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Project Title: Developing an Architecture for Multiagent Cyber-Physical Systems; the U.S. Electric Grid and the Proper Compensation of Distributed Energy Resources.

The emerging power grid is expected to be characterized by a large number of distributed energy resources (DERs), such as distributed generators (DGs), storage, and demand response (DR), operated by different stakeholders [1]. A common example of a DG is a private residential solar panel. At high levels of penetration however, DERs, particularly those that are intermittent, like renewable resources, disrupt conventional grid planning methods [2]. This makes grid dispatch and the real-time control of the grid more difficult. Many of the challenges associated with the integration of DERs are structural; namely, that the power grid and the subsequent power planning and delivery methods are built around the concept of large, centralized and controllable power stations overseen by a few stakeholders [1]. A decline in grid stability/efficiency can be expected if the prevailing system design is left unchanged [1].

This project will examine and analyze the behavior of the distribution grid while using a proposed distribution system retail market, by analyzing it as a cyber-physical multiagent system. These agents behave as per the distributed optimization methods, security mechanisms, and market structure outlined in [3] through [5], which will be briefly discussed below. In doing so, we hope to address the challenge of enabling the secure coordination of diverse and private assets in an electricity distribution grid, all acting as independent co-operative agents.

Under the current electricity market, some DERs are able to participate directly in the Wholesale Electricity Market (WEM). FERC Orders 719 and 745 requires Independent System Operators (ISOs) and/or Regional Transmission Organizations (RTOs) to remove market barriers of entry for DR units [6]. Based on an earlier analysis of market rule and requirements, there are still significant barriers of entry based on resource size, metering requirements, and bidding rules [2]. While regulatory requirements are improving for resources, the WEM may be insufficient in realizing efficient power delivery and electricity prices for market participants, especially for smaller resources. This is especially important for distribution grids, where many behind-the-meter units are smaller, and currently have no way to be compensated for their services [2].

Thus, the current electricity market structure has inefficiencies relating to the inadequate compensation for private, small-scale DERs to behave in accordance with the grid's overall "best interests" as opposed to exclusively their own, which could otherwise cause grid stability issues. A new retail market mechanism is thus required for the distribution grid, as proposed in [3], where distributed optimization algorithms are used to determine the distribution Local Marginal Prices (dLMPs). This retail market has the potential to address the need for well-behaved DERs, and result in an increase in revenue for grid operators [3].

We are interested in investigating how agents behave according to the market structure and the distributed proximal atomic coordination (PAC) algorithm developed in [3] and [5]. We would also like to determine whether the PAC algorithm is inherently capable of operating when agents in the network are grouped into self-contained islands. The PAC algorithm is a distributed optimization algorithm which makes use of computational units owned by different agents in a network, exploiting their resources to quickly and securely achieve globally optimal solutions. The PAC algorithm differs from the popular ADMM distributed algorithm in that it reduces the communication overhead that comes from frequent peer-to-peer exchanges between the processing units, and has enhanced privacy characteristics. Primarily, agents in this system maintain data privacy over their generation and consumption limits, cost of operation, and additional constraints, while still interacting with neighbouring agents to achieve network coordination [5]. The PAC algorithm can be applied to the distribution grid with independent DERs acting as distributed processing units. The market structure proposed in [3] uses the PAC algorithm to determine the dispatch of DERs, and adequately compensate them for their services, while interacting with the WEM.

Under a distributed paradigm, there is potential for resiliency and adaptability under cyber-events or cyber-attacks, which can be simulated through an implementation leveraging distributed computation and communication protocols. Paper [4] is of interest because it gives an overview of the system and control methods currently used to defend against cyberattack in cyber-physical systems. This added cybersecurity consideration is needed to: a) protect the information privacy of the DERs in the proposed platform; b) uphold a perfectively competitive market where no single agent can exercise market power; c) detect and expel rogue agents from the network; d) hedge against potential data corruption caused by rogue agents. Naturally, the research will include finding the pros and cons of various solutions. In general, we aim to implement scalable and distributed solutions.

We intend to use a platform composed of several BeagleBone Blacks, which are open-source single-board computers, that communicate using the RIAPS platform developed by Vanderbilt University, in this project. The architecture will be fully parallelized between agents and potentially applicable in other domains that are characterized by many agents. We also expect to find and resolve issues regarding the practical implementation of inter-communicating agents subject to physical constraints; namely, data corruption, communication loss, and feasibility issues (power balance constraints) that would otherwise compromise the security and reliable operation of the distribution grid.

Tentative Milestones

Within the three-month summer period:

- Adapting and extending preexisting multiagent system (MAS) platforms/testbeds into a custom physical testbed (using multiple BeagleBone Blacks) for the purposes of testing and analyzing PAC, in addition to addressing cybersecurity concerns in the context of an electric distribution grid.
- Implementing agent behavior (i.e. information sharing, data management).
- Conducting scenario analysis to stress test the PAC implementation, focusing on simulating cyber-events and failures, to improve the mechanisms developed in [3] and [4].

- Time permitting, provide useful insight into the development of an *asynchronous* PAC algorithm (the algorithm currently relies on all agents being synchronized).

More specifically:

- Month 1 and the first half of Month 2: Design and implement the PAC algorithm on a custom testbed.
- Remainder of Month 2 and first third of Month 3: Run scenario analysis under varying conditions (i.e. data dropping, stricter network constraints) and network topologies. Testbed will be improved as needed.
- Remainder of Month 3: Write documentation for and package the custom testbed; also write reports on results. Additionally, set up foundation for creating a standalone device, which when interfaced with a grid device such as an inverter, imbues it [the inverter] with the multiagent capabilities developed in the testbed.

Personal Statement

My broad interest is in multiagent systems (MAS). Specifically, I'm interested in platforms that give 'dumb' assets (e.g. PV systems, EVs) on the U.S. electric grid agency – which includes autonomy, some limited understanding of causality and transactive capabilities – for the purposes of a flexible ad-hoc network. Through various signals (i.e. price signals), agents respond to grid events autonomously, quickly, with minimal communication overhead and in a coordinated fashion. The aims of said multiagent approach include but are not limited to: 1) enabling more sophisticated demand side response; 2) enhancing grid awareness and observability; 3) accommodating more intermittent renewables; 4) removing market inefficiencies; 5) using *lots of data smarter*.

I hope this research project will inform how I go about evaluating and implementing my own proposal. I look forward to working with Rabab Haider and the AACLAB team.

Previous UROP Experience

I have researched with the same lab (AACLAB) in the past on a project that examined the market pairing of natural gas and wind power producers via bilateral contracts. I have also done independent research with Dr. Peter Fisher on the interactions between charging stations and electric vehicles.

Both projects encouraged me to work independently in pursuit of a goal. I learned that I occasionally overcomplicate and go beyond the scope of the project; this means I sometimes (in my opinion) under-deliver on certain portions of the project. As I go forward, I will keep this in mind and follow a milestone sheet made at the start of the project. In addition, I also learned the benefits of my nonlinear style of working, namely, that working on several aspects of a project simultaneously enables me to be more creative.

References

Note that the URLs to the papers below are hyperlinked through the paper's title.

[1] Ali Ipakchi and Farrokh Albuyeh. Grid of the Future. In *IEEE Power & Energy Magazine*, 2009.

[2] J. MacDonald, P. Cappers, D. Callaway, and S. Kiliccote. Demand Response Providing Ancillary Services. Ernest Orlando Lawrence Berkeley National Laboratory, 2012.

[3] S. Baros, Y. Wasa, J. Romvary, A. M. Annaswamy, R. Haider, and K. Uchida. Towards a Retail Market for Distribution Grids. In *IEEE Transactions on Smart Grids*, 2019 (submitted).

[4] S.M. Dibaji, M. Pirani, D. Flamholz, A.M. Annaswamy, K.H. Johansson, and A. Chakrabortty. A Systems and Control Perspective of CPS Security. In *Annual Reviews in Control*, 2019 (submitted).

[5] J. Romvary and A. M. Annaswamy. A Proximal Atomic Coordination Algorithm for Distributed Optimization. In *IEEE Transactions on Automatic Control*, 2018 (submitted).

[6] FERC. Demand Response Compensation in Organized Wholesale Energy Markets. *United States of America Federal Energy Regulatory Commision*, 2011.