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Real-Time Auction Models for Optimal Operation and Control of Power Networks

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Outline

- **Background and Motivation**
- **Power Demand-Supply Networks**
- **Elements and Framework of Auction**
- **Competition Models** ongoing
- **Mechanism Design Models**
- **Conclusion**

Background and Motivation

- **Electricity Deregulation is ongoing in Japan**
  "Electric energy must be treated as commodity…" (Schweppe et al. 1988)
- **Strategic Behaviors of supply side and demand side (demand response) will be only normal**
- **Renewables involve large uncertainty and, meanwhile, promotes Ancillary Service Market**

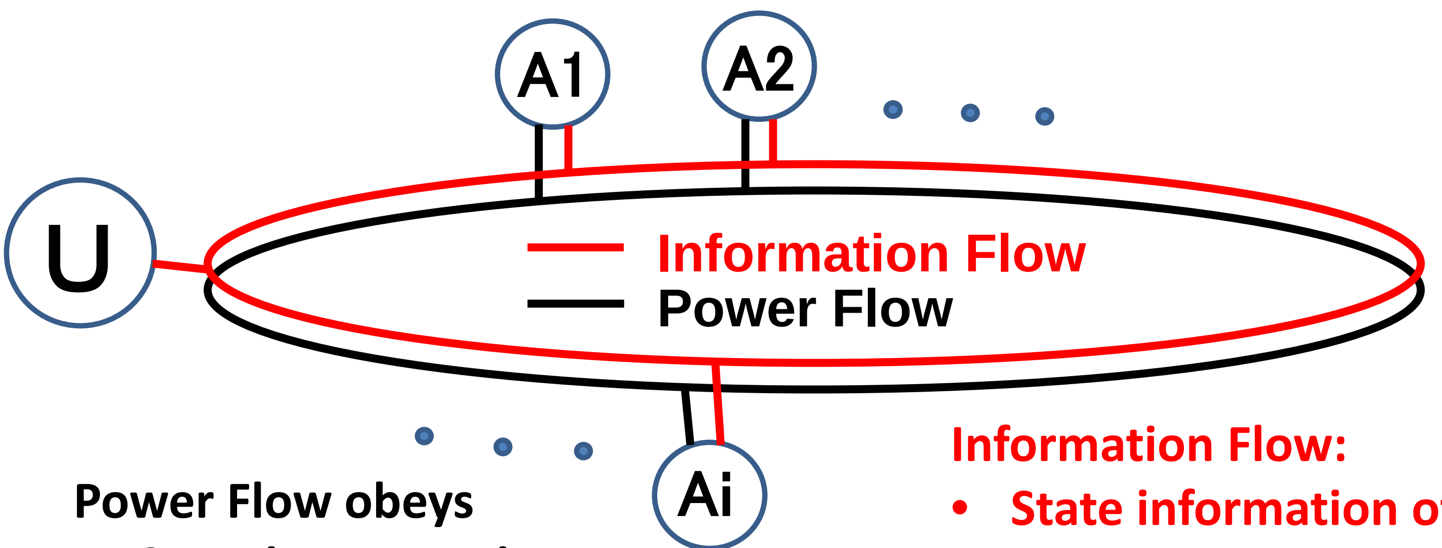
➡ **Auction model with fast transaction for dynamic operation and control**

Power Demand-Supply Networks

Social Planer (Mechanism Designer)

U: Public Utility Commission

Ai: Agent (Consumer/Generator, Aggregator/Industry)



Power Flow obeys

- Capacity constraint
- Flow constraint

Information Flow:

- State information of agent
- Type information of agent's dynamics and cost
- Environmental information

Conceptual Illustration of Power Demand-Supply Networks

Power Demand-Supply Networks

- **Utility Dynamics (interaction model, balance model):**

$$\dot{x}_0 = f_0(x_0, x_1, \ldots, x_N) = f_0(x_0, x_i, x_{-i}) = f_0(x)$$

$$-i = (1, \ldots, i-1, i+1, \ldots, N)$$

- **Utility Performance :**

$$J_0(t, x_0) = \int_t^{t_f} l_0(x_0(\tau))d\tau \quad \left(-l_0 \geq 0\right)$$

Evaluation over future time interval "model predictive"

- **Agent Dynamics (generator, consumer, e.g., air conditioner):**

$$\dot{x}_i = f_i(x_i, \underline{y_i}, u_i)$$

Type parameter of agent's dynamics and cost

- **Private Utility/(-Cost):**

$$J_i(t, x_i; \underline{y_i}, u_i) = \int_t^{t_f} l_i(x_i(\tau), \underline{y_i(\tau)}, u_i(\tau))d\tau \quad \left(-l_i \geq 0\right)$$

Elements and Framework of Auction

- ☐ **Utility's public (a prior, global) Information:**

  $$(f_0, l_0), (f_i(\cdot, y_i, \cdot), l_i(\cdot, y_i, \cdot)), \quad y_i \in Y_i, \quad i = 1, \dots, N$$

- ☐ **Agent i's private (real-time, local) information:**

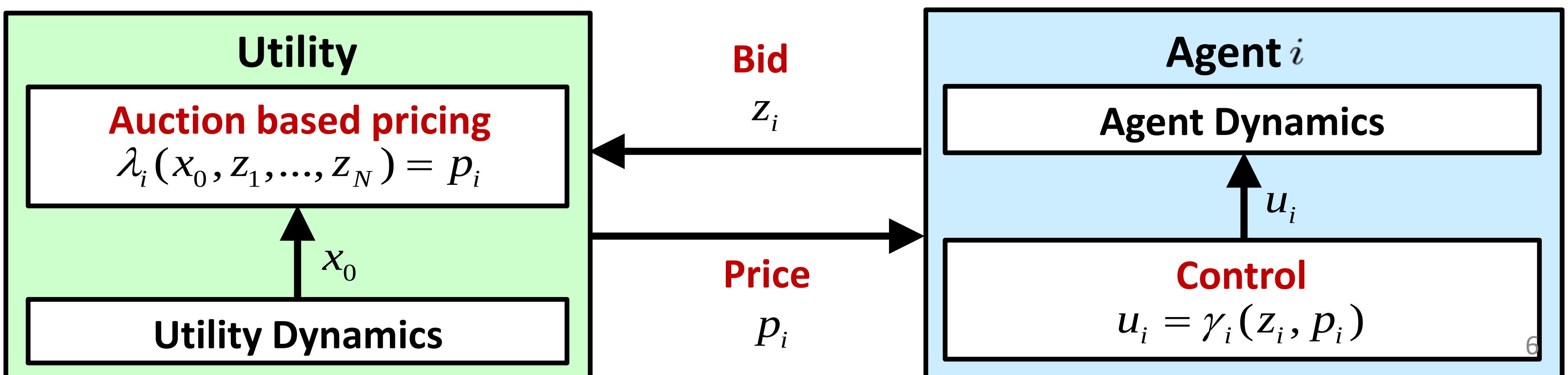
  $$z_i(\tau) = (x_i(\tau), y_i(s), \tau \le s \le t_f)$$

For prediction of agent's state trajectory

- ☐ **Action in auction:** **Bid:** $z_i(\tau)$

  Pricing : $p_i(\tau, z) = \lambda_i(x_0(\tau), z_1(\tau), \dots, z_N(\tau))$

  Control: $u_i(\tau) = \gamma_i(z_i(\tau), p_i(\tau, z))$



Elements and Framework of Auction

□ Market Clearing Condition (MCC) :

$$\frac{1}{t_f - t} J_0(t, x_0) = \frac{1}{t_f - t} \int_t^{t_f} l_0(x_0(\tau)) d\tau \geq K(x_0(t))$$

Utility's performance, Network constraints

□ Hard-Constrained Market Clearing Price:

Shadow price of constrained social loss minimization

$$V^{**}(t, z) = \max_{u=(u_1,\ldots,u_N)} \left[\sum_{i=1}^{N} J_i(t, x_i; y_i, u_i) \mid \text{subject to MCC} \right]$$

$$p^{**}(t, z) = \frac{\partial V^{**}(t, z)}{\partial x}$$ **Hard-constrained MCP**

Elements and Framework of Auction

☐ Soft-Constrained Market Clearing Price:

penalty

Shadow price of social welfare maximization

$$V^*(t,z) = \max_{u=(u_1,\ldots,u_N)} W(t,z;u) \qquad (W = J_0 + \sum_{i=1}^{N} J_i)$$

$$p^*(t,z) = \frac{\partial V^*(t,z)}{\partial x}$$

Soft-constrained MCP = "MCP"

Remark

Each agent i's control that maximizes the social welfare is given by the decentralized calculation:

$$\gamma_i^*(x_i, y_i, p_i) = \arg\max_{u_i} [p_i f_i(x_i, y_i, u_i) + l_i(x_i, y_i, u_i)]$$

"decentralization by dual decomposition"

Elements and Framework of Auction

- **Social Welfare Function:**

$$W(t,z;u) = J_0(t,x_0) + \sum_{i=1}^{N} J_i(t,x_i;y_i,u_i)$$

$$z(t) = (x(t), y(\tau), t \le \tau \le t_f)$$

- **Agent i's Profit Function:**

$$\Pi_i(t,z;u) = T_i(t,z;u) + J_i(t,x_i;y_i,u_i)$$

- **Transfer Payment Function (Incentive, Tax, Subsidy) :**

"Social planner designs transfer payment functions"

$$T_i(t,z;u) \begin{cases} < 0 & \text{Payment from Agent i to Utility} \\ > 0 & \text{Payment from Utility to Agent i} \end{cases}$$

Remark

Bidding 1 (State and Type parameter bidding)

Agent bids $z_i(t) = (x_i(t), y_i(\tau), t \le \tau \le t_f)$

Utility has a prior Information (assumption):

$$(f_i(\cdot, y_i, \cdot), l_i(\cdot, y_i, \cdot)), \quad y_i \in Y_i$$

so that utility can predict agents' state trajectory

$$x_i(\tau), t \le \tau \le t_f$$

Bidding 2 (State trajectory bidding)

Agent bids $x_i(\tau), t \le \tau \le t_f$

Competition Models

Assumption: Transfer Payment Function is given as

$$T_i(t,z;u) = \int_t^{t_f} l_{0i}(x_0(\tau))d\tau$$

$$l_0(x_0) = \sum_{i=1}^{N} l_{0i}(x_0)$$

$$\Rightarrow \quad J_0(t,x_0) = \sum_{i=1}^{N} T_i(t,z;u)$$

"Budget Balanced Transfer"

$\Downarrow$

Agent i's Profit Function is rewritten as

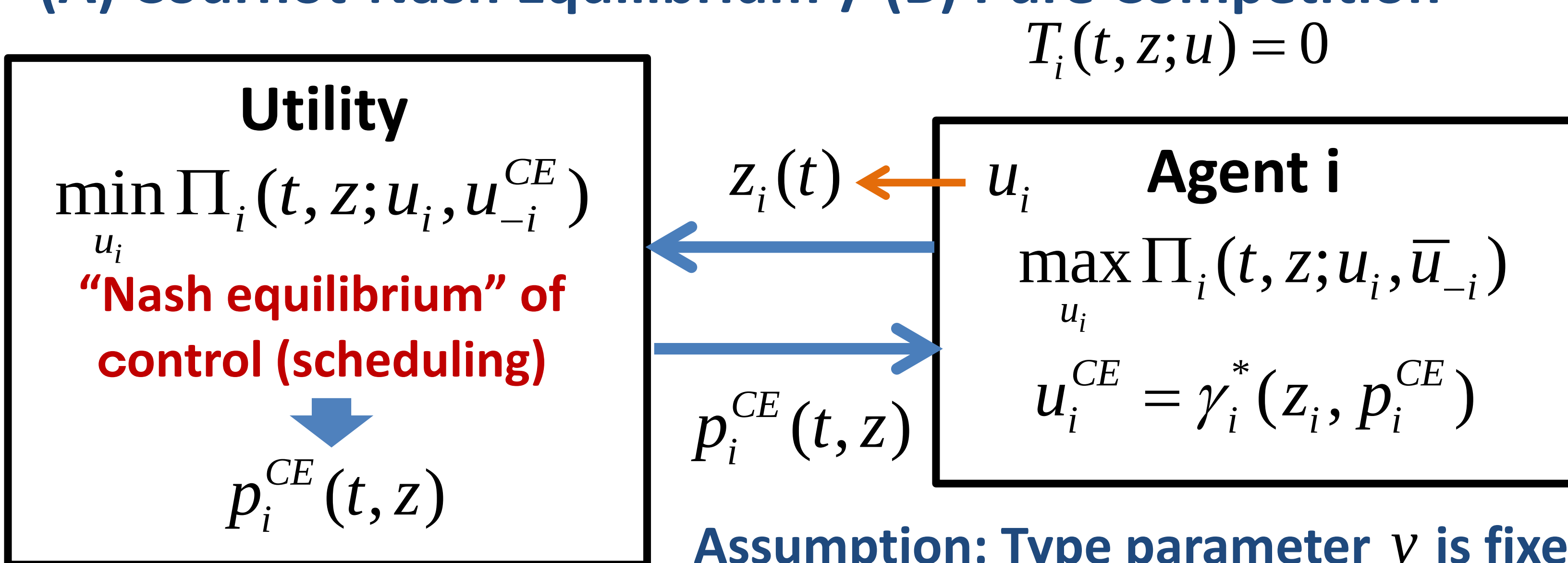
$$\Pi_i(t,z;u) = \int_t^{t_f} [l_{0i}(x_0(\tau)) + l_i(x_i(\tau), y_i(\tau), u_i(\tau))]d\tau$$

and, if utility chooses MCP $p^* = (p_1^*, \ldots, p_N^*)$ **, is a so-called "residual demand" type profit function.**

Competition Models

(A) Cournot-Nash Equilibrium (CE) Model
(B) Pure Competition (PC) Model
(C) Supply/Demand Function Equilibrium (SE) Model
⋮

(A) Cournot-Nash Equilibrium / (B) Pure Competition



Assumption: Type parameter y is fixed.

Open-loop Nash dynamic game

Competition Models

(A) Cournot-Nash Equilibrium (CE)

$$V_i^{CE}(t,z) = \max_{u_i} \Pi_i(t,z;u_i,u_{-i}^{CE}) = \Pi_i(t,z;u_i^{CE},u_{-i}^{CE})$$

$$p_i^{CE}(t,z) = \frac{\partial V_i^{CE}(t,z)}{\partial x_i},$$

(B) Pure Competition (PC)

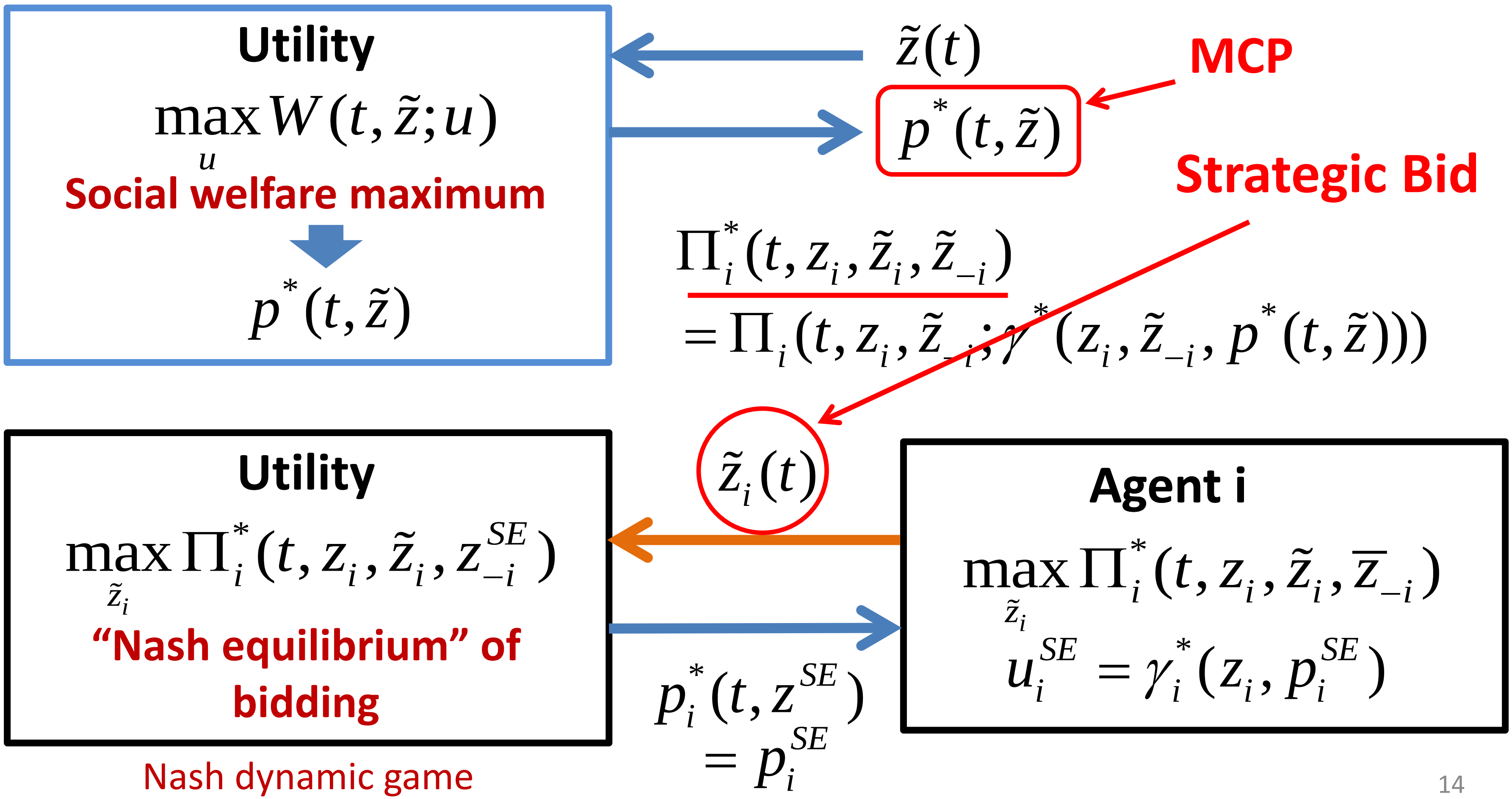
$$V_i^{PC}(t,z) = \max_{u_i} \Pi_i(t,z;u_i,u_{-i}^{PC}) = \Pi_i(t,z;u_i^{PC},u_{-i}^{PC})$$

$$p_i^{PC}(t,z) = \frac{\partial V_i^{PC}(t,z)}{\partial x_i},$$

assuming that MCC is fulfilled $(T_i(t,z;u^{PC}) = 0)$

Competition Models

(C) Supply/Demand Function Equilibrium (SE)



Competition Models

(C) Supply/Demand Function Equilibrium (SE)

$$V_i^{SE}(t,z) = \max_{\tilde{z}_i} \Pi_i^*(t, z_i, \tilde{z}_i, z_{-i}^{SE}) = \Pi_i^*(t, z_i, z_i^{SE}, z_{-i}^{SE})$$

$$p_i^{SE}(t,z) = p_i^*(t, z^{SE}(z))$$

$$u_i^{SE}(t) = \gamma_i^*(z_i(t), p_i^{SE}(t,z))$$

where p_i^*, γ_i^* **are given by social welfare maximization:**

$$p_i^*(t,z) = \frac{\partial V^*(t,z)}{\partial x_i} \qquad V^*(t,z) = \max_{u=(u_1,\ldots,u_N)} W(t,z;u)$$

$$\gamma_i^*(x_i, y_i, p_i) = \arg\max_{u_i} [p_i f_i(x_i, y_i, u_i) + l_i(x_i, y_i, u_i)]$$

Competition Models

CE Model leads to a Nash equilibrium in space of controls
SE Model leads to a Nash equilibrium in space of bids

1. **When do the equilibria exist ?**
2. **Is SE model superior to the CE model ?**
   e.g., in magnitude relations of

$$\{W(t,z;u^*), W(t,z;u^{CE}), W(t,z;u^{SE})\}$$

$$\{\Pi_i(t,z;u^*), \Pi_i(t,z;u^{CE}), \Pi_i(t,z;u^{SE})\}$$

Quick observation:

$$\{W(t,z;u^{CE}), W(t,z;u^{SE})\} \leq W(t,z;u^*) \leq W(t,z;u^{PC})$$

$$\{\Pi_i(t,z;u^*), \Pi_i(t,z;u^{CE})\} \leq \Pi_i(t,z;u^{PC})$$

Mechanism Design Models

IF transfer payment function $T_i(t, z; u)$ is VCG Type,

- **Optimal strategic bidding (Nash bidding equilibrium) is "Truth Telling" $\tilde{z} = z$: $z_i = \arg\max_{\tilde{z}_i} \Pi_i^*(t, z_i, \tilde{z}_i, z_{-i})$**
- **Budget balance is not assured.**

$$\Pi_i^*(t, z_i, \tilde{z}_i, \tilde{z}_{-i}) = \Pi_i(t, z_i, \tilde{z}_{-i}; \gamma^*(z_i, \tilde{z}_{-i}, p^*(t, \tilde{z})))$$

IF transfer payment function $T_i(t, z; u)$ is AGV Type,

- **Bayesian optimal strategic bidding (Bayesian Nash bidding equilibrium) is "Truth Telling" $\tilde{z} = z$.**
- **Budget balance is assured.**

These facts for a LQG setting were reported by Murao et al. at CDC 2013, 2014.

Conclusion

We have discussed elements and framework of the real-time auction, and provided real-time auction models for dynamic power networks based on model predictive control and economics notions.

Challenges:

- **Analysis and evaluation of real-time auctions from the viewpoint of economics, e.g., quantification and evaluation of market power in real-time auctions.**
- **Feasibility of numerical computation and mathematical elaboration. （GMRES ）**
- **Design of transfer payment functions by social planner in competition models.**

JST-CREST-EMS Team:

Principle Design, Experimental Proof, Implementation and Policy Recommendation to Establish Energy Supply-demand Networks based on Integration of Economic Models and Physical Models

Principal Investigator: Kenko Uchida

Prof. Takanori IDA Kyoto U.

Demand Response; Field Experiment

Policy Recommendation

Prof. Kenko UCHIDA Waseda U.

Demand Response; Laboratory Experiment

Economic Model, Market Mechanism

Prof. Toshiyuki OHTSUKA Kyoto U.

Physical Model, Market Model

Real-time Algorithm for NMPC

Prof. Toru NAMERIKAWA Keio U.

Physical Model, Market Model

Decentralized Optimization

Prof. Yasumasa FUJISAKI Osaka U.

Quality of Energy Service

Reliability, Physical Model