Distribution grid monitoring: *Addressing IT Challenges in developing PMU-rich feeders*

Time series Compression & Distributed Optimization

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Introductions

- What keeps me up at night?

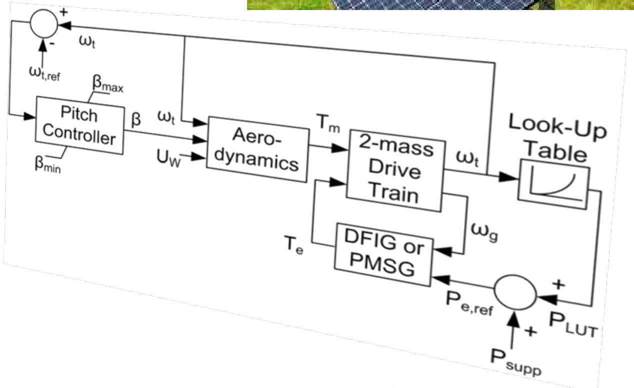
  Wide integration & *seamless* operation of (volatile) renewables in electrical grids

- How do I make what I care about possible?

  Control, system modeling, optimization, heuristic methods (AI & ML), standards

- Who am I working with?

  X, REN, Dept. of Energy, NYISO, Duquesne, Depsys, VT-IoT, Xeal, IEEE, IET, NASPI



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Outline

- *Introduction:* Why are we concerned about Information & Tel/com (IT) bottlenecks at the distribution level?
- *Part 1:*
  Time series compression techniques (Wavelet Synopses)
- *Part 2:*
  Distributed Optimization with Consensus+Innovation
- *Conclusion & Path Forward*

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The value of synchronized, real-time measurement of electrical grid operation

- Devices capturing the time-varying signals of voltage & current
- Named “***Phasor*** MU” because they determine the phase angle of signals
- Simplified description of a PMU: ‘repurposed oscilloscope’
- Standardized equipment (e.g. IEEE Std C37.118.1 - new update coming)

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IT challenges in Distribution Grids

- [1]Advanced Meter Infrastructure (AMI) data more than 100TB in 2012
  - 65M AMI devices in 2015 (<50% of end customers with AMI in 2016)
- uPMU data of measurements of 1 feeder at the GB/day scale[2]
- Not all data points valuable (e.g. most of daily load curve, steady state, etc)
- Smarter, IoT & electronics devices introduce new functionalities/concerns
- Networked systems over large areas with several “control” points
- Privacy concerns closer to the edge of the grid
- Alternative control architectures introducing non-uniform perspectives

1. Yu et al, "Big data analytics in power distribution systems," ISGT 2015, Washington DC
2. von Meier et al, "Precision micro-synchrophasors for distribution systems: A summary of applications," IEEE Trans. on Smart Grid, 8(6), 2017

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Overall Value Proposition for IT Bottlenecks

- Deal with issues & events locally
- Reduce transmitted data sizes
- Consider hierarchical but robust control/sensing architectures
- In the following slides:
  - Reduce time-series sizes
  - Optimize locally

Wavelet Synopsis Techniques

Compressing Time Series Data based on
Error Effects to Critical Information

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What is a Wavelet

- Signal processing
- Fourier transform captures periodic behaviors (sinusoidal wavelet basis)
- For signals with *discontinuous* (non-recurring, non-repetitive, non-periodic) behaviors we need a different wavelet
- System faults, machine start-ups, inter-area trades, renewable generation, small-scale load behavior => *non-continuities*

Proposition: Determine wavelet transformation of time series of power system data to represent the series itself (lossless representation)

Haar Wavelet

- N-sized time series signal *A* ($N=2^{j+1}$) and *j, k*:

$$0 \le j < \log(N)$$
$$0 \le k < 2^j$$

- *N* basis functions φ_i are defined:

$$\phi(x)[0,0] = \sqrt{\frac{1}{N}},\ for: x \in [0, N-1]$$
$$\phi(x)[j,k] = +\sqrt{\frac{2^j}{N}},\ for: x \in [kN/2^j, kN/2^j + N/2^{j+1} - 1]$$
$$\phi(x)[j,k] = -\sqrt{\frac{2^j}{N}},\ for: x \in [kN/2^j + N/2^{j+1}, (k+1)N/2^j - 1]$$
$$\phi(x)[j,k] = 0,\ for: x \notin [kN/2^j, (k+1)N/2^j - 1]$$

- Transformation: $C[i] = \langle A, \varphi_i \rangle$ Reverse Transformation: $A = \sum_{i \in [0, N-1]} C[i] \cdot \varphi_i$

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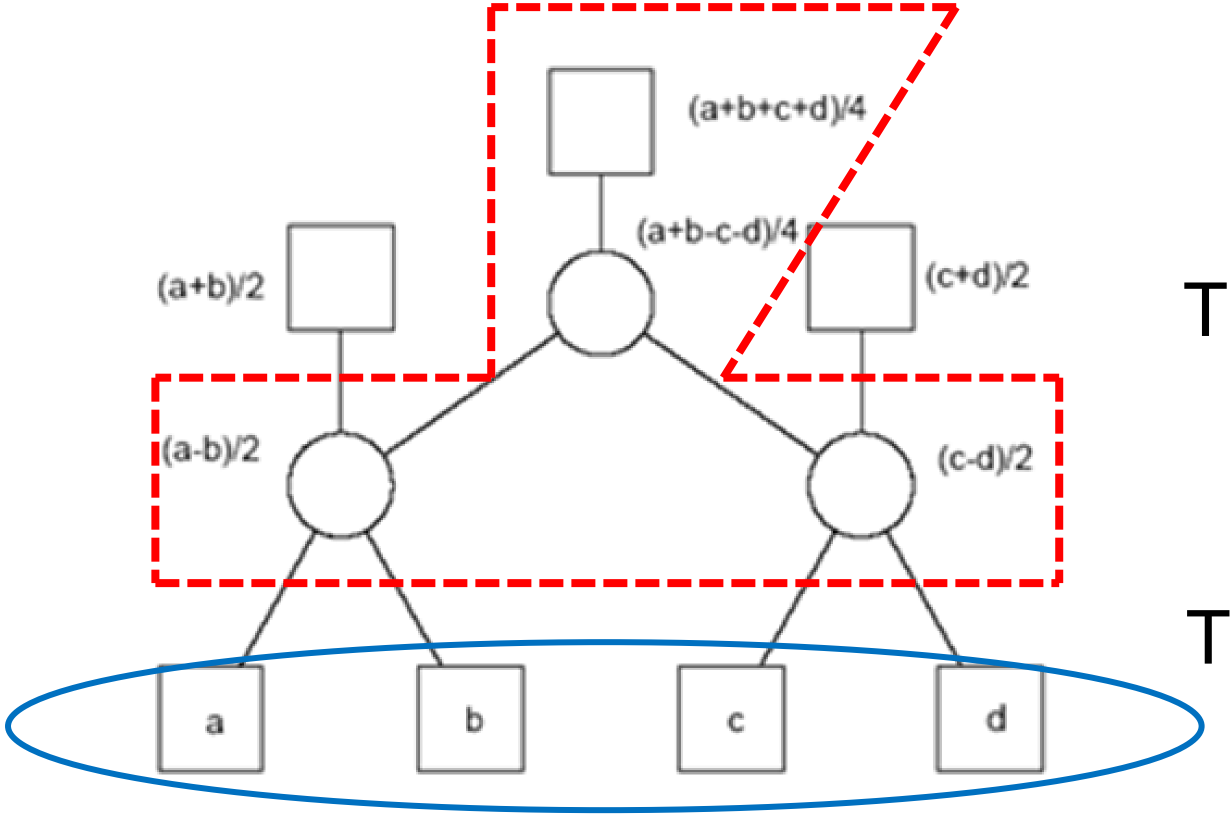
Haar Transformation



time-series signal

Transformation:

$$\frac{a+b}{2}+\frac{a-b}{2}=a$$

$$\frac{a+b}{2}-\frac{a-b}{2}=b$$

Reverse Transformation:

$$\frac{c-d}{2}-\frac{a+b-c-d}{4}+$$

$$+\frac{a+b+c+d}{4}=c$$

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Wavelet Synopsis
(or time series compression via medium)

- Step 1: Transform the power system time-series data via Haar
- Step 2: Synopsize the Haar transformation
  - Step 2.a: Choose a wavelet synopsis method
    {Garofalakis-Kumar, Greedy, Top-k Haar coefficients}
  - Step 2.b: Define the acceptable error of the synopsis

Error Metrics

- **Not one Error Metric fits all Synopses! What is the data use?**
- Synopsis of the initial signal A[0..N-1] is B[0..Λ-1], where B ⊆ A and Λ<<N
- Let A'[0..N-1] be the reconstructed signal out of B[0..Λ-1]
- $error = f_{metric}(A - A') = \| A - A' \|_{fmetric}$
  - Most commonly used error metrics
    - $L_{\infty} = \max_{0 \le i < N} |A[i] - A'[i]|$
    - weighted $L_p = \sum_i w_i (|A[i] - A'[i]|)^p \Rightarrow L_2 = \sum_i (|A[i] - A'[i]|)^2$

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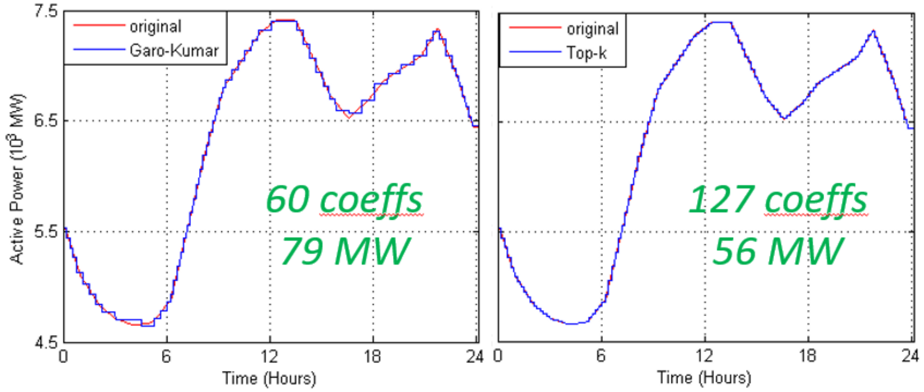
Some Examples of Wavelet Synopses

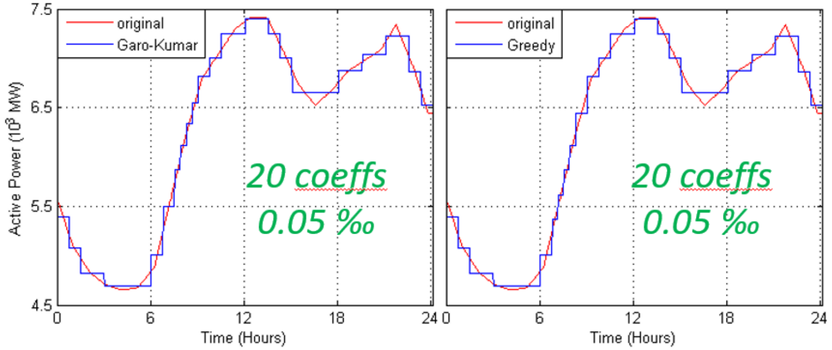
a) Peak of Load Power Demand

L∞ = Primary Reserve = 80 MW, **1024 coeffs**



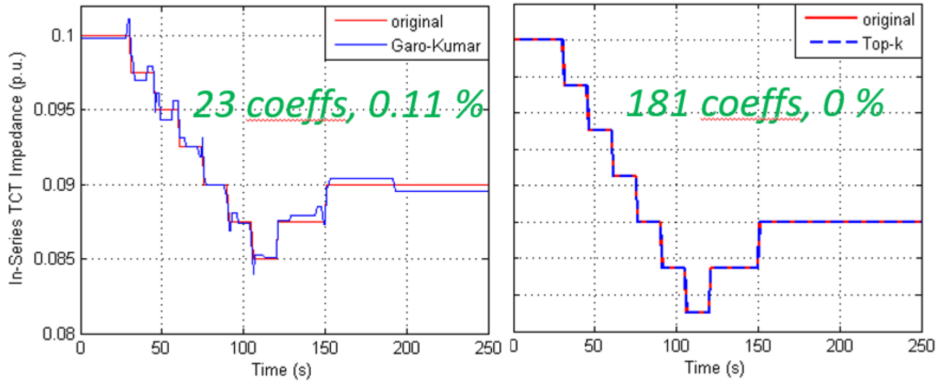
b) Daily Cost of Energy

Weighted_L2 = $\sum_i \frac{SMP_i}{SMP_{\max}} \left(|\delta P_i|\right)^2$, **1024 coeffs**



c) Tap-Changing Transformer Level

L∞ = half of tap-changer step, **256 coeffs**



d) Power Switch Status

L∞ = 0, **1024 coeffs**

Garofalakis-Kumar: *27 coeffs*

Top-k: *469 coeffs*

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Closing Remarks on Wavelet Synopses

- Compression of time series data ranges from 50% to more than 100-fold
- Error Metrics defined separately for each value/use case
- Balance between maximum compression and speed needs to be defined

Publications & Funding

- **Moutis, P.** and Hatziargyriou, N.D., 2011, December. Using wavelet synopsis techniques on electric power system measurements. In 2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (pp. 1-7). IEEE.
- **Moutis, P.,** 2010, November. An introduction to wavelet synopses of electric power system measurements. In 7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2010) (pp. 1-6). IET.

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Distributed Optimization with Consensus+Innovation

Distributed Optimization Premise & Methods

<u>Decomposition to subproblems distributed to agents/processors</u>

- Analytical target cascading: hierarchical with a central entity
- Alternate Direction Multipliers Method (ADMM): decentralized but sequential (not *literally* parallel)
- Proximal Message Passing: properly parallelized ADMM
- Optimality Condition Decomposition: 1st order optimality conditions decomposed and updated with Newton-Raphson
- Auxiliary Problem Principle: duplicate coupling variables and penalize their deviations to convergence
- Consensus+Innovation (C+I): consensus over marginal price and optimality conditions as innovation terms

C+I on DC OPF

- Determine the Lagrangian

$$L = \sum_{i\in g} C\left(P_{g,i}\right) + \sum_{i\in B} \lambda_i \cdot \left[-P_{g,i} + P_{l,i} + \sum_{j\in NBi} \left(g_{ij} - b_{ij}\right) \cdot (\theta_i - \theta_j) \right] + \sum_{i\in g} u_{P,i} \cdot \left(P_{g,i} - P_{g,i,M} + T_{P,i}^2\right) + \sum_{i\in g} l_{P,i} \cdot \left(-P_{g,i} + P_{g,i,m} + K_{P,i}^2\right)$$

$$+ \sum_{i\in B} \sum_{j\in NB_i} u_{ln,1,ij} \cdot \left(-b_{ij} \cdot \left(\theta_i - \theta_j\right) - S_{ij,M} + T_{ln,1,ij}^2\right) + \sum_{i\in B} \sum_{j\in NB_i} l_{ln,1,ij} \cdot \left(b_{ij} \left(\theta_i - \theta_j\right) - S_{ij,M} + K_{ln,1,ij}^2\right) +$$

$$+ \sum_{i\in B} \sum_{j\in NB_i} u_{ln,2,ij} \cdot \left(-b_{ij} \cdot \left(\theta_i - \theta_j\right) - S_{ij,M} + T_{ln,2,ij}^2\right) + \sum_{i\in B} \sum_{j\in NB_i} l_{ln,2,ij} \cdot \left(b_{ij} \cdot \left(\theta_i - \theta_j\right) - S_{ij,M} + K_{ln,2,ij}^2\right)$$

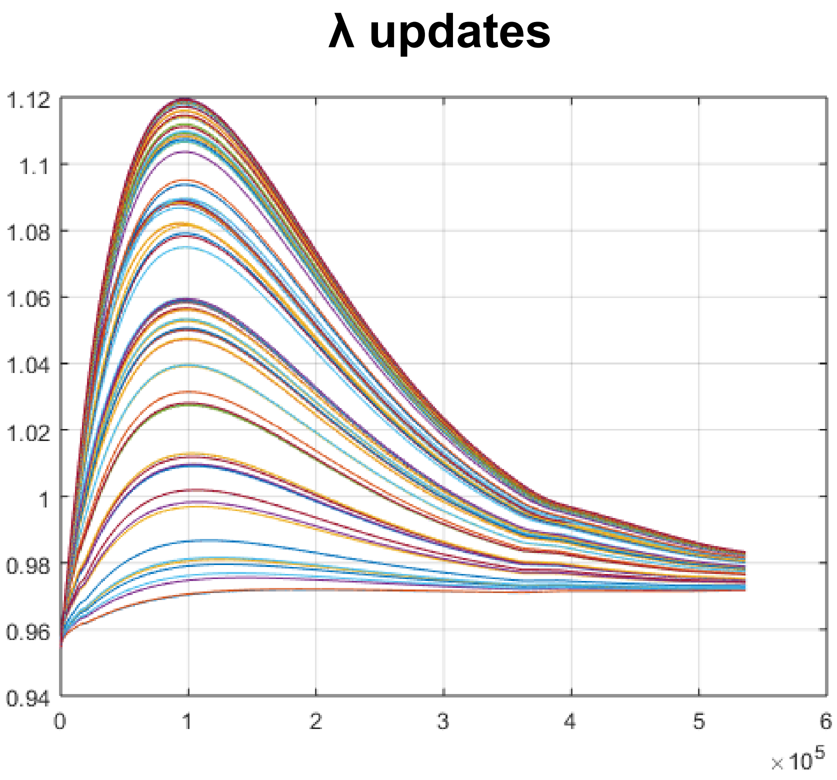
- Every summation term concerns one bus and angle info from its neighbor
- Optimal setting of variable x as $x^{(k+1)} = x^{(k)} + \text{term}(x) + \frac{dL}{dx}$

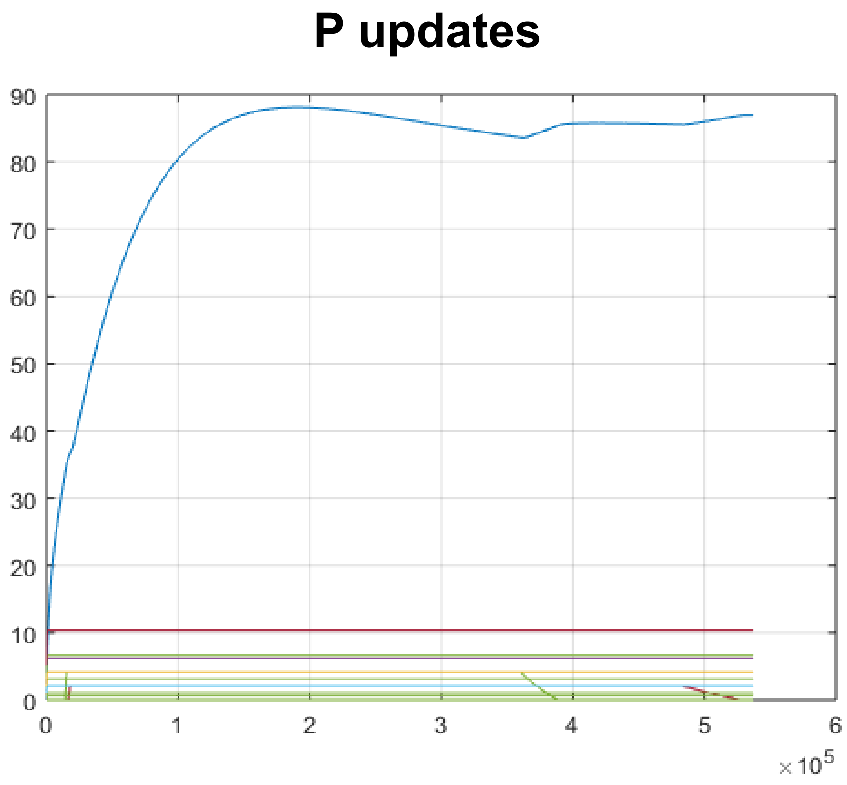
C+I on DC proven to converge to optimality

- Phase I: Proof that the C+I convergence (stationary) point is the optimal solution to the DC OPF centralized set-up[1]
- Phase II: Proof that C+I reaches a stationary point – almost[1], (proved recently and submitting it soon)

1. Mohammadi et al "Agent-based distributed security constrained optimal power flow." IEEE Trans. on Smart Grid, 9(2), 2016.

C+I on DC OPF example on IEEE-55 bus with typical DERs & others





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Closing Remarks on Distributed Optimization

- Proven and fast methods to optimize in decentralized manners
- Strong value propositions
- Assessment of practical IT effects an interdisciplinary problem

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Conclusions & Path Forward

Conclusions & Path Forward

- IT bottlenecks affect power systems ops and especially distribution
- Data sizes, use cases and needs growing fast and wide
- Pragmatic IT concerns might be even more critical than what was presented today – Cross-disciplinary projects are necessary
- The cross-disciplinarity requires contributions from mostly 2 fields:
    - Databases
    - Hardware in the Loop with Communication

Thanks for your attention!

Questions, please?

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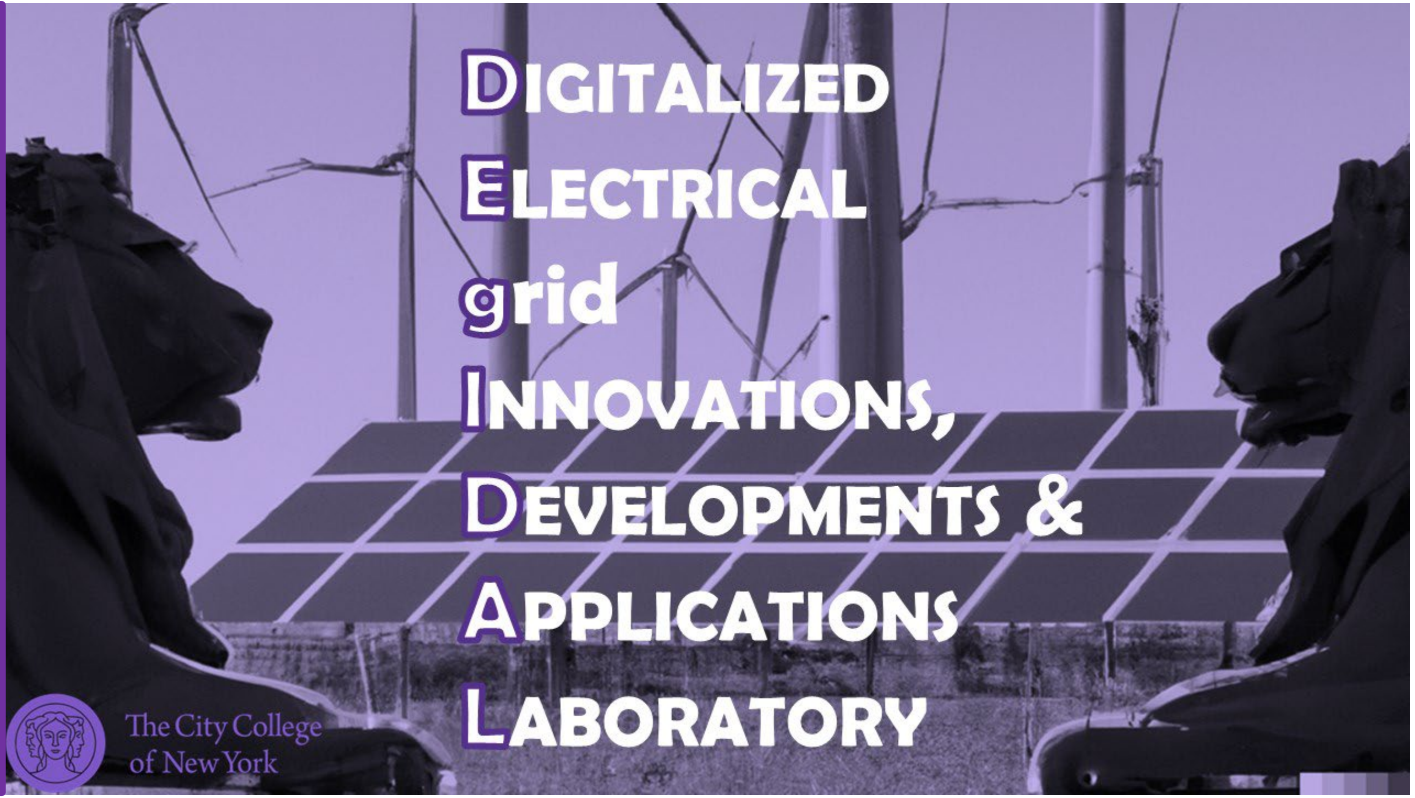

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