An Autonomous Decentralized Mechanism for Energy Interchanges with Accelerated Diffusion Based on MCMC

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Outline

• Background
  • Renewable energy and large-scale microgrid
• Objective
  • To propose an autonomous decentralized mechanism for promoting effective use of renewable energy
    • Use of energy interchange between distributed batteries
• Design
  • Basic idea: diffusion equation and MCMC
  • Expression of energy interchange amount
• Evaluation
  • Effectiveness of our proposed mechanism
• Summary
Background

- Renewable energy (e.g., sunlight and wind)
  - Is clean and inexhaustible
    - to be alternative energy of conventional fuels
  - Depends on geographical conditions and time of day
    - Difficulty supplying energy appropriately for energy demand
      - Major obstacle for the growing availability

We are attempting to alleviate this obstacle by utilizing large-scale microgrids.
Large-Scale Microgrid

- Is an electricity system interconnecting distributed batteries in a wide area (e.g., island)
- Would be a key technology to provide energy supply appropriately for energy demand
- By energy interchange between batteries

How should nodes transmit energy to realize such a energy supply?

- Network to transmit energy in a microgrid
- Battery with a function of energy interchange
- Other equipments: generator using renewable energy, electric loads
Related Work for the Energy Interchange

- An energy trading algorithm proposed in [4] for energy interchange on the basis of machine learning
- Supposes a virtual energy market
  - To manage the energy interchange between batteries
  - A kind of centralized mechanism
    → Low robustness for disaster compared with ADM

Objective

• Propose an **autonomous decentralized mechanism** of the energy interchanges in large-scale microgrids
  • Goal
    • Energy supply appropriately for energy demand when using renewable energy as main power source
  • Design
    • The energy interchange amount transmitted between batteries on the basis of …
    • **Diffusion equation**
    • **MCMC** (Markov Chain Monte Carlo)
• Clarify the fundamental property of the proposed mechanism
  • Simulation experiment with a simple model
System Model

- Network $G=(V, E)$ for energy interchange
  - $V$ : set of nodes, $E$ : set of links
  - If $(i, j) \in E$, nodes $i$ and $j$ can mutually transmit energy
- Node
  - Has battery, generator, load
  - Transmits energy to another node according to sufficiency levels

Sufficiency level of node $i$

$$\hat{q}_i(t) := q_i(t) - \theta_i$$

Energy interchange amount from node $i$ to node $j$

$J_{i \rightarrow j}(t)$

How should we design? 

Realize energy supply appropriately for energy demand
Basic Idea to Degin $J_{i \rightarrow j}(t)$

- Derive the expression of energy interchange amount $J_{i \rightarrow j}(t)$ on the basis of the diffusion equation.
  
  - Absolutely converges to the uniformed state.
  
  - Use MCMC for accelerating the uniforming speed of $\hat{q}_i(t)$.
  
    - MCMC : Markov Chain Monte Carlo.
    - Can fast decrease the variance of sufficiency levels $\hat{q}_i(t)$ by using MCMC.

Time evolution of particle density by the diffusion equation on 1 dimension.
Expression of $J_{i\rightarrow j}(t)$ Based on the Diffusion Equation

- Derive expression of $J_{i\rightarrow j}(t)$ from the diffusion equation
  1. Consider the discrete diffusion equation
     \[ \hat{q}_i(t + \Delta T_J) - \hat{q}_i(t) = k' \Delta T_J \sum_{j \in a_i} (\hat{q}_j(t) - \hat{q}_i(t)) \]
  2. Divide into the behavior of each node
     \[ J_{i\rightarrow j}(t) = k' \Delta T_J \hat{q}_i(t) \]
     - Only depends on $\hat{q}_i(t)$
     - Cannot preferentially transmit energy to a node with energy shortage
     - Poses a slow uniforming of $\hat{q}_i(t)$
Acceleration of the Uniforming on the Basis of MCMC[8]

- MCMC (Markov Chain Monte Carlo)
- A method to control the probability distribution of a metric
- A metric for fast uniforming sufficiency levels $\hat{q}_i(t)$

Variance of sufficiency levels $\hat{q}_i(t)$

$$\text{Var}(\hat{Q}(t)) = \frac{1}{|V|} \sum_{i=1}^{|V|} (\hat{q}_i(t) - \text{E}(\hat{Q}(t)))^2$$

Average of sufficiency levels

$$\text{E}(\hat{Q}(t)) = \frac{1}{|V|} \sum_{i=1}^{|V|} \hat{q}_i(t)$$

P(Var) control the distribution to decrease the variance

realize fast uniformizing

Expression of $J_{i\rightarrow j}(t)$ Based on MCMC

- $J_{i\rightarrow j}(t)$ based on the diffusion equation
  - Only depends on $\hat{q}_i(t)$
    → Same value if $\hat{q}_j(t)$ is different

$$J_{i\rightarrow j}(t) = k' \Delta T_J \hat{q}_i(t) \quad (5)$$

- $J_{i\rightarrow j}(t)$ based on MCMC
  - Depends on $\hat{q}_i(t)$ and $\hat{q}_j(t)$

$$J_{i\rightarrow j}(t) = k' \Delta T_J f_{i\rightarrow j}(\hat{q}_i(t), \hat{q}_j(t)) \hat{q}_i(t) \quad (7)$$

\[
f_{i\rightarrow j}(\hat{q}_i(t), \hat{q}_j(t)) = 1 - \kappa' \left| \hat{q}_j(t) - \hat{q}_i(t) \right| \left[ \hat{q}_j(t) - \hat{q}_i(t) \right]^+\]

where $[x]^+ = \max(0, x)$.

Energy interchange by Eq. (7)

\[\hat{q}'(< \hat{q}^*) \quad \hat{q}^*\]

Realize fast uniforming (decreasing the variance)

\[\hat{q}^* = \hat{q}^*\]
Evaluation Using Simulation Experiment

• Investigate the **fundamental property** of the proposed mechanism
  • Can it supply energy appropriately for energy demand?
• Use simple simulation model to focus on **uniforming sufficiency levels** \( \hat{q}_i(t) \) by the proposed mechanism
  • Assume ‘generated energy’ = ‘consumed energy’
  • Ignore any loss of energy interchanges
  • Set demand amount \( \theta_i \) to a time-invariant value
• Use the following simulation procedures
  • Randomly set battery remaining amount \( q_i(0) \sim N(\mu_q^{st}, \sigma_q^{st}) \)
    at the start of simulation
  • Repeat energy interchange between nodes during simulation
Network Topology: 
$N_k$-th Nearest Neighbor Network

- Is generated by the following procedure
  1. $N$ nodes are randomly placed in the 2-dimensional plane
  2. Each node selects $N_k$-th nearest nodes as its adjacent nodes
- Represents actual property
  (a) geographical dispersion of nodes
  (b) wiring const between nodes

An example of $N_k=5$ and $N=100$
Result to Confirm the Uniforming Sufficiency Levels

- Time evolution of battery remaining amount $q_i(t)$
- Demand amount $\theta_i$ for all node = 50
- Average of $q_i(0) = 5$ in the center region
- Average of $q_i(0) = 50$ in the other region

The proposed mechanism can uniform them
Result to Confirm Energy Supply Appropriately for Energy Demand

- Time evolution of battery remaining amount
- Set a few nodes to high demand amount \(75\)
- Set other nodes to demand amount \(50\)

The nodes with high demand \(\theta_i\) have high \(q_i(t)\)

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demand amount \(\theta_i\)

\[t = 0\] [unit time]  
\[t = 500\] [unit time]

battery remaining amount \(q_i(t)\)
Result to Confirm Convergence Property in the Uniforming

- Time evolution of statistics of energy remaining amount $q_i(t)$
- Demand amount $\theta_i$ for all node = 50
- Average of $q_i(0) = 50$

The proposed mechanism can faster energy supply for nodes with a shortage of energy
Result to Confirm the Uniforming Speed

- Time constant for different average of $q_i(0)$
- Demand amount $\theta_i$ for all node = 50
- Time constant is the time required for decreasing initial variance $\text{Var}(\hat{Q}(0)) (= \text{sqr. of } k_\sigma \mu_q^{st})$ to $e^{-1} \text{Var}(\hat{Q}(t))$

The proposed mechanism has high effectiveness for too energy shortage and surplus situations.
Summary

- Proposed an autonomous decentralized mechanism of the energy interchanges in large-scale microgrids
- Derived the expression of energy interchange amount $J_{i\rightarrow j}(t)$ from the diffusion equation
- Improved the derived expression by using MCMC for fast uniforming $\hat{q}_i(t)$
- Clarified the fundamental property of the proposed mechanism
- Confirmed the proposed mechanism can fast supply energy appropriately for energy demand
Future Work

- Clarify the performance of the proposed mechanism in a realistic situation with considering …
  - Battery physical properties
    - The rate capacity effect
    - The degrading its performance
  - Energy loss of interchanges
  - Time variability in energy generation and consumption
- Integrate a conventional generator into our proposed mechanism
  - For satisfying energy demand of all nodes in microgrids
- Design the setting policy of energy demand
  - For the efficient use of energy in microgrids
Thank you