FRIENDS in the context of micro grid research

Background

COP3 Kyoto Protocol: 6% CO₂ Reduction from 1990

Energy Demand in Japan

- Industry sector
- Residential sector
- Business and Commercial sectors

Leveled off: progress in energy conservation
Still increasing: both in per house consumption and the number of households

Kiichiro Tsuji
Osaka University
Analysis on energy systems in urban area

Search for “optimal " systems:
environmentally compatible energy efficient infrastructure

JSPS research project: 1997-2001
Handai Frontier Research Center research project: 2002-2004
Integrated energy service system and multiple objective optimization

Target Area (e.g. 2km × 2km)

Energy Supply by CHP (DHC) Plant

Individual Energy Systems

Local Energy Center

Cogeneration System

Office Building

Hotel

Apartment

Office Building

Detached House

Electricity

City Gas

Kerosene

Integrated energy service system and multiple objective optimization
Energy system optimization for specific area:
Concepts of modeling

Facilities represented by floor space:
- Office buildings
- Hotels, Stores
- Restaurants
- Hospitals
- Detached Houses
- Apartments

Energy systems represented by discrete options

Area purchases:
electricity, city gas and kerosene

- Piping network (Simplified)
- Piping network (Detailed)

- Areas with district heating and cooling System
- Areas with individual energy systems
## Energy system options

### (a) Residential Houses

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNV</td>
<td>Air-conditioner + Stove + Gas boiler</td>
</tr>
<tr>
<td>SLR</td>
<td>CNV + Solar generation system + Solar-type water heater</td>
</tr>
<tr>
<td>ELE</td>
<td>Air-conditioner + Electric water heater + Electric cooking appliance</td>
</tr>
<tr>
<td>DHC</td>
<td>DHC(District Heating &amp; Cooling)</td>
</tr>
</tbody>
</table>

### (b) Business & Commercial Buildings

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARH</td>
<td>Absorption refrigerator and heating unit</td>
</tr>
<tr>
<td>ER</td>
<td>Electric turbo refrigerator + Boiler</td>
</tr>
<tr>
<td>GE1, GE2 FC1, FC2</td>
<td>Electric turbo refrigerator + Boiler + CGS(FC or GE) + Absorption refrigerator</td>
</tr>
<tr>
<td>HP</td>
<td>Heat pump system with heat accumulation equipment</td>
</tr>
<tr>
<td>DHC</td>
<td>DHC(District Heating &amp; Cooling)</td>
</tr>
</tbody>
</table>

### Graphs

- **Graph 1**: 
  - Electric demand
  - Commercial power
  - Operation of GE1 FC1

- **Graph 2**: 
  - Electric demand
  - GE(FC) output
  - Commercial power
  - Operation of GE2 FC2
DHC plant configuration and constraints

Energy flow constraints in DHC plant

\[
\begin{align*}
\eta_{gt} \cdot x_{1,s,t} + x_{6,s,t} - x_{9,s,t} &= E_{DHC,s,t} + x_{3,s,t} \\
\eta_{er} \cdot x_{3,s,t} + \eta_{ar(st)} \cdot x_{4,s,t} &= C_{DHC,s,t} \\
\eta_{hc} \cdot x_{5,s,t} &= H_{DHC,s,t} \\
\eta_{gt} \cdot x_{1,s,t} + \eta_{br} \cdot x_{2,s,t} &= x_{4,s,t} + x_{5,s,t} + x_{8,s,t} \\
x_{7,s,t} &= x_{1,s,t} + x_{2,s,t}
\end{align*}
\]
Multiple objective linear optimization model

Evaluation Indices:
- Cost
- Primary Energy Consumption
- CO₂ Emission

Variables:
- Share of energy system options
- Capacity and operational strategy for DHC co-generation plant

Reference Scenario

<table>
<thead>
<tr>
<th></th>
<th>Office</th>
<th>Hotel</th>
<th>Hospital</th>
<th>Retail Store</th>
<th>Restaurant</th>
<th>Detached House</th>
<th>Apartment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ARH(24.4%)</td>
<td>ER</td>
<td>ER</td>
<td>ER</td>
<td>ER</td>
<td>CNV</td>
<td>CNV</td>
</tr>
</tbody>
</table>
### Input data: Area for study

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Floor area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office</td>
<td>807,610</td>
</tr>
<tr>
<td>Hotel</td>
<td>58,349</td>
</tr>
<tr>
<td>Hospital</td>
<td>54,743</td>
</tr>
<tr>
<td>Retail store</td>
<td>281,219</td>
</tr>
<tr>
<td>Restaurant</td>
<td>53,780</td>
</tr>
<tr>
<td>Detached house</td>
<td>1,250.973</td>
</tr>
<tr>
<td>Apartment House</td>
<td>879,753</td>
</tr>
</tbody>
</table>
Input data: End-use energy demand for 12 representative days

Office

Space heating

Space cooling

Hotel

Winter

Summer

Hospital
Input data: End-use energy demand for 12 representative days

Retail store

Restaurant

Residential house
Tradeoff curves: Cost vs. CO₂ emission

Distributed generation will increase as CO₂ constraint get more severe
Tradeoff curves: Cost vs. Primary energy consumption

Distributed generation will increase as primary energy constraint get more severe
Needs for new electric energy delivery system

[1] Penetration of Distributed Generation

   Photovoltaic
   Wind
   Micro Cogeneration

   Reverse power problem
   Frequency fluctuation
   Voltage rise in distribution line
   Protection problem in distribution system

[2] • Deregulation of Electricity Market
   • Diversification of Customer Needs

   Unbundled power quality service
   uninterruptible power
   lower-price power
Quality of Power

Definitions of Events by IEEE Std.1159-1995

Voltage Stability
- Under-voltage & Over-voltage
- Voltage Sag
- Voltage Swell
- Phase Shift
- Flicker
- Frequency

Continuity of Supplying Power
- Momentary Interruption
- Temporary Interruption
- Sustained Interruption

Voltage Waveform
- Transient
- Three Phase Voltage unbalance
- Harmonic Voltage, Current
- Notch
Does every customer request very high quality in power supply? What if a customer can choose power of different quality with different levels of reliability?

- Power system configuration that allows a customer to choose.
- Can be realized by the use of power electronics.
By use of QCC (Quality Control Center)

[1] Several qualities of power are supplied to customers.

[2] Unbalance and harmonics current from loads are compensated.

[3] Power fluctuation from distributed generators (DG) and loads is compensated, and reverse power from DGs is absorbed.

(Flexible Reliable and Intelligent Electrical eNergy Delivery System)
Conventional Radial Distribution Network

- Feeder
- Bus
- Distribution Substation
- Load

Normal Open

Normal Close

Circuit Breaker
FRIENDS Network

Distribution Substation

- Power Interchange
  - QCC
  - Trans. Interchange

- Normally OPEN
- Flexibel reconfiguration using solid-state switches in QCC
- Multi-quality Power Supply to Customers
Example of QCC: *Power flow in normal operation*

- Compensation of unbalanced power
- Absorption of reverse power
**Power flows in emergency**

Sags are compensated for in Premium and High Quality.

**Thyristor OFF**

**Inverter Control OFF**

**UPS operation at Premium Power**
# Levels of Power Quality in 3phase4wire System

<table>
<thead>
<tr>
<th>Events</th>
<th>Normal</th>
<th>High</th>
<th>Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Sags</td>
<td>×</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Voltage Swells</td>
<td>×</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Phase shift</td>
<td>×</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Instantaneous Outage</td>
<td>×</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Short time outage</td>
<td>×</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Long time outage</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Unbalance in 3 phase</td>
<td>△</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>Flicker</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Unbalanced Current</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Harmonic Current</td>
<td>○</td>
<td>○</td>
<td>○</td>
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Example of QCC:
**Power Flows in Normal Operational Condition**

- **22[kV]:400[V]**
- **Distributed Source**
- **Premium Power** Normally ON
- **Hybrid Switch** Normally OFF
- **Absorption of Fluctuation**
- **Secondary Battery**
- **Fuel Cell**
- **Normal Power**
- **Load**
Power Flows in UPS Operation

Distributed Sources

Premium Power

Hybrid Switch OFF

Bi-directional Inverter

Stop control

DC Voltage Control

Load

Secondary Battery

Fuel Cell

G

22[kV]:400[V]

P
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<td>○</td>
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Concept of Power Exchange among QCCs

- DG: Distributed Generator
- ESS: Energy Storage System

First priority
- Premium Quality Power Load
- DG
- Normal Quality Power Load
- DG

If possible
- Premium Quality Power Load
- Normal Quality Power Load
- DG

Utility Grid

Power Exchange

Bi-directional Rectifier

Inverter

QCC1

QCC2

Shotage

Other QCCs

→ First priority  ← If possible
**QCC:** Quality Control Center  **CGS:** Cogeneration System  **DHC:** District Heating and Cooling

**ESS:** Energy Storage System  **HP:** Heat Pump  **SL:** Solar energy Utilization System

---  **Electric Power**  ---  **City Gas**  ---  **Thermal Energy**
Optimization of QCC Allocation

Minimization of Total Cost of Distribution Lines

\[ F(x_1, x_2, \ldots, x_n) = \left(\frac{1}{2}\right) \int C_i \left( \min_{v_i} \|x - x_i\|^2 \right) P(x) \, dx \]

\[ = \left(\frac{1}{2}\right) \sum_{i=1}^{n} \int_{v_i} C_i \|x - x_i\|^2 P(x) \, dx \]

where, \( C_i \): (cost of unit power transmission)/(capacity of QCC \( i \))
\( x \): location of a load point, \((x^1, x^2)\)
\( x_i \): location of QCC \( i \), \((x_i^1, x_i^2)\)
\( P(x) \): specific load at load point \( x \)
Optimization of Network

[Objective function]

Min. \( \alpha \left( \sum_{n=1}^{ND} (aX_n + bYN_n) + \sum_{m=1}^{BR} c_m YL_m \right) + \beta \sum_{t=1}^{T} Oloss^t \)

\( \text{Distributed generation cost} \quad \text{Transmission line cost} \quad \text{Transmission loss} \)

[Constraints]

(DG’s maximum capacity)

\( X_n \in \{x^1_n, x^2_n, \ldots, x^i_n, \ldots, x^L_n\} (n = 1, \ldots, ND) \)

(Expected power interruption cost)

\( \sum_{t=1}^{T} \sum_{r=1}^{FLT} \frac{1}{T} p_r BLCost^r_t \leq \varepsilon \)

(Line power flow capacity)

\( \overline{P_m^r} \leq P_m^r (m = 1, \ldots, BR) (r = 1, \ldots, FLT) (t = 1, \ldots, T) \)
Possible Image of FRIENDS in the Context of Micro Grid

- Prefixed QCC
- Location optimized QCC
- Utility substation
- Thermal network
- Distribution network
Concluding Remarks

1) Energy system optimization for specific area under the CO₂ reduction constraint results in introducing various distributed power generation

2) Power distribution network must be redesigned: New concepts are necessary

3) FRIENDS is one of the possible forms of micro grid
   Current status of research:
   - Various forms and circuits of QCC have been proposed
   - Some of the types of QCC have been constructed and tested in lab
   - Customized or Unbundled Power Quality Services can be realized
   - Power exchange between QCCs have been tested in lab

Thank you for your attention