Coupled Cascading Failure in Energy CPS: Modeling, Prevention, and Restoration

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Motivation | Cascading failures in the electrical energy cyber-physical system (CPS) have caused a significant amount of customer-hours of lost electricity service that is comparable to major natural disasters. Modeling, prevention, and recovery is the focus.

Objectives | The goal is modeling, prevention, and restoration of coupled cascading failures in power and communication systems.

Key challenges

Modeling cascading failure
- Striking a balance between accuracy vs complexity - Hybrid modeling
- Unifying independent CPS models of SCADA and WAMPAC

Prevention of cascading failure
- Mitigating cascade by generation rescheduling considering stability limits and uncertainty in controllability and observability
- Integrating the proposed preventive controls with CPS model

Restoration following cascading failure/natural disaster
- Lack of information from sensors
- Uncertainty about failure location

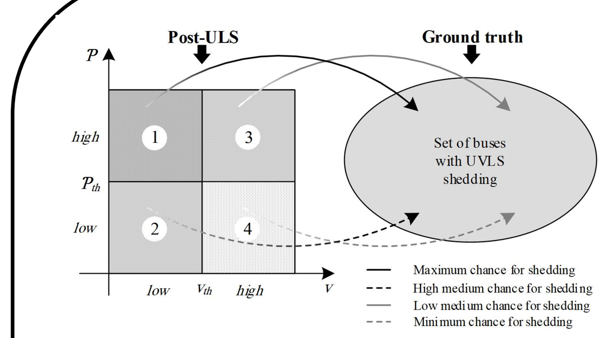
Modeling of cascading failure

- Inclusion of pre-existing UVLS scheme in AC-QSS cascading failure model to mimic the ground truth
- Proposed AC-QSS cascade failure model verified against a suitable dynamic model

Proposed AC-QSS model
- Pre-existing UVLS action
- UFLS action
- Governor action
- Multi-slack bus

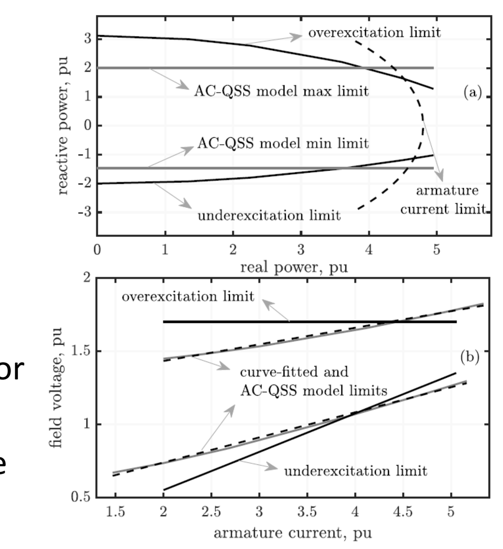
Proposed Dynamic model
- Suitable for AC-QSS verifications
- Q-limits of generators
- Appropriate protective actions
- Revealing the proximate ground truth

Proposed AC-QSS and Dynamic models

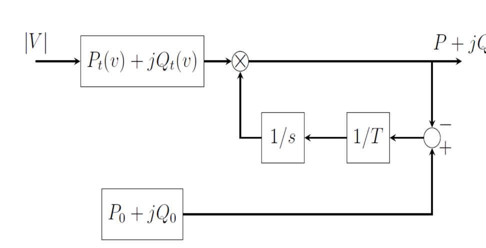


Identification of candidate buses for load shedding in the AC-QSS model

- V/Q sensitivity + Voltage magnitude



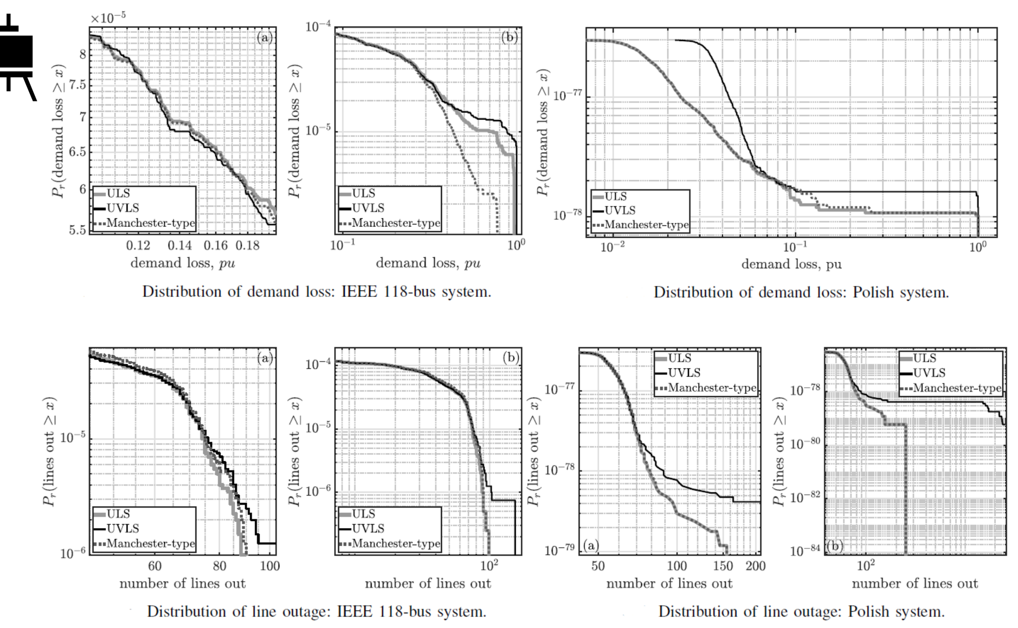
Proposed approach to enforce Q-limit of machines in the Dynamic model



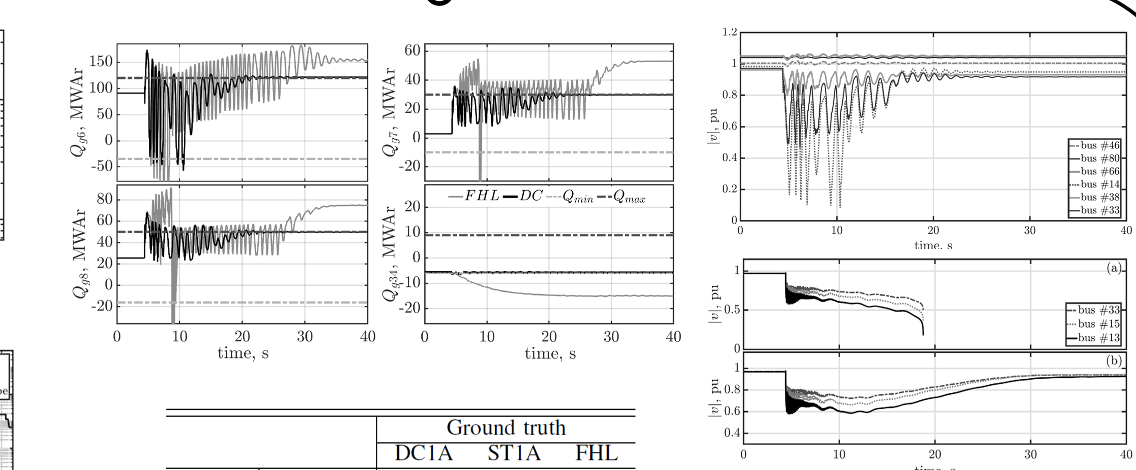
ZIPE load model in Dynamic model

Restorative load model as constant power load

Results of modeling



Different cascade propagation paths in the proposed model and benchmarks (Cascade model based on Uniform Load Shedding, ULS, and Manchester model)



		Ground truth		
		DC1A	ST1A	FHL
case 1	miss	3	3	53
	fauls trip	0	0	0
case 2	miss	0	0	0
	fauls trip	3	3	9
case 3	miss	2	1	14
	fauls trip	0	0	0

	mean	min	max
miss, %	7.368262	0	25
false trippings, %	2.930844	0	18.18182

Verification of UVLS model based on proposed dynamic model

Prevention of cascading failure

Proposed model: Maximizing the total controllability/reliability after failure by selecting up to B non-PLCC links with a baseline where all the communication links are PLCC. (NP-hard problem)

$$max \sum_{i \epsilon N} \gamma_i \left[1 - \prod_{m \epsilon P_i} \left(1 - \prod_{l \epsilon m} (R_l \rho_1 + (1 - R_l)\rho_0)\right)\right]$$
$$s.t. \sum_{l \epsilon L} R_l \ll B$$
$$R_l \ \epsilon \ \{0,1\}, \forall \ l \epsilon L$$

R_l indicates whether link l is a non-PLCC link and ρ_1/ρ_0 is the reliability of non- PLCC/PLCC link, node weight which e.g. "power injection ×BC"

Algorithms:

A. Generic heuristic: It provide suboptimal solutions and works by modifying a population of possible solutions repeatedly such that the population evolves toward an optimal solution.

B. Domain-specific heuristic: Finding optimal location of non-PLCC links with a budget constraint in non-ideal DC-QSS model

We know: i) The budget, ii) Location of access node (AN), & iii) Subgraphs in the network

1. In i –th subgraphs (SG) – If $G_i > L_i$, choose all generator nodes in this SG as candidate control nodes (CCN). If $G_i < L_i$, choose all generator nodes in this SG as CCN. If $G_i = L_i$, choose all load nodes in this SG as CCN.
2. Solve the following unconstrained optimization problem
   - a) We preprocess the network topology graph by contracting all ANs, after which there is only one virtual AN.
   - b) The resulting problem of connecting this virtual AN to all nodes of interest (candidate generators/loads with degree > 1 from step a) is a Steiner tree problem on graphs, which is NP-hard but has approximation algorithms.

   Input: Access node locations. **Output:** Candidate links and nodes for non-PLCC.

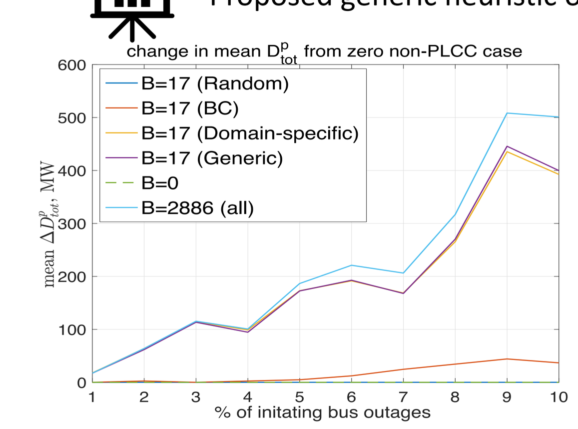
   Define: $w_i = P_i K_i$ and $v_i = \min(L_i, G_i)/K_i$.
3. a) Assume $u_i = \alpha w_i + (1-\alpha) v_i$, $\alpha = (0,1]$. Sort SGs from high to low value of u_i. Check if the SG contains an AN. If not, then connect (i.e. make the links non-PLCC) one Gateway node (GN) (from the candidate nodes obtained from 2) in the SG to one GN in a SG containing AN using candidate links. There could be multiple options to do so, choose the one that uses minimum number of links.

   b) Spend rest of budget to enable non-PLCC links
   - i. **Area with ANs:** Order them from highest to lowest u_i. At the end of 3)a, we obtain a set of gateway nodes in areas that are connected to other areas without ANs. We calculate betweenness centrality (BC) of ALL nodes in such areas w.r.t. the GNs and the AN. Enable candidate links with connection to the node with highest BC.
   - i. **Area without ANs:** Same as 3)b)i, but We calculate BC w.r.t. the GNs and candidate G_i/L_i nodes.
   - ii. Keep repeating 3)b)i and 3)b)ii with progressively lesser BCs until budget runs out.

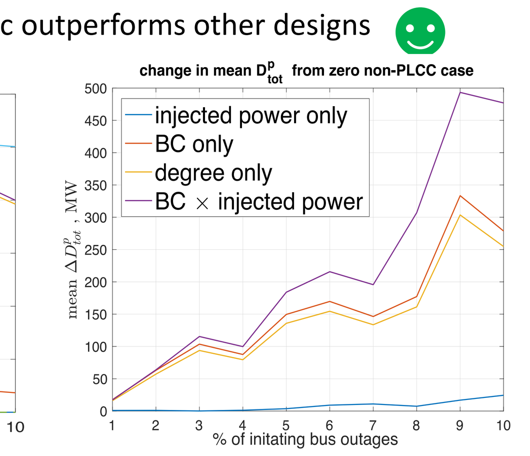
BC benchmark: allocating non-PLCC links by ranking the nodes in descending order of their BC and selecting all the links incident to each node as non-PLCC links until the budget runs out

Test results: on 2383-bus Polish system. DC-QSS model with trip delay considered

Proposed generic heuristic outperforms other designs



Comparison of all methods



Comparison of Generic method under different weight definition

Restoration following cascading failure

Proposed modeling: find the smallest failed link set compatible with available measurements (NP-hard problem)

$$\min_{y_H, \Delta_H} \|y_H\|_0 \quad \text{(Number of failed edges are relatively small)}$$
$$\text{s.t. } B_{H|G}(\theta - \theta') - \Delta_H = D_H y_H \quad \text{(Topology and power flow constraints)}$$
$$\Delta_i \geq 0, i \in \{i \mid V_i \in V, P_i > 0\}$$
$$\Delta_i \leq 0, i \in \{i \mid V_i \in V, P_i < 0\}$$
$$\Delta_i = 0, i \in \{i \mid V_i \in V, P_i = 0\} \quad \text{(Constraints on load shedding)}$$

Algorithms:

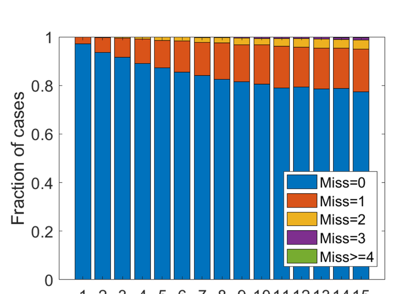
A. **Phase angle recovery:** solving a linear system

B. **Post-attack topology estimation:** LP-relaxation of the proposed NP-hard problem followed by rounding fractional numbers to integers

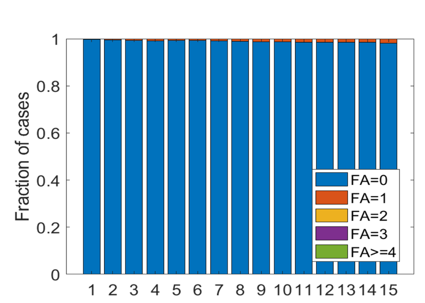
Experimental results on Polish grid:

A. **Performance**: Almost no false alarm; no miss detection in most cases; 1-2 out of 15 links if there exists miss detection

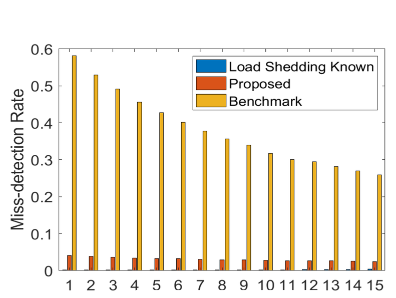
B. **Compared to benchmarks:** 1) much better than the state-of-the-art; 2) performance close to the upper-bound where load shedding is known.



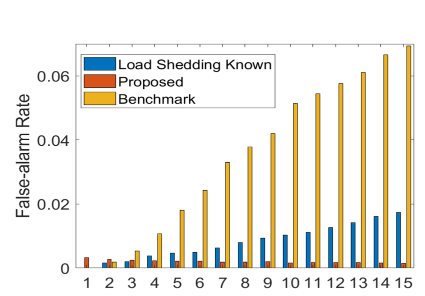
Performance – miss detection



Performance – false alarm



Compare with benchmark – miss detection



Compare with benchmark – false alarm

Theoretical guarantees:

A. **Phase angle recovery:** correctness guaranteed if submatrix of admittance $B_{\bar{H}|H}$ has full column rank.

B. **Post-attack topology estimation:**
1) the status of a link must be correctly identified if certain conditions on power flow of other links sharing the same end-node are satisfied;
2) verifiable conditions to check the correctness of detection algorithm on each link.

Scientific and broader impacts

Theories developed for fundamental understanding of cascading failures in energy CPS can be applied to other CPSs, which are coupled cyber-physical systems having a dynamic physical system.

Proposed preventive control strategy can protect critical infrastructures from large-scale outages.

Proposed recovery strategy is applicable in the aftermath of a blackout caused by cascades, a natural disaster, or other event, which will reduce downtime of the critical infrastructure.

Publications

1- S. Gharebaghi, S. G. Vennelaganti, N. R. Chaudhuri, T. He and T. L. Porta, "Inclusion of Pre-Existing Undervoltage Load Shedding Schemes in AC-QSS Cascading Failure Models," Early Access in *IEEE Transactions on Power Systems*.

2- S. Gharebaghi, S. G. Vennelaganti, N. R. Chaudhuri, T. He and T. L. Porta, "Solving the Divergence Problem in AC-QSS Cascading Failure Model by Introducing the Effect of a Realistic UVLS Scheme," 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 2020, pp. 710-714.

3- S. Gharebaghi, S. G. Vennelaganti, N. R. Chaudhuri, T. He and T. L. Porta, "A More Realistic AC-QSS Cascading Failure Model with Decentralized UVLS and Centralized RAS," 2021 IEEE Power & Energy Society General Meeting (PESGM), Accepted for publication.

4- F. Vajiheh, S. G. Vennelaganti, N. R. Chaudhuri, T. He, and T. La Porta, "Budget-Constrained Reinforcement of SCADA for Cascade Mitigation", ICCCN 2021.

5- Y. Huang, T. He, N. R. Chaudhuri, and T. L. Porta, "Power grid state estimation under general cyber-physical attacks," in IEEE SmartGridComm, 2020. **(Best paper runner-up)**

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