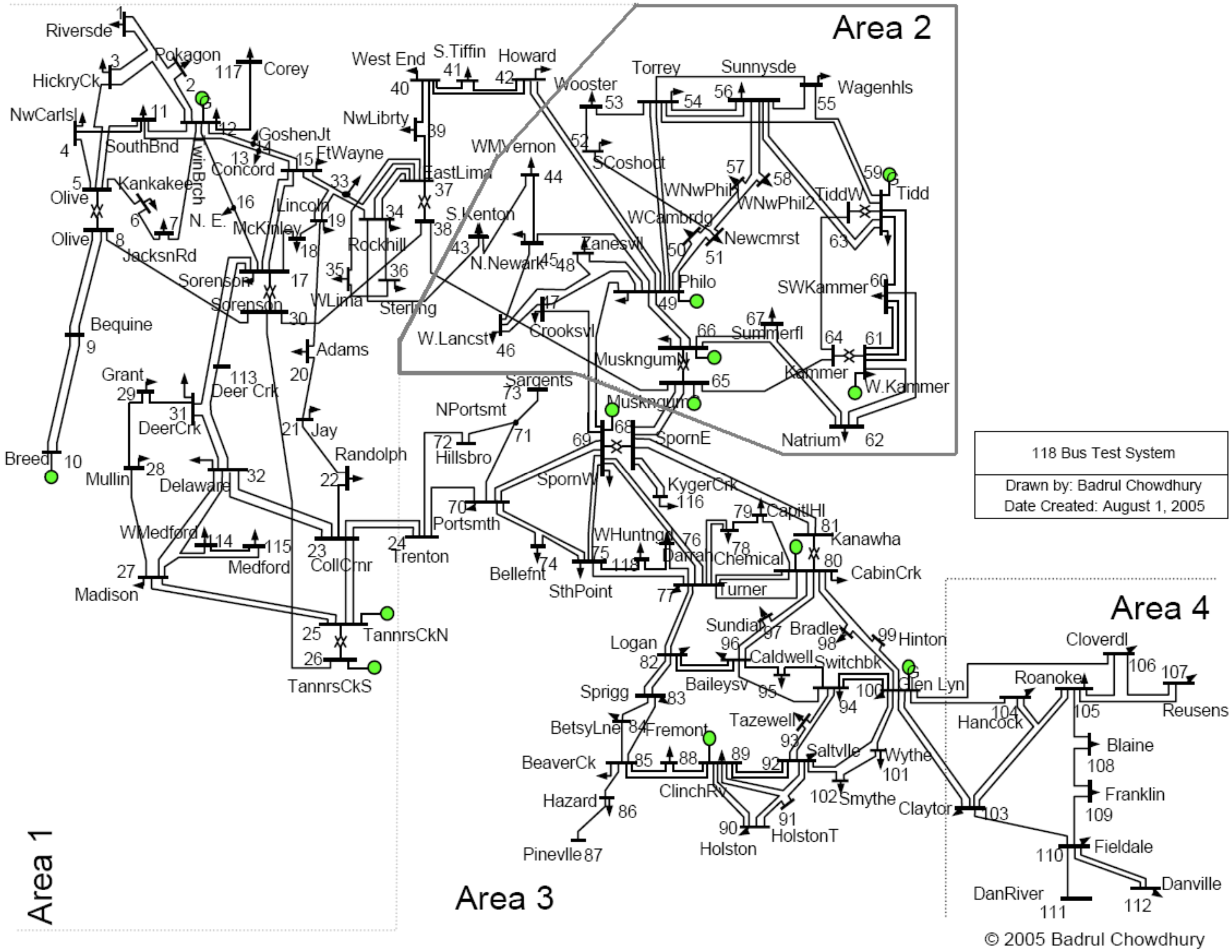


Performance Measure

- UPFC placements are evolved to maximize the percentage of system demand met
- Fault scenarios are evolved to minimize the percentage of system demand met

Experimental Setup

- Steady state Newton-Raphson load flow
- Iterative load shedding employing optimal multiplier
- Islanding
- Fault scenarios limited to two-line outages
- Multiple iterations to simulate time / cascading failures
- SQP control of UPFC devices [2]
- Highly stressed version of IEEE 118-bus test system: Area 2 (41 lines)


Area 1
Area 2
Area 3
Area 4
118 Bus Test System
Drawn by: Badrul Chowdhury
Date Created: August 1, 2005
Riversde
Pokagon
HickryCk
Corey
NwCarlsl
SouthBnd
Olive
Kankakee
JacksnRd
Concord
GoshenJt
FtWayne
N. E.
McKinley
Lincoln
Rockhill
Sorenson
Bequine
Grant
Deer Crk
DeerCrk
Mullin
Delaware
Breed
WMedford
Medford
Madison
CollCrnr
TannrsCkN
TannrsCkS
Adams
Jay
Randolph
Trenton
West End
S.Tiffin
Howard
NwLibrty
WMVernon
EastLima
S.Kenton
N.Newark
WLima
Sterling
W.Lancst
Crooksvl
Zanesvll
Wooster
SCoshoct
Torrey
Sunnysde
Wagenhls
WNwPhil
WNwPhil2
WCambrdg
Newcmrst
Philo
TiddW
Tidd
SWKammer
Summerfl
Kammer
W.Kammer
Natrium
Muskngum
SpornE
SpornW
KygerCrk
Sargents
NPortsmt
Hillsbro
Portsmth
Bellefnt
SthPoint
WHuntngd
Darrah
Chemical
CapitlHl
Kanawha
CabinCrk
Turner
Logan
Sundial
Bradley
Hinton
Caldwell
Switchbk
Baileysv
Sprigg
BetsyLne
Fremont
Tazewell
Saltvlle
Wythe
Smythe
BeaverCk
Hazard
Pinevlle
ClinchRv
Holston
HolstonT
Glen Lyn
Cloverdl
Roanoke
Reusens
Hancock
Claytor
Blaine
Franklin
Fieldale
DanRiver
Danville
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Case Study Results

- Best solutions produced by armsraces evaluated over all single & double line outages
- Baseline (system without UPFCs) served an average of 85.42% of the demand

Algorithm	Ave. Demand Servedx	Ave. Num. of UPFCs
CoEA	93.67%	5.29
CoSA	93.49%	6.36
CoGA	93.01%	5.1

Conclusions

- We presented a sophisticated computational methodology for increasing the robustness of CPS systems
- Proof of concept results of the methodology were shown for a power transmission system case study

References

[1] W. Siever, A. Miller, D. Tauritz. Blueprint for Iteratively Hardening Power Grids employing Unified Power Flow Controllers. Proceedings of IEEE SoSE 2007 - the 2nd International Conference on System of Systems Engineering, pages 1-7, San Antonio, Texas, April 16-18, 2007

[2] W. Siever, A. Miller, D. Tauritz. Improving Grid Fault Tolerance by Optimal Control of FACTS Devices. International Journal of Innovations in Energy Systems and Power, 2(1):44--49, June 2007

References (cont.)

[3] T. Service, D. Tauritz, W. Siever. Infrastructure Hardening: A Competitive Coevolutionary Methodology Inspired by Neo-Darwinian Arms Races. Proceedings of COMPSAC'07 – the 31st IEEE Computers, Software, and Applications Conference, pages 101-104, Beijing, China, July 23-27, 2007

[4] T. Service, D. Tauritz. Increasing Infrastructure Resilience through Competitive Coevolution. New Mathematics and Natural Computation. In Press.

[5] T. Service, D. Tauritz. Co-Optimization Algorithms. Submitted to GECCO 2008 – the Genetic and Evolutionary Computation Conference.

Q & A

Evaluation Functions

- Hardening Eval:

$$F(H) = C(H) + \sum_{\sigma \in \Omega} E_\sigma \cdot L(H, \sigma)$$

- Fault Scenario Eval:

$$G(\sigma) = \sum_{H \in \Sigma} [E_\sigma \cdot L(H, \sigma) + C(H)]$$