Carnegie Mellon

Modeling Future Cyber-Physical Energy Systems

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ABSTRACT

- Modeling future cyber-physical energy systems
- Systems are represented as modules connected by an electric transmission network
- Modules that cannot be modeled from first principles are represented using a cyber model
- Cyber models are formulated using statistical system identification techniques
- Resulting cyber-physical infrastructure of interconnected system preserves the original structure of the energy system
- Provides an enhanced description of system stability

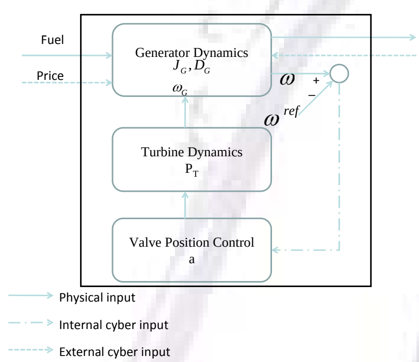
Motivation

US Electric Power Network

- Structure preserving models for the electric power systems
- Detailed description of the load dynamics
- Dynamic load aggregation over broad ranges of system conditions
- Explicit Interactions between the load modules and the network
- Enhanced framework to analyze system instabilities

Generator Module

Power Plant Cyber- Physical Dynamics



Load Forecasting using Cyber Models

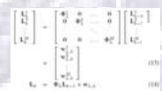
- Load is modeled using a time-varying load predictor

$$L_k = \Phi_L L_{k-1} + w_L$$

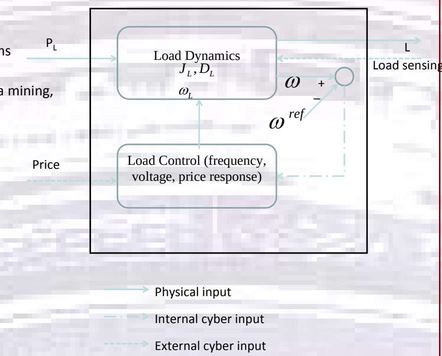
- The variable Φ_L is computed using data mining algorithms
- The variable w_L is random noise
- Using, e.g., autoregressive (AR) process of order p for data mining, the load at the ith zone is given by

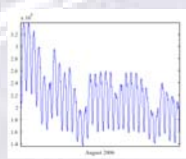
$$L_k^i = \sum_{j=1}^{p} \phi_j^i L_{k-j}^i + w_{L,k}^i$$

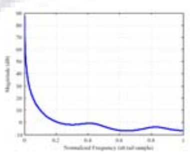
- The load at all the zones can be represented by

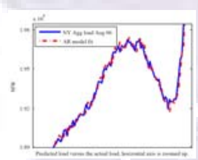


Load Module Cyber-Physical Dynamics





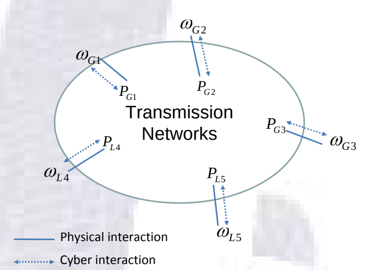




Prediction results on the aggregated load from NY-ISO collected at 5-min interval in the month of Aug 2006, [7]

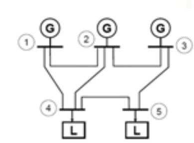
Overall Cyber-Physical Model

- Generators are modeled using physical descriptions
- Loads are modeled using cyber descriptions
- Overall network is modeled with intertwined cyber-physical description
- The resulting dynamics are structure preserving

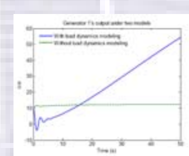


Cyber-physical interactions of future energy systems

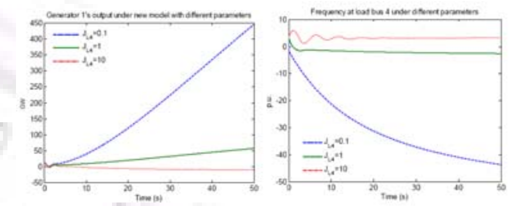
(Example Part I) Enhanced Stability Analysis



5 bus power system



(Example Part 2) The Impact of Load Model Parameters on System Dynamics



Future Work

- Application of the cyber-physical model to distributed control
- Application of the cyber-physical model to distributed estimation, [10]
- Analytical stability analysis for distributed energy integration
- Designing information structure for guaranteed performance
  - under broad range of operating conditions

References

[1] M. D. Ilić, Jason W. Black, Marija Prica. ”Distributed Electric Power Systems of the Future: Institutional and Technological Drivers for Near- Optimal Performance” Electric Power Systems Research, Elsevier. Available online Nov 2006 at www.sciencedirect.com.

[2] M. D. Ilić, ”Providing Energy Services of the Future by Means of Dynamic Energy Control Protocols (DECPs)”, Proceedings of the IEEE SMC, 2007, Montreal, CA.

[3] Elizondo, Marcelo, M. D. Ilić, and Pedro Marcado. ”Determining the Cost of Dynamic Control Capacity for Improving System Efficiency.” Proceedings of the IEEE General Power Meeting, Montreal CA, June 2006, paper # PESGM2006-000839.

[4] M. D. Ilić, “Model-based Protocols for the Changing Electric Power Industry”, Proceedings of the Power Systems Computation Conference, June 24-28, 2002, Seville, Spain.

[5] M. D. Ilić (Ed), ”Engineering Electricity Services of the Future”, Springer, 2008 (to appear).

[6] M.D. Ilić and J. Zaborszky, Dynamics and Control of Large Electric Power Systems, New York: Wiley Interscience, 2000.

[7] Available online at http://www.nyiso.com/public/market data/load data.jsp.

[8] J. Cardell, M. D. Ilić and R. Tabors, “Integrating Small Scale Distributed Generation into a Deregulated Market: Control Strategies and Price Feedback,”MIT Energy Laboratory Technical Report MIT-EL-98-001, 1998.

[9] L. Ljung, System Identification: Theory for the User, Prentice Hall, Upper Saddle River, NJ, 1999.

[10] U. A. Khan and J. M. F. Moura, “Distributing the Kalman Filters for Large-Scale Systems”, submitted to IEEE Transactions on Signal Processing, 30 pages, Initial submission: Aug. 1, 2007, Revised: Feb. 22, 2007, http://arxiv.org/PS_cache/arxiv/pdf/0708/0708.0242v2.pdf

[11] J. W. Taylor, “Short-term electricity demand forecasting using double seasonal exponential smoothing,” Journal of Operation Research Society,vol. 54, pp. 799–805, 2003.

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