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
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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
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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)
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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

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Ave. Demand Served (%)</th>
<th>Ave. Num. of UPFCs</th>
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</thead>
<tbody>
<tr>
<td>CoEA</td>
<td>93.67%</td>
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<tr>
<td>CoSA</td>
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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


References (cont.)


Q & A

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Evaluation Functions

- Hardening Eval:

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

- Fault Scenario Eval:

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