Coalitional Game Theory for Micro-Gird Distribution Networks

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Outline

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    • Game formulation
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Smart Grid

- Key features:
  - Integration of microgrids, diverse generation and storage resources
  - Incorporating “smart” demand-side management,
  - The three “s”: self-healing, self-optimizing, self-configuring
  - Communications: handling large amounts of data and securing this data (e.g., PMU data)

- Many definitions found: IEEE, DOE, Wiki, FERC

- We are continuously defining the smart grid through research!
Micro-grid Distribution Networks

- **Components**
  - Electrical substations that link to the high voltage transmission network
    - Composed of transformers and serving an area or city
  - Distribution wiring
    - Distributed energy sources or micro-grids
      E.g., Solar or Wind farms
- **Role of micro-grids**
  - Can act autonomously and/or in coordination with the main macro-grid
  - Serve as a backup to the main macro-grid whenever there is an extensive demand
  - Can request energy from the macro-grid, if needed to service small areas
Micro-grid networks: Challenges

• When should the micro-grid energy sources act on their own or coordinate with the grid?
  – Control theory is useful to study distributed decisions of the micro-grids

• Which areas should the micro-grids service?
  – Depends on demand and supply as well as the possible use of storage

• How can the micro-grids interact to trade energy within a local exchange market?
  – If micro-grids are “smart” and equipped with communication capabilities, they can interact and possibly trade energy
System model

- Energy trading at the distribution network
- Cooperation needed to:
  - Exchange energy: sell surplus and overcome deficiency
  - Save wasted power over the transmission lines in the micro-grid
- Coalitional games!
Motivation for Game Approach

• What is Game Theory?
  – The formal study of conflict or cooperation
  – How to make an adversarial decision
  – Modeling mutual interaction among players that are rational decision makers

• Components of a “game”
  – Rational Players with conflicting interests or mutual benefit
  – Strategies or Actions
  – Solution or Outcome

• Nobel prizes
  – Nobel prize in Economic Sciences 1994 awarded to Nash, Harsanyi (Bayesian games) and Selten (subgame perfect equilibrium)
Coalitional Games Preliminaries

• Coalitional game \((N,v)\)
  – A set of players \(N\), a coalition \(S\) is a group of cooperating players
  – Value (utility) of a coalition \(v\)
  – User payoff \(x_i\): the portion received by a player \(i\) in a coalition \(S\)

• Transferable utility (TU)
  – The worth \(v(S)\) of a coalition \(S\) can be distributed arbitrarily among the players in a coalition hence,
  – \(v(S)\) is a function over the real line

• Non-transferable utility (NTU)
  – The payoff that a user receives in a coalition is pre-determined, and hence the value of a coalition cannot be described by a function
  – \(v(S)\) is a set of payoff vectors that the players in \(S\) can achieve

\[ v(S) \subseteq \mathbb{R}^{|S|} \]
Cooperative Eavesdropping: Gains

• Consider a coalition $S$ of micro-grids
  – The micro-grids are divided into sellers and buyers
  – Consider an ordering $\pi$ over the buyers in $S$
  – Inside $S$, each buyer attempts to buy from the seller that yields the smallest power loss

• For a given $\pi$, the losses over the distribution lines due to $S$ can be given by ($S_s$ subset of sellers, $S_b$ subset of buyers):

$$u(S, \Pi) = - \left( \sum_{i \in S_s, j \in S_b} P_{ij}^{\text{loss}} + \sum_{i \in S_s} P_{i0}^{\text{loss}} + \sum_{j \in S_b} P_{j0}^{\text{loss}} \right)$$

- Losses for power exchange between seller $i$ and buyer $j$ which depends mainly on the demand, the resistance and the voltage for distribution
- Power loss between seller $i$ and the macro-grid (depends on transformer losses, surplus, and resistance)
- Power loss between buyer $j$ and the macro-grid (depends on transformer losses, energy need, and resistance)
Coalitional game formulation: Value function

- Given these power losses, for any coalition S, we define the value function as
  \[
  v(S) = \max_{\Pi \in \Xi_S} u(S, \Pi)
  \]
  - The maximum is over all orderings of buyers

- The utility represents a cost paid per unit of power loss, hence, it can be considered as transferable utility

- To divide the utility between the players, we adopt a fair division proportional to the non-cooperative utility of each user:
  \[
  \phi_i = \alpha_i \left( v(S) - \sum_{j \in S} v(\{j\}) \right) + v(\{i\})
  \]
  Weight chosen according to micro-grid i’s non-cooperative utility
Coalition Formation: Merge and Split

- Define the Pareto order preference relation between two collections of coalitions $R$ and $S$

$$R \triangleright S \iff \{\phi_j(R) \geq \phi_j(S) \ \forall \ j \in R, S\},$$

with at least one strict inequality ($>$) for a player $k$.

- **Merge rule:** merge any group of coalitions where

$$\{\bigcup_{j=1}^{l} S_j\} \triangleright \{S_1, \ldots, S_l\}$$

- **Split rule:** split any group of coalitions where

$$\{S_1, \ldots, S_l\} \triangleright \{\bigcup_{j=1}^{l} S_j\}$$

- A decision to merge (split) is an agreement between all players to form (break) a new coalition.
Coalition formation algorithm

Initial Network State:
Non-cooperative energy trade

Merge-and-split iterations until convergence
- Each users (or coalition) surveys the neighbors for possible Merge

Each coalition investigates Split possibility

Final partition:
Cooperative power transfer inside each coalition of micro-grids (seller-buyer interactions)
Simulation results

[Graph showing Position in x (km) vs. Position in y (km) for various coalitions S1 to S5, and a graph showing Average payoff (power loss) per micro-grid (MW) vs. Number of micro-grids (N) with lines for Non-cooperative scheme and Proposed coalition formation algorithm.]
Summary

• Cooperative energy trading in micro-grid networks can be enabled using coalitional games

• Coalition formation for cooperative energy trading
  – Reduce the power losses over distribution lines and/or transformers
  – Create a local energy exchange market between micro-grids
  – Enable the micro-grids to better serve their consumers

• Future work
  – Capturing the seller-buyer interactions using auctions
  – Other types of games
  – Studying pricing schemes
Finally....

Thank You