Operational planning of an independent microgrid containing tidal power generators, SOFCs, and photovoltaics

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<td>書誌ID</td>
<td>102</td>
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<tr>
<td>発行年</td>
<td>2013-02</td>
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<tr>
<td>URL</td>
<td><a href="http://id.nii.ac.jp/1450/00007884/">http://id.nii.ac.jp/1450/00007884/</a></td>
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<tr>
<td>doi</td>
<td><a href="http://doi.org/10.1016/j.apenergy.2012.07.005">http://doi.org/10.1016/j.apenergy.2012.07.005</a></td>
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Operational Planning of an Independent Microgrid Containing Tidal Power Generators, SOFCs, and Photovoltaics

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Abstract

The development of local energy systems is important to curtailing global warming and improving public safety. Therefore, in this work, the basic performance of an independent
microgrid consisting of tidal power generators, photovoltaics, fuel cells, and heat pumps to locally produce energy for local consumption was analyzed. Fast tidal currents near inlets that join lakes to the sea were converted into electrical energy via a three-phase synchronized generator connected to Darius water turbines. On the basis of the results of an oceanographic survey, the production of electricity and the CO$_2$ emissions of each generator were calculated using balanced equations for electricity and heat. The calculations indicated that 33% of the CO$_2$ emissions were associated with the energy supplied through conventional methods during the summer season. Although the frequency and waveform of the electricity of the microgrid were high quality, improvement in the voltage regulation was still required.

1. Introduction

The examination of systems for locally producing energy for local consumption has accelerated in Japan because of the failure of the 1st nuclear power station of Fukushima in March, 2011. Distributed energy systems dominated by local energy sources have been examined [1-7]. Large-scale electrical power systems such as nuclear power plants require a long-distance distribution network to connect the power plant to the consumers. However, when electricity is supplied to an area of low population density far from a power plant, high costs associated with facilities maintenance increase the unit price of the electricity. Moreover, the introduction of a reliable electric power distribution network into areas of low population density is more economically difficult than in urban areas. If local energy systems are introduced into areas of low energy demand, the need for transmission networks, the distribution of exhaust heat, the unit price of the electricity, and the environmental impact of the energy production may all be reduced. Until now, generating power from fossil fuels or atomic energy cost less than generating power via green energy methods; in fact, local energy systems using green energy have not yet been developed. However, because of the recent concerns over nuclear power generation and the rising
demand for fossil fuels, the examination of independent power sources and the introduction of local energy systems have become necessary for energy security. For the distribution of power based on the local production and consumption of green energy, frequency and voltage changes in the power supply and the increased cost of the electricity must be considered. Distributing power from commercial electric power systems or older energy systems with grid connections has been studied [8-13]. This work considers the Lake Saroma green microgrid (SLMG) in the eastern area of Hokkaido as an example of an independent power source for local energy. Because the Lake Saroma area is typically cold and snowy, there is a large demand for heat during the winter. In addition, because there are no large-scale electric power plants in the suburbs, electricity is supplied over a long distance via transmission lines. Lake Saroma is surrounded by large land areas, a sea, lakes, and rivers; fast tidal currents are found in two of the lake inlets. This work investigates the fundamental effects of the SLMG’s tidal power generators, photovoltaics, fuel cells (solid oxide fuel cells, SOFCs), and heat pumps along with the independent microgrid designed to supply electricity to the area surrounding Lake Saroma using the aforementioned methods of power generation. Buildings in the area are heated by hot water from the exhaust of fuel cells and by electric heat pumps. Although there are other examples operational microgrids and tidal power generators [14-21], to the best of our knowledge, no reports describing a microgrid containing two or more power sources involving tidal power generation have yet been published. Furthermore, no other studies of the quality of electricity from independent power networks composed of tidal power generators, photovoltaics, and fuel cells are available, so this system is novel. Using numerical simulations, we establish the described system as a candidate for future local energy generation. This system will reduce the production of greenhouse gases and provide high-quality electricity (with respect to voltage, frequency, and waveform).

2. Outline of the Lake Saroma Green Microgrid
2.1 Characteristics of the Lake Saroma Area

Lake Saroma in Hokkaido is the third largest lake in Japan. The area is abundant in natural resources and is archaeologically important because of the Okhotsk and Ainu people that historically populated this area. Despite the area's desire for it, the introduction of green energy equipment has been difficult because of the pristine nature of the area. A map and the meteorological data of the Lake Saroma region are shown in Fig. 1. The first and second lake inlets are approximately 300 and 75 m wide, respectively. The tidal currents in these lake inlets are stable, and the flow velocity of these tidal currents is fast compared with the open sea. Therefore, as shown in Fig. 2, a tidal power generation system was installed in the seabed near these lake inlets, and a microgrid for supplying electric power and heat to the surrounding towns and harbor facilities has been planned. Because there is a cycle in the direction of the tidal current, the development of a compound power source using tidal power generators, photovoltaics (PVs), and solid oxide fuel cells (SOFCs) was examined. The microgrid with the described compound power source is referred to as the Lake Saroma green microgrid (SLMG) throughout this paper.

2.2 System Composition

As shown in Fig. 2, the operation of the SLMG for supplying the electricity to the towns (Toetoko and Sakaera) and harbor facilities around Lake Saroma was examined using computer analysis. Figure 3 illustrates the configuration of the SLMG. The system shown in Fig. 3 contains the following components: (a) tidal power generators installed near two lake inlets where Lake Saroma meets the open sea, (b) SOFCs, which use natural gas supplied by a pipeline, and (c) photovoltaics. The SLMG is an independent power supply network involving a local energy system without an external energy source (except for emergencies) to supply local fishing villages. A transmission line was constructed from Toetoko to Sakaera, and electricity from the PV and SOFC systems is supplied to the transmission network through an inverter and a harmonic filter.
The power transmission used the following parameters: 400 V (effective value), 50 Hz, and a three-phase alternating current. The overall length of the transmission line was 25 km. Eighty and twenty sets of the tidal power generation equipment (small Darius-type water wheels of 5 kW) were installed in the first and second lake inlets, respectively. The electricity from these tidal power generators was supplied to the transmission network.

2.3 Operational Method

The speed and direction of the tidal currents cycle at the two inlets of Lake Saroma. Therefore, tidal power generation at this location is less stable than other forms of green energy. During cycles when the power supplied from the tidal power generators and photovoltaics is insufficient to meet demand, power is supplemented by the SOFCs in the SLMG. Although partial load operation is typically undesirable because the SOFCs operate at high temperatures, improved operation has recently been reported [22]. The power added by three sets of SOFCs is determined according to the magnitude of the power load. The fuel consumption, \( w_{fuel,t} \), refers to consumption between the sampling time, \( t+1 \), and the time, \( t \). Based on the fuel consumption, \( w_{fuel,t} \), the CO\(_2\) emissions were calculated using the power generation efficiency, \( \eta \), of the SOFCs. CO\(_2\) emissions are calculated from the fuel consumption \( w_{fuel,t} \). The equation for \( w_{fuel,t} \) is as follows:

\[
w_{fuel,t} = \frac{P_{e,socf,t}}{\eta}
\]  

A maximum electric power point control was introduced into the photovoltaics, and a DC–DC converter, an inverter, and a harmonic filter were prepared in each photovoltaic cell and SOFC. However, control of the reactive power was required to transmit electricity with high efficiency from two or more power sources. Consequently, the voltages at the receiving end of each load were adjusted using a static compensator (STATCOM) to generate or absorb the reactive power. When the electricity from the tidal power generators and the photovoltaics exceeded the amount
3. **Energy Conversion of the Tidal Current**

3.1 Kinetic Energy of the Tidal Current

The speed of the tidal current of inflow mass \( m_{w,f} \) for 1 second to an area \( S \) is set to \( v_{w,f} \) at a sampling time \( t \); the kinetic energy, \( P_{w,f} \), is defined by the following equation:

\[
P_{w,f} = \frac{1}{2} \cdot m_{w,f} \cdot v_{w,f}^2
\]

in which \( m_{w,f} = \rho_w \cdot S \cdot v_{w,f} \) \( (2) \)

Extensive investigations of the ocean current and geographical features at the inlets of Lake Saroma have been conducted [23 and 24]. Figure 4 shows the locations at which the tidal current was measured in 2010. The water depth and flow velocity in the cross-section of the bay outside and the minimum cross-section in the first inlet of Lake Saroma are shown in Fig. 5 [23]. The position outside the inlet and the minimum cross-section in the first inlet of Lake Saroma are shown on the left side of Fig. 4. Figure 5 (a) shows the results of an ebbing tide that occurred on August 12, 2010, and Fig. 5 (b) shows the results of a flood tide that occurred on the same day. The ebbing tide flowed from Lake Saroma to the open sea (flowing north), and the flood tide flowed from the sea to Lake Saroma (flowing south). As shown in Fig. 5, the flow-velocity distribution of the tidal current differs in the direction of the flow. In addition, although the tidal current in the zone near the seabed was slow, the flow velocity increased significantly several meters away. In consideration of fishing boats, the tidal generator is installed at a depth of 3 m or less. Large quantities sea bottom sand accumulated in the first inlet of Lake Saroma because of the speed of
the tidal current. The size and position of the tidal power generation equipment were constrained by the water depth and the flow velocity of the tidal current. The size of the tidal power generation equipment should not interfere with shipping operations; therefore, the equipment should be placed in regions of fast tidal current.

Table 1 shows the maximum flow velocity and the direction of the tidal current at measurement positions P1 to P4 by the first and second lake inlets that are shown in Fig. 4. However, because the water was shallow at certain locations of maximum flow velocity, the values in Table 1 cannot be directly used in Eq. (2).

3.2 Speed of the Tidal Current and Position of the Power Generator

Figure 6 shows the flow velocity of the north–south component at a depth of 6 m at point P1 (Fig. 4). The results in Fig. 6 were obtained from August 5 to 19, 2010. The peak flow velocities accompanying the ebbing and flood tides occurred 4 to 5 times per day. In this experiment, a tidal power generator with a height of 1.9 m and a diameter of 1.0 m (a Darius water turbine) was used. Because a Darius water turbine does not depend on the direction of the tidal current, it can respond to changes in the tidal current from ebbing tides to flood tides. The turbine efficiency was set at 35%, the normal power was set to 5 kW, and 20 and 80 sets were installed in the first and second lake inlets, respectively. Figure 7 shows the position of the tidal power generation equipment in the first and second lake inlets. The position in the first lake inlet was determined from the flow velocity of the tidal current and the sea depth [24].

Figure 8 shows the current speed (blue curve) measured at position P1 (see Fig. 4 for this location) and the result of applying the proportionality coefficient $C_{lm}$ to the tide level difference between Lake Saroma and the Sea of Okhotsk (red curve). As shown in Fig. 8, the difference in the tide level and the characteristics of the tidal speed are in good agreement. Therefore, the tidal speed can be easily predicted from the difference in the lake and sea levels. Generally, the
Hydrographic and Oceanographic Department of the Japan Coast Guard offers detailed values for the differences in the lake and the sea levels at arbitrary times. Although this paper examines the SLMG using current speed measurements over 15 days in August, other arbitrary periods could be similarly investigated.

3.3 Production of Electricity via Tidal Power Generation

Figure 9 shows the output for 100 sets of the tidal power generation equipment. The flow velocity of the tidal current shown in Fig. 6 was calculated using Eq. 2: the results are shown in Fig. 9. The type, size, and turbine efficiency of the tidal power generation equipment are described in Section 3.2. Because the flow velocity of the tidal current dramatically influences the production of electricity, a large quantity of electricity was generated at the peak tidal current speed.

4. Method of Analysis

4.1 Electricity Supply and System Demand

(1) Power and heat balances

Equation (3) is the power-balance equation for a sampling time $t$ of the SLMG shown in Fig. 2. The left side of Eq. (3) is given in terms of electricity output, and the right side is in terms of the power consumption. No equipment designed to store electricity was installed in this proposed system. When the electricity is supplied to a transmission line from $N_{sofc}$ sets of fuel cells, $N_{tidal}$ sets of tidal power generators, and photovoltaics, the electricity will be consumed by the demand, $\Delta p_{e,need}$, and the power transmission loss, $\Delta p_{e,loss}$, as shown on right side of Eq. (3). As shown in Eq. (4), the electricity demand, $\Delta p_{e,need}$, is the sum of the mean power demands of Toetoko ($N_T$ houses), $\Delta p_{e,T}$, Sakaera ($N_S$ houses), $\Delta p_{e,S}$, and the electricity demand of the port facilities, $\Delta p_{e,facilities}$. The fuel cells were used when the power consumption
(\(\Delta p_{e,\text{need}t} + \Delta p_{e,\text{loss},t}\)) was larger than the output of the tidal power generators and the photovoltaics. In addition, when the electricity \((\sum_{i=1}^{N_{\text{tie}}} p_{e,\text{tie},i,t} + p_{e,\text{pv},t})\) generated by the green energy sources exceeded the demand \((\Delta p_{e,\text{need}t} + \Delta p_{e,\text{loss},t})\), the surplus power was supplied to a heat pump \((\Delta p_{e,\text{hp},t})\).

Equation (5) gives the heat balance equation. The terms on the left side are the output of the heat pump \((p_{\text{hp},t})\), the exhaust heat \((\sum_{j=1}^{N_{\text{sofc}}} p_{\text{sofc},j,t})\) of the SOFC, and the heat \((p_{\text{hst},t-1})\) of the heat storage tank described previously. The terms on the right side are the heat demand \((\Delta p_{h,\text{need}t})\) and the radiation loss \((\Delta p_{h,\text{loss},t})\). When the sum of the exhaust heat of the SOFC and the heat output of the heat storage tank was less than the sum of the heat demand and radiation loss, the electricity production of the SOFC was increased to increase the output of the heat pump. The COP (coefficient of performance) of the heat pump was set to 3.5. Because the output of the fuel cell is decided upon first, the amount of exhaust heat from the SOFC is predetermined. When the sum of the exhaust heat and the heat storage in a heat storage tank is greater than the heat demand, the surplus exhaust heat is stored in the heat storage tank. Therefore, the exhaust heat from the fuel cell can be supplied after shifting time.

\[
\sum_{i=1}^{N_{\text{tie}}} p_{e,\text{tie},i,t} + p_{e,\text{pv},t} + \sum_{j=1}^{N_{\text{sofc}}} p_{e,\text{sofc},j,t} = \Delta p_{e,\text{need}t} + \Delta p_{e,\text{hp},t} + \Delta p_{e,\text{loss},t} \tag{3}
\]

\[
\Delta p_{e,\text{need}t} = N_T \cdot \Delta \overline{p}_{e,T,t} + N_S \cdot \Delta \overline{p}_{e,S,t} + \Delta p_{e,\text{facilities},t} \tag{4}
\]

\[
P_{\text{hp},t} + \sum_{j=1}^{N_{\text{sofc}}} p_{\text{sofc},j,t} + p_{\text{hst},t-1} = \Delta p_{h,\text{need}t} + \Delta p_{h,\text{loss},t} \tag{5}
\]

(2) Electricity Demand

The populations of Toetoko and Sakaera are 561 and 292, respectively. The number of housing units in each town is 133 and 94, respectively. We investigated [25] the sum of the electricity and
heat demand in an average household and the electric power consumption of the harbor facilities (the sum of the two facilities was constant at 60 kW). On the basis of this research, the electricity demand of the SLMG shown in Fig. 10 was developed. The minimum power load, the average load, and the maximum load were 117 kW, 164.3 kW, and 240 kW, respectively. Figure 10 was produced from the actual measurement of the electricity load of a house. An electric light and a household appliance are contained in the power load and are shown in Fig. 10. Furthermore, a load consisting of a hot-water space heater, water heater, and a bathtub are included in the heat load. The load is not commonly used for cooling in the summer in Saroma residences. Figure 10 was produced from the actual measurement of the electricity load of a house. Therefore, because heating and air conditioning were not included in this electricity load, the electricity load of each day in Fig. 10 exhibited a similar form.

4.2 Solar Energy Power Generation System (PV)

The area of the PV installed in the SLMG was set at 650 m² with 18% power generation efficiency and a maximum output of 100 kW. The maximum PV power output was 60% of the mean SLMG power load. Figure 11 shows the current–voltage characteristics of the solar cell introduced into the system. By applying maximum power point control, the maximum dissipation in Fig. 11 was generated from the PV.

Figure 12 shows a control block diagram of the solar power generation system with a maximum output of 100 kW. MATLAB/Simulink R2011b software was used to analyze the electric power system in this study. The specifications of the equipment in Fig. 12 set the values and were based on the master plan of the SLMG. Because the output of a solar cell changes with the amount of insolation, a snubber circuit using a resistor and a capacitor was set just after the solar cell. The snubber circuit prevented damage to the DC–DC boost converter and the inverter that could be caused by a rapid voltage rise. The DC–DC boost converter converts the voltage of the solar cell
to the output voltage (an effective value of 400 V). The frequency and voltage were controlled by a DC–AC converter (inverter) and a transformer to a rated power output; a high harmonic wave was prevented by the use of a harmonic filter. The power specification of the bus SC_PV is shown in Fig. 12 (a), with an effective value of 400 V and a 50-Hz three-phase alternating current. Figure 12 (b) is a block diagram of the solar cell included in the PV panel in Fig. 12 (a). The current–voltage characteristics shown in Fig. 11 for the actual photovoltaic cell are used.

4.3 Fuel Cell System (SOFC)

Figure 13 shows a block diagram of the SOFC system. The rated power of each SOFC was 100 kW, and they were controlled by the power demand of the SLMG. Figure 13 gives an outline of the SOFC specifications, and Fig. 14 shows the current–voltage characteristics of the SOFC introduced into the proposed system. The specifications of the equipment in Fig. 13 and the characteristics of the SOFC in Fig. 14 determined the values based on the master plan of the SLMG. Figure 14 models the output characteristics of a measured SOFC. Because the operating point of the current–voltage characteristics changed with the load, a step-down or a higher pressure was applied to the output voltage of the SOFC by buck and boost converters. Moreover, the frequency and voltage were controlled at the rated value by an inverter and a transformer, and a higher harmonic wave was excluded using a harmonic filter.

Details of each component of the model are described in the literature [26].

4.4 Tidal Power Generation System

Figure 15 shows a block diagram of the tidal power generation equipment. For one set, the rated power was 5 kW, and it contained 80 and 20 sets of the tidal power generation equipment in the first and second lake inlets, respectively. The specifications of the STATCOMs, power lines, etc. were based on the master plan of the SLMG, and the loads were set at the maximum forecast
values. One set of the tidal power generation equipment comprising 400 and 100 kW components was installed in each of the lake inlets in the block diagram. Although a three-phase synchronized generator was used for tidal power generation, the tidal power generator was simulated using an input value of \( P_m \) corresponding to a change in the tidal current velocity for each sampling time as shown in Fig. 15 (a). To suppress a rapid change in voltage immediately after the output, a snubber circuit using a resistor and a capacitor was attached to the tidal power generation equipment.

4.5 Composition of the Microgrid

Figure 15 (b) shows a block diagram of the entire electrical power system of the SLMG. The electrical power and heat were supplied to Toetoko and Sakaeura by the SLMG, and Fig. 10 shows the power load of the entire SLMG. Taking into consideration the number of residents in each town and the location of the harbor facilities shown in Fig. 15 (b), the power load shown in Fig. 10 was distributed from Load 1 to Load 3. The power specifications of the busses SC_pv, SC_fc01 to SC_fc03, SC_tp01 and SC_tp02 in each power generator (Fig. 15 (b)) had an effective value of 400 V and a three-phase alternating current of 50 Hz. In addition, flexible alternating current transmission systems (STATCOM1 and STATCOM2) were installed at two points along the middle of the SLMG transmission line. Figure 15 (c) is a block diagram of the STATCOM. STATCOM1 and STATCOM2 adjusted the voltage of the transmission system busses (SC_st01 and SC_st02) by generating or absorbing reactive power. Each power source can be turned off in parallel with three-phase breakers using CB01 to CB06.

4.6 Control of the Generating Equipment

Figure 16 shows the control flow of the generating equipment. Any shortage or overage of the electric power from the SLMG is found by measuring the frequency of the electric power grid.
When the frequency exceeds the rated value, the production of electricity must be reduced. In contrast, when the frequency of the electric power grid is less than the rated value, the production of electricity must be increased. Therefore, the number of operating PVs, the current power generators, and the fuel cells are controlled according to the value of the frequency. The control method for the power source operation is described in Fig. 16.

5. Analysis, Results, and Discussion

5.1 Production of Electricity

Figure 17 shows the analysis outputs of the electricity production from the tidal power generators, the photovoltaics, and the fuel cells from August 5 to 19, 2010. The production of electricity for the tidal power generators is shown in Fig. 9, and the production of electricity from the photovoltaics was obtained from the amount of global solar radiation near the lake during the days of operation [27]. The fuel cell was activated when the power consumption of the SLMG exceeded the electric power generated by the tidal power generators and the photovoltaics as described in Section 4.1. Figure 18 shows the daily rate of electricity production for each type of power generator as a percentage of the integral power consumption. Although the capacity of the PVs was equivalent to 60% of the average load of the SLMG, the actual daily power production by the PVs was smaller than that for the other systems because cloud cover caused a lack of sunlight in the Saroma district during the testing period. The total introductory capacity (500 kW) of the tidal power generation equipment far exceeded the maximum (240 kW) power load of the SLMG; however, the integral power consumption for one day was approximately half of the maximum SOFC power generation because the fast tidal current only lasts for a short time each day. As shown in the example of the PV and tidal power generation described earlier, the initial power-generating capacity of the green-energy equipment cannot be simply predicted from the level of the electricity demand.
Figure 19 shows the amount of heat stored by converting electric power into heat when the green-energy (PV and tidal) electric power generation exceeds the electric power load. The proposed system does not include electricity storage facilities for use at times when large amounts of green energy are generated. Therefore, surplus electric power is converted into heat. To reduce the installed capacity of the system we would need to consider the introduction of electricity storage equipment. However, the introduction of electricity storage equipment will increase the unit price of electric power due to an increase in facilities cost.

5.2 Reduction in CO₂ Emissions

Energy in the Saroma district is often assessed using a hot water supply, heating via a kerosene boiler or stove, and purchasing electricity from commercial electric power sources. Figure 20 shows an analysis of the CO₂ discharge rate by the SLMG (the proposed method), the SOFC and heat pump system, and by conventional methods. The greenhouse gas emission factors for the commercial electric power and kerosene for the hot water supply were set to 0.517 kg CO₂/kWh and 0.244 kg CO₂/kWh, respectively [28 and 29]. The CO₂ emissions of the SLMG system were 33% that of the conventional method. Fig. 20 shows the results from August (midsummer); however, the heating demand will increase approximately 20 fold (heating–value ratio) during the winter (December to March). The introduction of the SLMG should be advantageous in the reducing the CO₂ emissions. The annual effects of the SLMG are investigated in detail below on the basis of the previously described investigation. Moreover, a detailed investigation into the quality of the electric power in the power network, the capacity of the combined equipment and CO₂ emissions is required. Although the power quality in the power network will be stabilized if the capacity of SOFC is increased, the amount of CO₂ emission will be determined by the operation of large-capacity SOFC. On the other hand, although CO₂ emissions fall with the increase in the capacity of the PV and tidal power generation, the problem of power quality is
more prominent. Careful consideration of these factors is needed when investigating the
maximum amount of green energy which can be linked to the microgrid.

5.3 Electricity Quality

Figure 21 shows the analysis output with various variables of the STATCOM of the voltage for
the three-phase alternating current (left side) and the currents (right side) of Load 1 to Load 3.
Figures 21 and 22 show the analysis of the SLMG maximum electric power load for August. As
variables ofSTATCOM, the magnetization resistance and inductance of the transformer are
considered. For the magnetization resistance R1 and inductance L1, the pu values are based on
the transformer rated power and on the nominal voltage of winding 1. The pu values for R2 and
L2 are based on the nominal voltage of winding 2. Figure 21 shows the analysis results for three
conditions of the STATCOM, and Figure 22 shows the typical characteristics of the analysis
results of 20 or more conditions of the STATCOM. The acceptable variation in voltage was within
±10%, and the zones are shown using broken lines on the left side of Fig. 21 (a) to (c). The peak
voltages of Loads 1 to 3 were within the acceptable range when the set variables of the STATCOM
were reasonable. The frequency and waveform were of high quality for all loads. The peak voltage
of Load 3 required improvement by adjusting the STATCOM1 or STATCOM2 parameters. Figure
22 shows the analysis results of the effective and reactive power of Load 1 to Load 3. When the
setup of the variable values of the STATCOM was appropriate, the convergence errors of Load 1
and Load 2 were less than 1%. The voltage of Load 3 (Fig. 21 (c)) and the convergence
characteristics of Load 3 (Fig. 22 (c)) required improvement as previously described. To
accomplish this improvement, the control method used to regulate the voltage of the transmission
line for the effective power and reactive power of the loads must be enhanced.

5.4 Equipment cost and fuel cost
Figures 23 (a) and (b) show the results of the analysis of the equipment cost and the fuel cost of the SOFC for 15 days of August. Here, 1 US$ is equivalent to 81 JPY (April 2012). The unit price of equipment and fuel in Table 2 is set to the product price in 2012 in Japan. The number of tidal power generators installed influences facilities cost gradually on the scale of the axis of Fig. 23 (a). In contrast, because the cost of a PV power generation unit is high, changes in the area of PVs strongly influence the facilities cost. However, since optimization of each installed capacity will be investigated after this, reduction of equipment cost and fuel cost is expected. The expected life of SOFC and PV is 10 to 15 years. However the expected life of the tidal power generators is 3 to 5 years. Moreover, annual maintenance requires for tidal power generators. Detailed cost of the life cycle of the system will be clarified by examination in the future.

6. Conclusions

Increasing interest in the local production of energy for local consumption led to a study of the possibility for a Lake Saroma green microgrid (SLMG) constructed from 100 sets of tidal power generators, photovoltaics, three sets of fuel cells (SOFCs), and a heat pump. A fast tidal current was observed at two inlets around Lake Saroma. In addition, the CO₂ reduction effects and the electric power quality of an SLMG centered on tidal power generators were investigated. The subjects of this study were as follows:

(1) The production of electricity from tidal power using turbine efficiency assuming Darius water turbines was investigated on the basis of the results of an oceanographic survey of the first and second inlets of Lake Saroma.

(2) The CO₂ emissions associated with the SLMG were 33% that of the conventional methods (commercial electric power and kerosene boilers). Because the heating demand in the winter causes an approximately 20-fold increase (heating–value ratio) in the demand for electricity
(December to March), the introduction of an SLMG is advantageous for reducing CO$_2$ emissions throughout the year.

(3) The frequency and waveform of the transmission line were of high quality. However, problem of voltage adjustment and the convergence characteristic in a part of loads occurred. Therefore, the voltage regulation of the SLMG requires improvement by optimization of parameters of STATCOM.

(4) Moreover, this research needs to investigate the relation between the system-wide CO$_2$ emissions, the cost of the facilities, and the electric power quality in more detail.

The optimization of the installed capacity of the SOFC, PV, and tidal power generators is currently under investigation. Moreover, we are investigating the relationship between the operating cost of the system and its installed capacity. An official announcement regarding these results is forthcoming.

**Acknowledgments**

The authors wish to thank the TEPCO Memorial Foundation for their partial support of this research.

**Nomenclature**

\[ C_{lm} \quad : \quad \text{Proportionality coefficient} \]

\[ m \quad : \quad \text{Mass [kg]} \]

\[ N \quad : \quad \text{Number} \]

\[ P_w \quad : \quad \text{Kinetic energy [N]} \]

\[ P_e \quad : \quad \text{Electric power [kW]} \]
\( p_h \) : Heat \([\text{KW}]\)

\( \Delta p_e \) : Consumption of electric power \([\text{KW}]\)

\( \Delta p_{e,S} \) : Mean consumption of electric power in Sakaewara \([\text{KW}]\)

\( \Delta p_{e,T} \) : Mean consumption of electric power in Toetoko \([\text{KW}]\)

\( S \) : Cross-section of the flow pass

\( t \) : Sampling time \([\text{Hour}]\)

\( v \) : Flow velocity \([\text{m/s}]\)

\( w \) : The amount of fuel consumption \([\text{KW}]\)

Greek characters

\( \rho_w \) : Density of seawater \([\text{kg/m}^3]\)

\( \eta \) : Efficiency

Subscript

\( \text{facilities} \) : Port facilities

\( \text{fuel} \) : Fuel

\( hst \) : Heat storage tank

\( hp \) : Heat pump

\( \text{loss} \) : Loss

\( \text{needs} \) : Demands

\( \text{pv} \) : Photovoltaics
\[ S \quad : \quad \text{Sakaeura} \]

\[ \text{sofc} \quad : \quad \text{SOFC} \]

\[ T \quad : \quad \text{Toetolo} \]

\[ \text{tidal} \quad : \quad \text{Tidal} \]

\[ w \quad : \quad \text{Tidal current} \]

References


<table>
<thead>
<tr>
<th>Location</th>
<th>Hokkaido, Japan</th>
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<tbody>
<tr>
<td>Area</td>
<td>151.82km²</td>
</tr>
<tr>
<td>Boundary length</td>
<td>87 km</td>
</tr>
<tr>
<td>Maximum water depth</td>
<td>19.6 m</td>
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<tr>
<td>Mean water depth</td>
<td>8.7 m</td>
</tr>
<tr>
<td>Storage capacity</td>
<td>1.3 km³</td>
</tr>
<tr>
<td>Origin</td>
<td>Inland sea-lake</td>
</tr>
<tr>
<td>Water</td>
<td>Brackish water</td>
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<tr>
<td>Type of lake and marsh</td>
<td>Eutrophic lake</td>
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<tr>
<td>Transparency</td>
<td>9.4 m</td>
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Fig. 1 Lake Saroma

Outside temperature and monthly sunshine of Okhotsk

![Graph of Outside temperature and monthly sunshine of Okhotsk]
Fig. 2 Lake Saroma green microgrid
Photovoltaics
Power grid 400V, 50Hz
DC power
Fig. 3 The proposed system
Heat grid (Hot water supply)
Power conditioner (1)
Power conditioner (2)
P1
P2
P4
Outside of the inlet
Minimum cross-section
(a) The first lake inlet
(b) The second lake inlet
Fig. 4 Observation points
Fig. 5  Conditions of cross section flow (August 12, 2010)
Fig. 6 Tidal current of the north-south component (August, 2010)
Fig. 7 The area surrounding Lake Saroma and the installation plan for the tidal power generators

Fig. 8 Relation between measurements of tidal speed, and the difference of the Lake Saroma and Sea of Okhotsk (Measurement position of P1 in Fig. 4)
Fig. 9 Total production of electricity for the Lake Saroma tidal power generators (50 sets, August, 2010)

Fig. 10 Power demand on the Lake Saroma green microgrid (August, 2010)
Fig. 11  Output characteristics of a 100 kW PV cell

(a) 100-kW-PV power generator

(b) PV panel

Fig. 12 PV system
100kVA Fuel Cell System No. 1

Number of cells 300
Nominal operating point 167 A, 600 V
Maximum operating point 257 A, 548 V
Nerst voltage of one cell 1.0335 V
Nominal stack efficiency 65 %
Operating temperature 1250 K
Nominal Air flow rate 0.1 m3/s
Nominal supply pressure, Fuel 0.2 MPa, Air 0.15 MPa
Nominal utilization Hydrogen 40.7%, Oxygen 43.0%

Fig. 13 SOFC system
Fig. 14  Output characteristics of a 100 kW SOFC

(a) Stack voltage vs current

(b) Stack power vs current

Fig. 14  Output characteristics of a 100 kW SOFC
Tidal power generator 80 sets

- Mechanical power supplied to the machine
- Mechanical torque
- Control blocks of tidal power generators and the entire electric power system

Tidal power generator 20 sets

- Mechanical torque
- Control blocks of tidal power generators and the entire electric power system

(a) 80 sets and 20 sets tidal power generators

(b) Whole electric-power system of the Lake Saroma green microgrid

<table>
<thead>
<tr>
<th>STATCOM1</th>
<th>STATCOM2</th>
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<tbody>
<tr>
<td>Vac. Regulator Gains: $K_p=0.55$, $K_i=2500$</td>
<td>Vac. Regulator Gains: $K_p=0.55$, $K_i=2500$</td>
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<tr>
<td>Vdc Regulator Gains: $K_p=0.001$, $K_i=0.15$</td>
<td>Vdc Regulator Gains: $K_p=0.001$, $K_i=0.15$</td>
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<tr>
<td>Current Regulators Gain: $K_p=0.8$, $K_i=200$, $K_d=0$</td>
<td>Current Regulators Gain: $K_p=0.8$, $K_i=200$, $K_d=0$</td>
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(c) STATCOM

- Universal bridge 1
- Universal bridge 2

- Nominal frequency: 50 Hz
- Winding 1 parameters: 400 Vrms, R1=0.06 pu, L1=0.18 pu
- Winding 2 parameters: 566 Vrms, R2=0.005 pu, L2=0.15 pu
- Magnetization resistance and inductance: $R_m=200$ pu, $L_m=200$ pu

- Nominal frequency: 50 Hz
- Winding 1 parameters: 400 Vrms, R1=0.245 pu, L1=0.725 pu
- Winding 2 parameters: 566 Vrms, R2=0.025 pu, L2=0.65 pu
- Magnetization resistance and inductance: $R_m=200$ pu, $L_m=200$ pu

Fig. 15 Control blocks of tidal power generators and the entire electric power system
Power output of the PVs with maximum power point tracking control

Power output of the tidal power generators

Input of the measurements of frequency

Frequency of the power grid

Yes

High

Low

High

Low

Yes

High

Low

High

Low

Start up some tidal power generators

Start up some PV power generators

Start up SOFC system

Fig. 16 Control flow of the generating equipment
Fig. 17 Electric power output of each generator (August, 2010)

Fig. 18 Rate of production of electricity (August, 2010)
Fig. 19 Surplus power of green energy (August, 2010)

Fig. 20 CO₂ emissions (August, 2010)
Fig. 21 Analysis results of voltage and current of the proposed system
Fig. 22 Analysis of the power of the proposed system
Fig. 23  Analysis results of equipment cost and fuel cost of the SLMG
Table 1  The maximum flow velocity at every measurement point

<table>
<thead>
<tr>
<th>Location</th>
<th>Direction of tide</th>
<th>Time of measurement</th>
<th>Depth of sea</th>
<th>Direction</th>
<th>Velocity</th>
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<tr>
<td>P1</td>
<td>Ebbing tide</td>
<td>2010.8.12  8:50</td>
<td>1.0 m</td>
<td>N</td>
<td>2.2 m/s</td>
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<td></td>
<td>Flood tide</td>
<td>2010.8.11  1:30</td>
<td>3.0 m</td>
<td>SSE</td>
<td>1.4 m/s</td>
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<td>P2</td>
<td>Ebbing tide</td>
<td>2010.8.10  6:30</td>
<td>1.5 m</td>
<td>NE</td>
<td>2.1 m/s</td>
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<tr>
<td></td>
<td>Flood tide</td>
<td>2010.8.11  1:10</td>
<td>1.0 m</td>
<td>S</td>
<td>0.8 m/s</td>
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<td>P3</td>
<td>Ebbing tide</td>
<td>2010.8.9    6:30</td>
<td>1.5 m</td>
<td>NNE</td>
<td>2.0 m/s</td>
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<td></td>
<td>Flood tide</td>
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<td>4.5 m</td>
<td>SSW</td>
<td>2.2 m/s</td>
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<td>P4</td>
<td>Ebbing tide</td>
<td>2010.8.10  7:30</td>
<td>2.0 m</td>
<td>NNE</td>
<td>2.6 m/s</td>
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Table 2  Unit price for set-up

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<th>Equipment</th>
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<tr>
<td>SOFC</td>
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<td>Photovoltaic</td>
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<td>Natural gas</td>
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Japanese yen (1 USD=81 JPY)