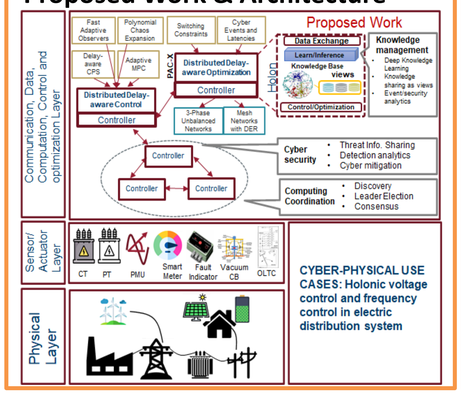
Award #1932574 - CPS:DFG Joint: Medium: Collaborative Research: Data-Driven Secure Holonic control and Optimization for the Networked CPS (aDaptioN)

A. Srivastava, J.Adan, N. Patari, West Virginia University, anurag.srivastava@mail.wvu.edu,
A. Annaswamy , R. Haider, Massachusetts Institute of Technology,
Y. Wu, Case Western Reserve University,
A. Monti, T. Heins, M. Josevski, S. K. Gurumurthy, RWTH Aachen University.

https://sum-em.github.io/NSF-CPS-WebRepo/

The objective of this project is to develop and validate holonic control and optimization algorithms for the critical cyber-physical networked infrastructures considering flexibility, scalability, tolerant to cyber events, data management and computing for a specific cyber-physical system: the distribution electric power grid specifically for its voltage and frequency control.

Proposed Work & Architecture



Distributed Delay – aware Control Architecture

Networked CPS model with latencies and disturbances

$$x_{k+1} = Ax_k + B_1(d)u_k + B_2(d)u_{k-1} + v$$

Proposed Estimated Polynomial Chaos Expansion

$$\hat{x}_{k+1} = A_k(\hat{\theta}_k)\hat{x}_k + B_k(\hat{\theta}_k)u_k + E_k(\hat{\theta}_k)\omega_k$$

$$J(x_o, u) = E_{pdf_\theta(\Delta\theta)}\left\{ l_N(x_{k+N|k}; \Delta\theta) + \sum_{j=0}^{N-1} l_N(x_{k+j|k}, u_{k+j|k}; \Delta\theta) \right\}$$

Adaptive Model Predictive Control

$$\begin{aligned} &minimize_u\ J(x_k, u) \\ &subject\ to\text{:}\ \hat{x}_{k+j,i} = a_{k+j,i}^T A(\Delta\theta)\,, \\ &\quad h(\hat{x}_{k+j,i}^{nom}, u_{k+j}, \Delta\theta) \le 0 \\ &\quad P_i(K_{1-\beta_i} Var[\hat{x}_{k+j,i}] + E[\hat{x}_{k+j,i}]) - q_i \le 0 \\ &\quad u_{k+j} \in U \\ &\quad x_k = x(k) \end{aligned}$$

Contributions: Adaptive MPC

- ❑ Computationally efficient methods to determine $\mathbf{a_k}$
- ❑ Extend to nonlinear dynamic systems while minimizing approximation error in chance constraints

Distributed Optimization and Control Algorithm for Frequency Control

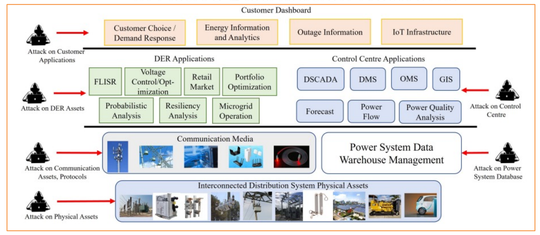
Partioned Frequency Prediction Model

$$x_i(k+1) = A_{ii}x_i(k) + B_{ii}u_i(k) + E_{ii}d_i(k) + \sum_{j\in\mathcal{N}_i} A_{ij}x_j(k) + B_{ij}u_j(k) + E_{ij}d_j(k)$$

Contributions: Distributed MPC

- ❑ Scalable solution achieves global frequency control while requiring only neighboring information
- ❑ Extension of Frequency Divider Theory by Trimming

Cyber-Physical Needs for DER based Voltage Control/ Optimization in Active Distribution Networks



- ❑ Common cyberthreats include network reconnaissance, spoofing, Denial of Service, Eavesdropping, Packet Replay, Man in the Middle Attack (MiTM), Modified Firmware upload, Log Manipulation.

Distributed Optimization Algorithm for Volt-Var Control

Proximal Atomic Co-ordination

$$min_{y\in\mathbb{R}^Y}\left\{ f(y) \triangleq \sum_{k\in|\mathcal{B}|} f_k(y) \right\} \quad subject\ to: Gy = 0_M$$

Global centralized voltage optimization problem

Atomized Standard Optimization (atomic equivalent of GSO)

$$min_{a\in\mathbb{R}^{|a|}} \sum_{j\in\mathcal{B}} \tilde{F}_j(a_j) \quad subject\ to:\ \tilde{G}_j a_j = 0,\ j\in\mathcal{B};\quad A_{j,-}a = 0,\ j\in\mathcal{B}$$

$$\begin{aligned} a_j[\tau+1] &= argmin_{a_j}\{\tilde{\mathcal{L}}_{\rho,\gamma}(a_j, \tilde{\mu}_j[\tau], \tilde{v}[\tau]; a_j[\tau])\} \\ \mu_j[\tau+1] &= \mu_j[\tau] + \rho\gamma\tilde{G}_j a_j[\tau+1] \\ \tilde{\mu}_j[\tau+1] &= \mu_j[\tau] + \rho\gamma\tilde{G}_j a_j[\tau+1] \end{aligned}$$

Communicate $\{a_j\}_{j\in\mathcal{B}}$ with neighbors

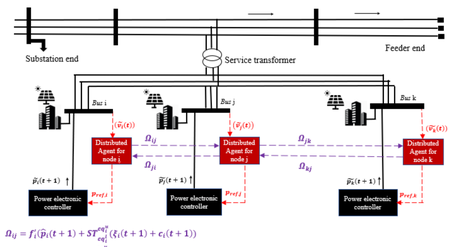
$$\begin{aligned} v_j[\tau+1] &= v_j[\tau] + \rho\gamma A_{j,-}a[\tau+1] \\ \tilde{v}_j[\tau+1] &= v_j[\tau] + \rho\gamma A_{j,-}a[\tau+1] \end{aligned}$$

Communicate $\{\tilde{v}_j\}_{j\in\mathcal{B}}$ with neighbors

Contributions (PAC-X)

- ❑ Develop PAC-X to address switching constraints
- ❑ Expand the problem to include multi-phase unbalanced distribution systems
- ❑ Include communication latencies that may occur in cyber events
- ❑ Expand the problem for meshed networks

Cyber Anomaly Aware Distributed Voltage Control with Active Power Curtailment and DERs



$$\Omega_{ij} = f_i'(\tilde{p}_i(t+1) + ST_{c\tilde{p}_i}^{\epsilon\eta_i^2}(\xi_i(t+1) + c_i(t+1))$$

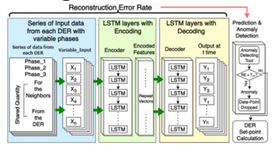
$$\Omega_{ji} = f_j'(\tilde{p}_j(t+1) + ST_{c\tilde{p}_j}^{\epsilon\eta_j^2}(\xi_j(t+1) + c_j(t+1))$$

$$\begin{aligned} &\tilde{p}_i(t+1) \\ &= \tilde{p}_i(t) - \alpha\left\{ (\bar{\lambda}_i - \underline{\lambda}_i) + \sum_{j\in\mathcal{N}} [\bar{Z}^P]^{-1}\left[f_i'(p_i) + ST_{c\tilde{p}_i}^{c\tilde{p}_i}(\xi_i + c\tilde{p}_i) \right] \right\} \end{aligned}$$

$$\xi_i(t+1) = \xi_i(t) + \beta ST_{c\tilde{p}_i}^{c\tilde{p}_i}(\xi_i + c\tilde{p}_i) - \frac{\xi_i(t)}{c}$$

$$\begin{aligned} \bar{\lambda}_i(t+1) &= \bar{\lambda}_i(t) + \gamma[(v^{meas}(t) - \overline{v}_i]^+ \\ \underline{\lambda}_i(t+1) &= \underline{\lambda}_i(t) + \gamma[(v^{meas}(t) - \underline{v}_i]^+ \end{aligned}$$

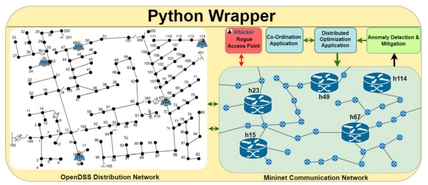
Multivariate LSTM for Anomaly Detection and Mitigation



Contributions:

- ❑ Distributed primal dual algorithm for unbalanced multiphase systems .
- ❑ LSTM is used to detect MitM, DoS and replay attacks.

Cyber-Power Testbed for Validation



Contributions:

- ❑ Each node as independent host through Mininet.
- ❑ Each host communicates and python wrapper acts as interface.

Resulting Publications (Partial List)

- ❑ A. Vosughi, A. Tamimi, A. King, S. Majumdar, A. Srivastava "Cyber--physical vulnerability and resiliency analysis for DER integration: A review, challenges and research needs", in *Renewable and Sustainable Energy Reviews*, 2022.
- ❑ P. S. Sarker, M. F. Rafy, A. K. Srivastava and R. K. Singh, "Cyber Anomaly-Aware Distributed Voltage Control With Active Power Curtailment and DERs," in *IEEE Transactions on Industry Applications*, vol. 60, no. 1, pp. 1622-1633, Jan.-Feb. 2024
- ❑ S. Majumder and A. K. Srivastava, " Resilience-Driven Integration of Distributed Energy Resource (DER): Coordinating DER Services for Value," *IEEE SG eBulletin*, 2022
- ❑ M. Menazzi, C. Qin and A. K. Srivastava, "Enabling Resiliency Through Outage Management and Data-Driven Real-Time Aggregated DERs," in *IEEE Transactions on Industry Applications*, vol. 59, no. 5, pp. 5728-5738, Sept.-Oct. 2023
- ❑ S. Majumder, A. Vosughi, H. M. Mustafa, T. E. Warner and A. K. Srivastava, "On the Cyber-Physical Needs of DER-Based Voltage Control/Optimization Algorithms in Active Distribution Network," in *IEEE Access*, vol. 11, pp. 64397-64429, 2023.
- ❑ S. Konar, A. K. Srivastava and A. Dubey, "Distributed Optimization for Autonomous Restoration in DER-Rich Distribution System," in *IEEE Transactions on Power Delivery*, vol. 38, no. 5, pp. 3205-3217, Oct. 2023.

Broader Impact (Societal Impact and Outreach)

- ❑ Improve robustness and resiliency of key national infrastructures: electric distribution grid and can be extended to multiple CPSs.
- ❑ Testbed will be made available open source on CPS-VO
- ❑ Plan to organize a workshop in the third year to demonstrate the science and technology of holonic control and CPS optimization

Broader Impact (Students and Training)

- ❑ Number of graduate students working on this project: 4
- ❑ 2 UGs as REU, 2 Female Students, presented to number of conferences
- ❑ Tutorial sessions on distributed optimization were provided on Distributed Optimization at the IEEE **ISGT 2022 and PESGM 2022**
- ❑ Journals: 6, Monograph: 1, Bulletin: 1, Conference: 9 (2023)

2022 NSF Cyber-Physical Systems Principal Investigators' Meeting
November 8-9, 2022

Award ID#: 1932574