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Agent-based Informatics for Autonomous Microgrids

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OBJECTIVES

- Investigate intelligent agent-based informatics architectures for coordination and control of interconnected ***autonomous microgrids***
- Design and evaluate in simulation a prototype autonomous microgrid with an agent-based coordination system
- Design and evaluate in simulation a prototype agent-coordinated network composed of interconnected, interoperating autonomous microgrids

BACKGROUND

- Def: ***grid informatics*** - information science, information technology, controls science, software engineering, computation and algorithms, and social sciences applied to modern power grid engineering
- Def: ***autonomous microgrid*** *(AMG)* - a microgrid operated and coordinated by intelligent automatic controls without significant reliance on human intervention
- Def: ***cellular power network*** *(CPN)* - a large-scale dynamic-topology power network composed of local autonomous microgrids that exhibits self-similar properties to enable scale-up
- **Grid informatics Development Task**: design an *intelligent control system* for interconnected AMGs based on *Multiagent Systems theory* and technology
- Multiagent system (MAS) design involves two primary tasks:
  1. Definition and design of the various *agent classes*, including sensing and control actions, system models, optimization algorithms, and human interfaces
  2. Development of peer-to-peer *interaction protocols*- timely interactive computations and messages exchanged by agents that induce within the system:
     - cooperation and cohesion
     - functional redundancy
     - coordinated planning and execution
     - contingency response
     - global stability
- The AMG domain is *diverse*: agents need *specialized models* of the the functions and behaviors of heterogeneous electrical equipment and of the other agents in the "power society" to communicate effectively and to coordinate their collective actions
- The AMG domain is *tightly-coupled:* to maintain voltage and adapt to variable sources and loads, agents must conduct *high-intensity interaction protocols* that have stringent requirements for timing, efficiency, and fault tolerance

APPROACH

- Organize agent structure and behavior into five general classes based on functional roles: generation, load, storage, connection, and transmission.
- Organize agent operations into *cohorts* of peers that achieve *virtualization* though mechanisms to achieve common goals and optimize performance
- Organize agent interaction protocols for efficiency into two general classes: *intra-cohort* protocols conducted among agents of the same class; and *inter-cohort* protocols conducted among agents of different classes
- Imbue agents with highly-refined models of electrical systems based on network theory that enable real-time, *knowledge-based* reasoning about dynamic network properties
- Imbue agents with the necessary social *norms and obligations* that ensure admissible solutions to power flow negotiations while meeting the economic needs of human principals and organizations
- Design flexible, *polymorphic* agent codes that facilitate in-time transition of agents among different roles in a CPN
- Design *composition-safe* agent codes that enable self-similar aggregations of agents into cellular power networks at various scales

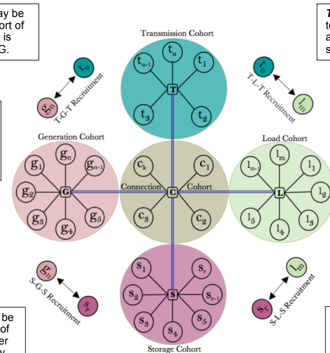
MICROGRID MULTIAGENT ARCHITECTURE

***Transmission Cohort* -** The T-cohort forms a virtual transmission hub, dynamically brokering power flow among AMGs by controlling interconnection and harmonizing the global properties of the CPN.

T-G-T Recruitment - A T-agent may be temporarily recruited into the G-cohort of an interconnected AMG if that AMG is consuming power from another AMG.

T-L-T Recruitment - A T-agent may be temporarily recruited into the L-cohort of an interconnected AMG if that AMG is supplying power to another AMG.

***Connection Cohort* -** The C-cohort forms an intelligent virtual bus that is the locus of AMG topology, security and safety. C-agents cooperate to mediate the membership of the AMG bus by managing connectivity among agents.



***Load Cohort* -** The L-cohort forms a virtual load center, coordinating demand among individual loads, forecasting desired and critical load levels, and negotiating load-shedding.

***Generation Cohort* -** The G-cohort forms a virtual generator, coordinating the operation of individual generators and forecasting aggregate power availability for the AMG.

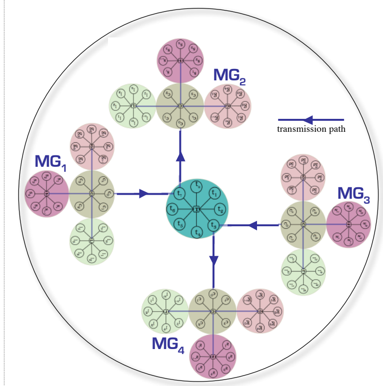
S-G-S Recruitment - An S-agent may be temporarily recruited into the G-cohort of an AMG if it is required to provide power to the bus and it is has sufficient energy to meet the demand.

S-L-S Recruitment - An S-agent may be temporarily recruited into the L-cohort of an AMG to consume excess power or if it requires energization to fulfill a future generation role in the G-cohort.

***Storage Cohort* -** The S-cohort forms a virtual power store that maintains excess power to smooth variations in supply and demand over different time scales while managing the life-cycle properties of individual storage elements.

INTERCONNECTED MICROGRIDS

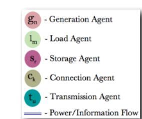
Microgrids MG_1 and MG_2 are interconnected through T-agent T_7 and their respective C-agents. Power flows from MG_1 to MG_2. Agent T_7 participates in the G-cohort protocols of MG_2 and in the L-cohort protocols of MG_1. When MG_2 no longer needs the excess power from MG_1 the links are disconnected and the T_7 resigns from the respective G and L cohorts. T_7 can then broker other connections.



If the MG_1-MG_2 CPN and the MG_3-MG_4 CPN can *improve their mutual stability by power sharing*, and if a transmission path exists between them, the agents T_7 and T_3 can broker their interconnection within the T-cohort subject to constraints on transmission channels.

The bulk utility grid can act through the T-agent cohort to supply power to individual AMGs or to CPNs at various levels of aggregation. Hence utility T-agents will appear in the respective G-cohorts of client AMGs representing a high-capacity source that is always available.

Microgrids MG_3 and MG_4 are interconnected through T-agent T_3. Power flows from MG_3 to MG_4 as long as their joint supply-demand function satisfies their local economic constraints and demand profiles. Either microgrid can terminate the exchange in response to changing local conditions subject to contractual obligations and contingency plans.



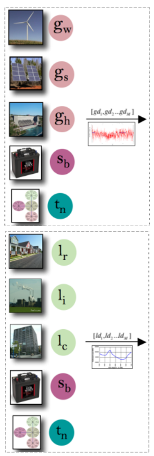
FORECASTING

Generation

G-agents perform historical time-series analyses of power production for their respective devices. Prediction algorithms forecast the future supply of each unit. S-agents must predict discharge rates of batteries, and T-agents provide the forecasted excess power of their client AMG to net supply calculations.

Demand

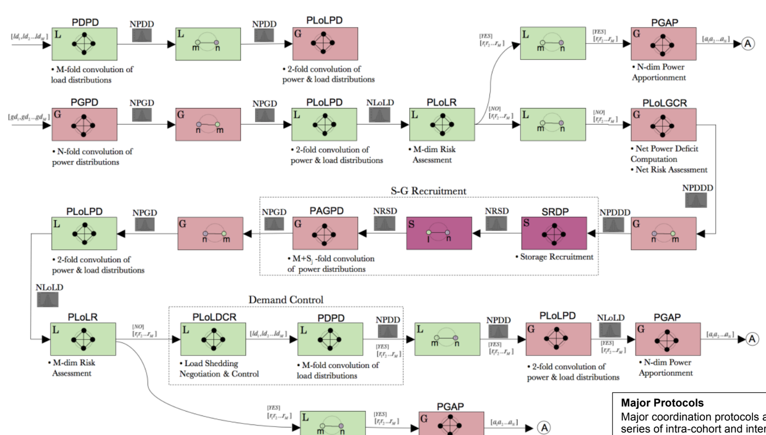
L-agents perform historical time-series analyses of demand on their load elements. S-agents predict charging rates and load for batteries. T-agents represent the net forecasted power deficit of their client AMG to net demand calculations.



Exception-Driven Re-Planning

Each agent must *continuously* forecast power demand / supply to some future horizon and engage their respective L/G cohorts to update the master power coordination scheme if significant changes occur. On-site forecasting by individual agents and exception-driven activation of interaction protocols is essential to manage the computational and communications complexity of AMG coordination, especially for AMGs with large memberships.

MULTIAGENT INTERACTION PROTOCOLS



Power Capacity Risk Planning Protocol #1 (PCRPP1 - example)

PCRPP1 SUB-PROTOCOLS

PDPD - Power Demand Probability Density (PD)
PGPD - Power Generation Probability Density
PLoLPD - Power Loss-of-Load PD
PGAP - Power Generation Apportionment Protocol
PAGPD - Power Augmented Generation PD
PLoLR - Power Loss-of-Load Risk
PLoLDCR - Power LoL Demand Control Response
PloLGCR - Power LoL Generation Control Response
SRDP - Storage Recruitment Demand Protocol

PCRPP1 RESULTS

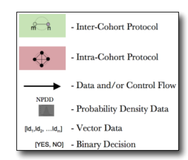
NPDD - Net Power Demand Density
NPGD - Net Power Generation Density
NLoLD - Net Loss-of-Load Density
NPDDD - Net Power Deficit Demand Density
NRSD - Net Recruited Storage Density

Demand Control Protocols

L-agents request power according to graded levels of priority, from desired to critical, below which the load experiences unacceptable failures or costs. Generally requests are in the form of demand density functions. If storage recruitment and transmission recruitment fail to provide requested demand, L-agents must negotiate shedding loads and institute load control policies that cap individual loads.

Major Protocols

Major coordination protocols are composed of a series of intra-cohort and inter-cohort sub-protocols. Two major classes of protocols are Planning Protocols and Execution Protocols. Planning protocols harmonize power flow and are usually computation intensive, involving iterative stochastic nonlinear optimization algorithms. Execution protocols coordinate actions and are usually communication intensive, requiring fast port-to-port response times. Planning protocols generally result in a master coordination scheme for the AMG over some time period that is enacted by an execution protocol.



CHALLENGES

- The demands of AMG coordination require a very high-performance and modern multi-agent software platform
- Unlike large-scale power grids in which the law of large numbers reduces sensitivities, microgrid collectives are sensitive to individual generators and loads
- Planning toward reasonable time horizons that involves both stochastic sources and stochastic loads is computationally intense
- Stability analysis of multiply-connected CPNs is a complex nonlinear dynamics problem
- Accurate forecasting of renewable sources remains a core challenge to the community, but is especially crucial to the successful coordination of autonomous microgrids
- Designing secure agents and secure protocols that address cyber and insider threats significantly increases the complexity of the system and impacts real-time performance
- Modeling electric vehicles as mobile S-agents requires geospatial reasoning functions and traffic pattern estimation algorithms incorporated into generation and load planning protocols