Architecture for Future Distribution Systems Including Active Consumers with Rooftop Solar Generation

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Project Team

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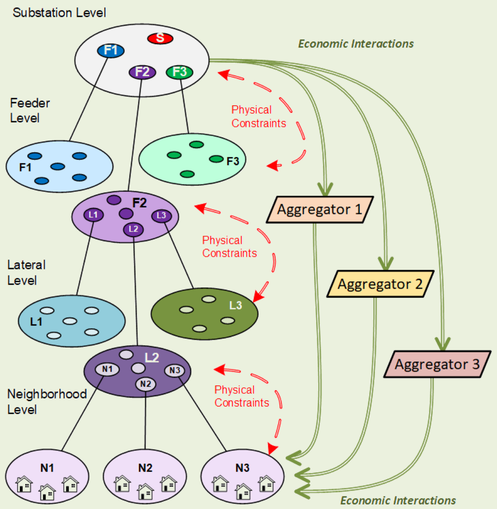
Current Graduate Students: Kumarsinh Jhala, Ahmad Khaled Zarabie, Haitham Kanakri

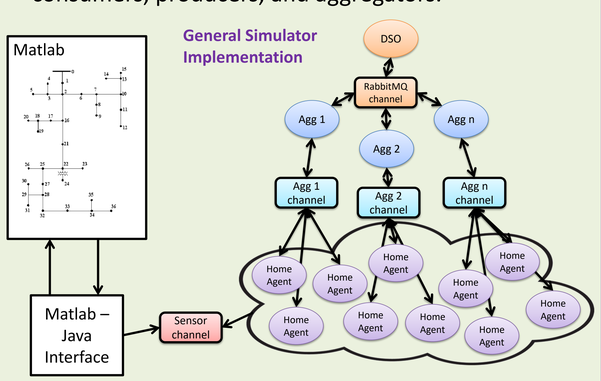
Abstract: This project aims to create a *Holonic Multiagent System* (HMAS) architecture to support transactive energy market of "active consumers" engaged in buying and selling electricity (locally generated from resources such as rooftop solar photovoltaic) in response to real time electricity pricing. The architecture should require little change to the existing investment in power distribution systems while allowing for the dynamic, adaptive control required to integrate active consumers with current and future combinations of high-variability distributed power sources, such as PV generators and storage batteries. Specific research issues to be addressed include 1) an HMAS architecture for integrating the cyber and physical system aspects all the way from the consumer level to the power grid, 2) stochastic models for consumer behavior that capture consumer preferences and reactions to changing electricity prices, and 3) distributed control actions the utility can take to mitigate adverse effects associated with active consumers and to proactively create conditions beneficial to consumers and the utility.

HMAS Simulation

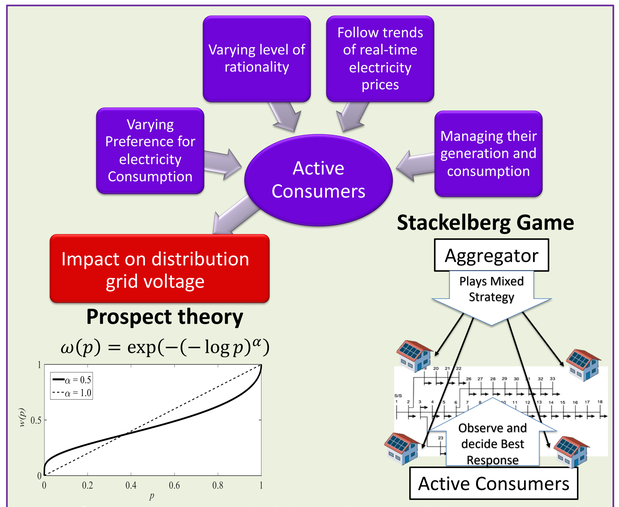
System Architecture:



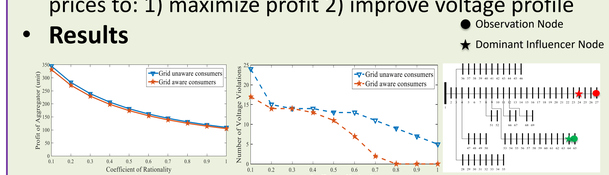
- Holonic multi-agent architecture provides generality and scalability and supports integration of transactive energy markets.
- Architecture supports multiple levels of energy auctions and formation of stable coalitions of consumers, producers, and aggregators.



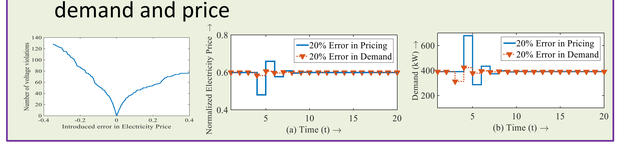
Impact of Consumer Actions



- **Active consumers** decide their electricity consumption based on: 1) Comfort 2) Cost and 3) Grid Awareness
- **Aggregator** decides probability distribution of electricity prices to: 1) maximize profit 2) improve voltage profile
- **Results**

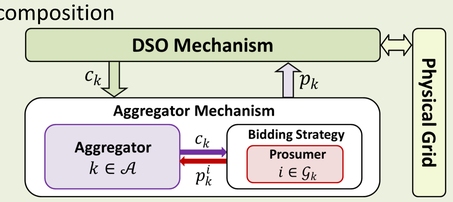


- **Dominant influencer of voltage fluctuations:** the largest contributing source of voltage change at a given bus
- Analytical and computationally efficient information theoretic metrics as indicators of the dominant influencer of the voltage fluctuations
- **Impact of Cyber-attack** on load/price signal in TEM
- BIBO stability of discrete time non-linear autonomous dynamical system and impact of FDI attack on electricity demand and price



Day-Ahead Energy Trading

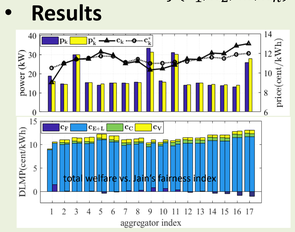
- Developing an iterative, efficient, bi-level energy trading mechanism in power distribution market without accessing prosumers private information such as utility curves and generation while 1) Maintaining spatial fairness 2) Maximizing social welfare 3) DLMP decomposition



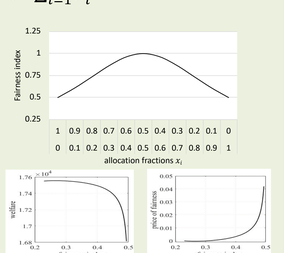
- **Prosumers** as selfish agents, try to maximize their payoffs by comparing the energy price with their marginal utility to determine their power bids
- **Aggregators** communicate the price signals and combined power bids between the DSO and prosumers
- **DSO** solves a grid constrained, fairness regularized optimization problem to maximize total utility and to determine DLMP: $\mathbf{c}^{\text{new}} = \mathbf{c}_V + \mathbf{c}_C + \mathbf{c}_{E+L} + \mathbf{c}_F$.
- **Jain's Fairness Index** is used to charge prosumer in a more equitable manner

$$J(x_1, x_2, \ldots, x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n * \sum_{i=1}^{n} x_i^2}$$

- **Results**



(top) - unit costs and allocated power to each aggregator without(blue) and with(yellow) fairness regularization
(bottom) - Corresponding DLMP comments



price of fairness vs. Jain's fairness index

- A stochastic optimization model to develop an efficient trading mechanism for aggregator in day ahead and real time market that finds hourly price offered to customers and maximize aggregator profit while minimizing risk.

Broader Impacts

Papers:

1) K. Jhala, B. Natarajan and A. Pahwa, "Prospect Theory based Active Consumer Behavior Under Variable Electricity Pricing," in IEEE Transactions on Smart Grid. doi: 10.1109/TSG.2018.2810819
2) K. Jhala, B. Natarajan and A. Pahwa, "Probabilistic Voltage Sensitivity Analysis (PVSA)—A Novel Approach to Quantify Impact of Active Consumers," in IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 2518-2527, May 2018. doi: 10.1109/TPWRS.2017.2745411
3) K. Jhala, B. Natarajan and A. Pahwa, "Probabilistic voltage sensitivity analysis (PVSA) for random spatial distribution of active consumers," 2018 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, 2018, pp. 1-5. doi: 10.1109/ISGT.2018.8403341
4) HS Karimi, K. Jhala and B. Natarajan, "Impact of Real-Time Pricing Attack on Demand Dynamics in Smart Distribution Systems" 2018 IEEE North American Power Symposium (NAPS), Fargo, ND, 2018.
5) M. N. Faqiry and S. Das, "Distributed Bi-level Energy Allocation Mechanism with Grid Constraints and Hidden User Information," IEEE Transactions on Smart Grid, early access.
6) M. N. Faqiry and S. Das, "Double Auction With Hidden User Information: Application to Energy Transaction in Microgrid," IEEE Transactions on Systems, Man, and Cybernetics: Systems, early access.
7) S. Das, M. N. Faqiry, K. Zarabie and H. Wu, "Game Theoretic Equilibrium Analysis of Energy Auction in Microgrid," International Journal of Electrical and Electronic Engineering & Telecommunications, in press.
8) M. N. Faqiry, A. K. Zarabie, F. Nassery, H. Wu, and S. Das, "A Day Ahead Market Energy Auction for Distribution System Operation," in Proceedings of IEEE Conference on Electro-Information Technology, 2017, pp. 1–6.
9) P. Janovsky and S. A. DeLoach, "Increasing coalition stability in large-scale coalition formation with self-interested agents (short paper)," European Conference on Artificial Intelligence (ECAI), 2016.
10) P. Janovsky and S. A. DeLoach, "Multi-agent simulation framework for large-scale coalition formation," 2016 IEEE/WIC/ACM International Conference on Web Intelligence, 2016.
11) P. Janovsky and S. A. DeLoach, "Increasing use of renewable energy by coalition formation of renewable generators and energy stores," European Conference on Multi-Agent Systems EUMAS 2016, 2016.
12) P. Janovsky and S. A. DeLoach, "Forming stable coalitions in large systems with self-interested agents," European Conference on Multi-Agent Systems EUMAS 2016, 2016.
13) P. Janovsky and S. A. DeLoach, "Increasing coalition stability in large-scale coalition formation with self-interested agents," European Conference on Artificial Intelligence (ECAI), 2016.
14) P. Janovsky and S. A. DeLoach, "Multi-agent simulation framework for large-scale coalition formation," IEEE/WIC/ACM International Conference on Web Intelligence, 2016.
15) P. Janovsky and S. A. DeLoach, "Increasing use of renewable energy by coalition formation of renewable generators and energy stores," European Conference on Multi-agent Systems EUMAS, 2016.

Thesis/Dissertations:

16) Kumarsinh Jhala, PhD Dissertation, "Modeling of active consumers and their impact on the Smart Grid: A cyber physical social and economic perspective," August 2018.
17) Pavel Janovsky, PhD Dissertation, "Large-scale coalition formation: application in power distribution systems," May 2017.
18) M. N. Faqiry, PhD Dissertation, "Efficient double auction mechanisms in the energy grid with connected and islanded microgrids," May 2017.

Participation and Training:

- 5 graduate students and 2 undergraduate students participated in research and presented posters and papers at various conferences.

Integration of teaching and Research: Topics integrated in following courses

- ECE 887 - Distribution System Engineering
- ECE 949 – Multi-agent Game Theory

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