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

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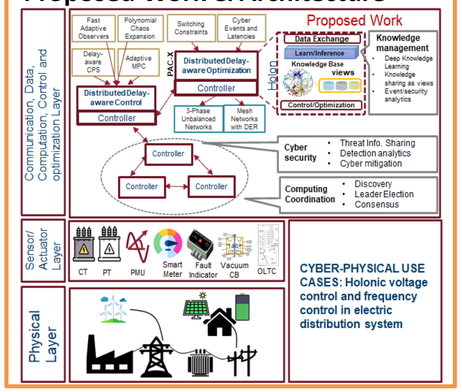
https://sum-em.github.io/NSF-CPS-WebRepo/

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

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

Adaptive Model Predictive Control

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

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

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

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

Contributions: Distributed MPC

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

Distributed Approaches with Discrete Control Variables

- Convexification is necessary.
- Combinatorial algorithms need coordinator → not resilient
- Convergence is not always guaranteed.

App.	Problem Specification	Discrete Algorithm	Distributed Algorithm	Comm. Requirement	Comments
A	MINLP	Quadratic penalty term for non Integer values	ADMM	Neighbor Agents	– May diverge due to nonconvexity.
B	MIQP	Quadratic penalty for non integer values for Increments	ADMM	Neighbor Agents	- Convergence guarantee with ADMM. Better privacy due to only sharing the incremental values.
C	MISOCP & Cutting Planes	Branch and Bound	ADMM	Neighbor agents & Root system	- Optimality and convergence guaranteed. Capacitor bank position not considered.
D	MIQP	Ordinal Optimization	Dual Decom-position	Neighbor agents & Root system	- Root Subsystem needed. Sub-optimal but good enough solution. No convergence guaranteed.
E	MICP with Linearized constraint	Proximal Operator With Projection	ADMM	Neighbor Agents	-Inner Binary Variables are determined by MICP solver – Convergence relies on ADMM Parameter
F	MISOCP	Relaxed and Projected	ADMM	Neighbor agents	– Direct projection may fluctuate convergence – convergence is not guaranteed

Distributed Optimization Algorithm for Volt-Var Control

Proximal Atomic Co-ordination

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

Global centralized voltage optimization problem

Atomized Standard Optimization (atomic equivalent of GSO)

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

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

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

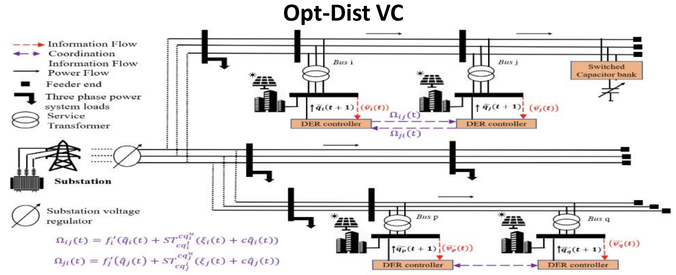
$$\begin{aligned} v_j[\tau+1] &= v_j[\tau] + \rho\gamma A_{j,-}a[\tau+1] \\ \bar{v}_j[\tau+1] &= v_j[\tau] + \rho\gamma A_{j,-}a[\tau+1] \end{aligned}$$

Communicate $\{\bar{v}_j\}_{j\in\mathcal{B}}$ 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

Opt-Dist VC



Contributions:

- ❑ Distributed primal dual algorithm for unbalanced multiphase systems .
- ❑ Mechanism for dead band control to avoid frequent switching of DERs

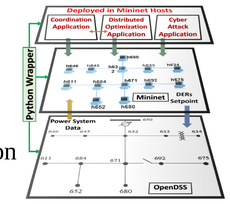
Updating 3phase variables

$$\begin{aligned} \hat{q}_k(t+1) &= \hat{q}_k(t) - \alpha\Big\{\bar{\lambda}_k(t) - \underline{\lambda}_k(t) + d\hat{q}_k(t) \\ &\quad + \sum [Z^Q]_{kj}^{-1}\left[f_j'(\hat{q}_j(t)) + \mathrm{ST}_{cq_j}^{c\hat{q}_j}(\xi_j(t) + c\hat{q}_j(t)) \right] \Big\} \\ \xi_k(t+1) &= \xi_k(t) + \beta\frac{\mathrm{ST}_{cq_k}^{c\hat{q}_k}(\xi_k(t) + c\hat{q}_k(t)) - \xi_k}{c} \\ \bar{\lambda}_k(t+1) &= [\bar{\lambda}_k(t) + \gamma(v_k(t) - \bar{v}_k)]^+ \\ \underline{\lambda}_k(t+1) &= [\underline{\lambda}_k(t) + \gamma(\underline{v}_k - v_k(t))]^+ \end{aligned}$$

Validation Plan

Validation with Prototype

- ❑ Validated the algorithm via developed distributed testbed using OpenDSS/mininet.
- ❑ The testbed facilitates performance evaluation against realistic communication challenges.



Broader Impact (Potential Impact)

- ❑ Number of graduate students working on this project: 4 so far
- ❑ Number of downloads from Github: N/A
- ❑ Number of outreach activities for underrepresented in broadening participation: 2 UGs as REU, 3 Female Students so far

Research Pulications

- ❑ J.Adan, S.Majumder, A.Srivastava "Distributed Optimization Approaches with Discrete Variables in the Power Distribution Systems" (presented in NAPS'22)
- ❑ doi: 10.1109/MSCPES55116.2022.9770160.
- ❑ doi: 10.1016/j.epsr.2022.108874
- ❑ doi: 10.1109/TIA.2021.3114388
- ❑ P.S. Sarker, S. Majumder, Md F. Rafy, A. Srivastava, "Impact Analysis of Cyber-Events on Distributed Voltage Control with Active Power Curtailment" (accepted in PEDES'22)
- ❑ doi: 10.1016/j.rser.2022.112794
- ❑ doi: 10.1109/TPWRS.2022.3173634
- ❑ doi: 10.1109/TPWRS.2021.3132348

Broader Impact (Impact on Society)

- ❑ 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
- ❑ Journals: 3, Conferences: 3

Broader Impact (Education & Outreach)

- ❑ Tutorial sessions were provided on Distributed Optimization at **ISGT 2022 and PESGM 2022.**
- ❑ We will target programs that focus on students from underrepresented groups: The Hispanic Youth Exploring Engineering (HYEE) camp and Pacific Northwest Louis Stokes Alliance for Minority Participations