Optimal Energy Management System for Isolated Micro Grids

Yoshihisa ISHIGAKI*, Yoshitaka KIMURA, Ikumi MATSUSUE, Hidekazu MIYOSHI and Kentarou YAMAGISHI

We have developed an energy management system (EMS), which controls power generation and consumption optimally based on the mixed integer linear programming method. The EMS has now been under long term and verification using the isolated micro grid in our Osaka Works, comprising renewable energy sources, a secondary battery and loads. The system aims to control unstable renewable energy, monitor the battery's state of charge (SOC), and maintain the automatic operation. The system has successfully achieve the goals and have operated for over one year without any significant failure.

Keywords: micro grid, supply-demand control, renewable energy, mixed-integer linear programming method

1. Introduction

Facing the recent growing concern about the environment and electric power crisis triggered by the Great East Japan Earthquake, efficient use of energy has become an important issue. A smart grid that is a next-generation electric power network is expected to be one of the solutions and to form an enormous market. Aiming to enter this new smart grid market, Sumitomo Electric Industries, Ltd. established a special R&D department in January 2010. This department has been actively developing equipment and systems for a smart grid.

A smart grid controls the flow of electric power on both the supply and demand sides to ensure efficient use of energy. In particular, a small-scale electric power network comprising dispersed power sources and electrical loads is called a micro grid system. In June 2011, Sumitomo Electric built an isolated micro grid system[(1),(2)] in its Osaka Works. Separated from the commercial transmission grid of an electric power company, this system uses photovoltaic generators and a wind turbine generator to produce electricity, and a redox flow (RF) battery to store the electricity produced by these generators.

Since this micro grid system is isolated and comprises generators that use only renewable energy, the electric power produced by these generators fluctuates sharply, making it difficult for the system to supply electric power with stable quality. This system's electric power generation also depends on weather conditions, meaning that this system cannot always generate electric power in response to demand. In other words, this system faces two problems: (1) stabilizing the quality of electric power, and (2) supplying electric power in response to demand. To solve these problems, we developed an energy management system (EMS). This paper describes and discusses the verification results of the EMS.

2. Construction of an Isolated Micro Grid System

The micro grid system developed by Sumitomo Electric is shown schematically in **Fig. 1**. This system is isolated from a commercial transmission grid, and comprises a dispersed power source in which a 4 kW commercially available polycrystalline silicon photovoltaic unit (SiPV), a 2 kW commercially available copper indium gallium (di)selenide compound photovoltaic unit (CIGSPV), a 1 kW in-house developed concentrator photovoltaic (CPV)[(3),(4)], and a 1 kW wind turbine are linked together by a total 1-km-long DC bus via DC/DC converters.

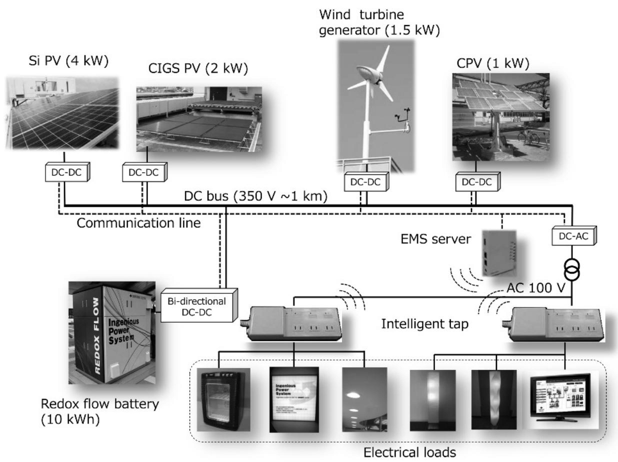


Fig. 1. Isolated micro grid system

At nearly the midpoint of the bus, an RF battery[(5)] is connected through a bidirectional DC/DC converter as an electrical storage device. The RF battery has a maximum charge/discharge capacity of 4 kW and a storage capacity of 10 kWh. The voltage of DC power generated by the above generators is directly boosted to 350 V by the DC/DC converter, carried by the DC bus to the RF battery, and stored in this battery. Otherwise, the DC power is converted to AC power by an inverter having a maximum output of 4 kW and located at one end of the DC bus, and supplied to various electrical loads via a smart power distribution panel and the intelligent tap. When the electric power produced by the generators is less than the demand of the electrical loads, the electric power that has been stored in the RF battery is discharged and supplied to the loads. Six electrical loads with a total demand of 750 W have been connected to this micro grid system. The construction of the micro grid system is summarized in **Table 1**.

Table 1. Construction of isolated micro grid system

DC bus (voltage, length)			350 V, 1 km
Storage of electricity	Redox flow battery (max. output, capacity)		4kW,10kWh
Power generation	Photovoltaic power	SiPV	4 kW
		CIGSPV	2 kW
		CPV	1 kW
	Wind turbine generator		1.5 kW
Consumption	Inverter (max. output)		4 kW
	Electrical load	Television	150 W
		Floor lighting 1	10 W
		Floor lighting 2	100 W
		Down lighting	180 W
		Panel lighting	250 W
		Wine cooler	60 W

The DC/DC converter connected to each of the generators and RF battery, the inverter, and the intelligent tap, which is connected to electrical loads, are connected to the EMS server through wired/wireless networks. Thus the EMS server collects information on the generation, charge/discharge, and consumption of electric power and remotely controls the operation of the generators and electrical loads. The measurement data on the generation, charge/discharge, and consumption of electric power are used not only for optimal management of the battery's state of charge (SOC), which is the main subject of discussion in this paper, but also for displaying the data on a real-time basis as well as trends of power generation and consumption of electric power.

3. Energy Management System

3-1 General description

Focusing attention on the fact that only the RF battery can control the balance between the supply and demand of electric power in this micro grid system, both sharp fluctuation of available renewable energy and excess or deficiency in demand for generated electric power must be compensated by charging or discharging the battery. It is a matter of course that, to maintain the RF battery to be chargeable or dischargeable, the SOC of the Battery must not be full or empty. To avoid the SOC being full or empty, consumption and generation of electric power must be managed appropriately.

In order to meet such requirements, we have developed an EMS as indicated in **Fig. 2**. The EMS consists of two major function blocks, a DC bus voltage stabilization control block and a SOC optimal management block. The former unit achieves a balance between the supply and demand of electric power under a condition in which the SOC is not full or empty, while the latter unit restrains the generation and consumption of electric power based on the power generation forecast and demand pattern, thereby avoiding the SOC being full or empty.

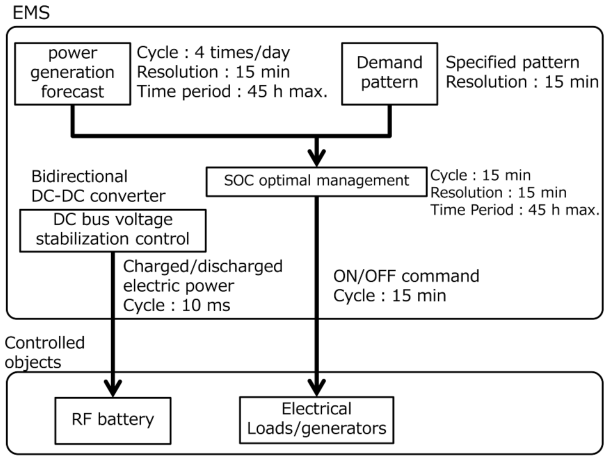


Fig. 2. Block diagram of EMS

In SOC optimal management block, the optimal operation plan for a maximum of 45 hours at a resolution of 15 minutes is calculated at 15-minute intervals so as to cope with such disturbances as model error and power generation forecast error. When determining the time period of the plan, we took into account the fact that this micro grid system's electric power generation depends largely on photovoltaic generators, therefore the power consumption plan for the day should be established after predicting the weather for at least the next day.

3-2 DC bus voltage stabilization control

In this micro grid system, electric power is supplied from the power generators to the DC bus and are withdrawn from the bus by the electrical loads. If the supply of electric charges exceeds their demand, the bus voltage will increase and vice versa. To maintain a balance between the supply and demand of electric power, the bidirectional DC/DC converter connected to the battery monitors the bus voltage at all times. If the bus voltage exceeds a preset level, the converter is controlled to charge the battery. In contrast, if the bus voltage drops below the preset level, the converter is controlled to discharge the battery. In this manner, the DC bus voltage is controlled to a constant value. This control system maintains a balance between the supply and demand of electric power by performing the above feedback control at a high-speed cycle of 10 ms. This paper defines this control scheme as "DC bus voltage stabilization control," the details of which have been reported in the reference(7). Meanwhile, an RF battery has a high response characteristic and a long charge/discharge cycle life independent of the depth of charge/discharge. An RF battery with these features is suitable for DC bus voltage stabilization control(5).

3-3 Power generation forecast

The photovoltaic power generation and wind power generation to be used for optimal management of the SOC are forecasted four times a day every 15 minutes for a maximum of 45 hours in advance(6). The forecast details are shown in **Table 2**.

Although the demand for electric power is one of the objects to be forecasted in general case, the demand here was excluded from the objects. Instead, the demand pattern was set arbitrarily in this verification.

Table 2. Power generation forecast

Forecast time	Forecast period
6:00	For 27 hours (till 9:00 the next day) in advance
9:00	For 27 hours (till 12:00 the next day) in advance
12:00	For 27 hours (till 15:00 the next day) in advance
15:00	For 45 hours (till 9:00 the day after next) in advance

3-4 Optimal SOC management

The objects to be controlled by optimal SOC management are ON/OFF of the socket for each electrical load (household electrical appliance) connected to the intelligent tap, start/stop of the boosting converter connected to each generator, and start/stop of the bidirectional converter connected to the RF battery. The electrical loads are controlled to avoid the SOC being full or empty, while the generators are controlled to avoid fully charging the battery. Start/stop of the battery is controlled to reduce power consumption by auxiliary electrical devices in the event all power generators and electrical loads are switched off.

The principal objective of controlling the SOC is to avoid the SOC being full or empty. This system controls the generation and consumption of electric power as a means of controlling the SOC of the battery. However, restraining power generation means wasting intrinsically useful energy and is contrary to our intention of using energy effectively. Restraining the consumption of electric power is also undesirable because the system cannot sufficiently supply electric power that consumers need. Although restricting the generation and consumption of electric power is unavoidable to control the SOC, it is crucial to minimize the degree of the restraint.

Optimal SOC management defines "the degree of dissatisfaction with restraint" that should be determined on the basis of the priority of a preset load and generator. When it is unavoidable to restrict the generation and consumption of electric power, the system is operated so that the degree of dissatisfaction decreases to a minimum.

3-5 Constraint of the SOC

Penalties for the SOC are set as shown in **Fig. 3**. The SOC is limited to "more than 4% but less than 96%" at any planned time (t) in order to avoid the SOC being full or empty. In addition, after considering that forecast errors, disturbances, and other factors would cause a difference between the planned and actual values, penalties were established. The penalties increase as the SOC decreases from 8% to 4% (or increases from 92% to 96%), as shown in **Fig. 3 (a)**. Further, for the last 15 minutes within the planned time period (the last time planned), a low degree of penalty was set for the SOC less than a preset value, as shown in **Fig. 3 (b)**. The purpose was to prepare for unanticipated situations in the future beyond a finite foreseeable time period.

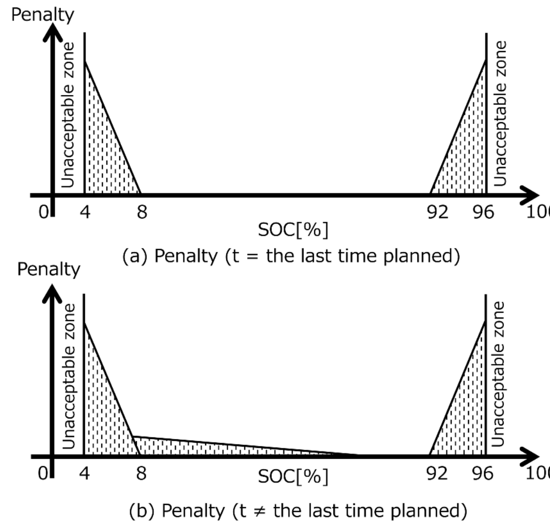


Fig. 3. Setting constraint on the SOC

3-6 Demand pattern and degree of dissatisfaction with restraint

A demand pattern of the electrical loads is shown in **Fig. 4**. All the installed electrical loads are turned on during the day and turned off during the night. Although this pattern was set arbitrarily for an experiment, the shape of the pattern does not impose any problem since the gist of the verification is to develop a system that can reduce the degree of dissatisfaction to a minimum no matter how the demand pattern changes.

The degree of dissatisfaction with restraint was set to be minimized when the above demand pattern is satisfied and the degree would increase as the tightness of restraint increases. The degree of dissatisfaction with restraint on a higher-priority electrical load was set to be higher than that on a lower-priority electrical load.

Here, the conditions specific to this micro grid system

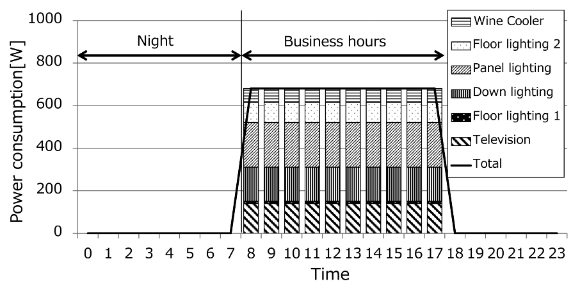


Fig. 4. Demand pattern

are taken into account. Since this system was constructed to verify the performance of the system and also to demonstrate our technological competence, many people visit irregularly to see this system.

Visitors' schedule is preliminarily input into the system. When the visitors see the system, a guide needs to turn on a specific electrical load to explain the system operation. **Table 3** shows the degree of dissatisfaction (penalty) that has been set for ordinary days and on days receiving visitors.

Table 3. Setting the degree of dissatisfaction with restraint on electrical load

	Degree of dissatisfaction (penalty)	
	Ordinary times	When receiving visitors
Television	6	Necessary to turn on
Floor lighting 1	5	Necessary to turn on
Floor lighting 2	2	2
Down lighting	4	Necessary to turn on
Panel lighting	3	Necessary to turn on
Wine cooler	1	1

3-7 Degree of dissatisfaction with restraint on power generation

Since it is also preferable not to restrain power generation, the degree of dissatisfaction was set to the minimum when the generators are operated without any restraint, and the degree would increase as the degree of restraint increases. Among the power generators, restraining the operation of a higher-priority generator has a higher degree of dissatisfaction than the operation of a lower-priority generator. **Table 4** shows the degree of dissatisfaction with restraint (penalty) on power generation.

Table 4. Setting the degree of dissatisfaction with restraint on generator

		Degree of dissatisfaction (penalty)
Photovoltaic	SiPV	3
	CIGSPV	2
	CPV	4
Wind turbine		1

3-8 Other condition settings

The other conditions were set as follows:

(1) The RF battery should be operated without fail when any of the generators or electrical loads is operated.

(2) All the generators, electrical loads, and battery should be stopped on Saturdays, Sundays, and holidays.

3-9 Formulation

For processing the system as an optimization problem, all the above conditions are formulated as follows:

[Objective function]

Minimize Σ penalties

[Constraints]

(1) Continuity of the SOC along the time axis
(2) Upper/lower limits of the SOC
(3) Penalty for the SOC zone near the upper/lower limits
(4) Penalty for the SOC at the final time planned
(5) Constraint of the charge/discharge capacity of battery
(6) Constraint of the demand/supply balance of electric power
(7) Setting the degree of dissatisfaction with restraint on electrical load
(8) Setting the degree of dissatisfaction with restraint on generator

[Variables]

(1) ON/OFF of various electrical loads
(2) Start/stop of various converters

4. Verification Results

4-1 Balancing power supply-demand control by DC voltage stabilization control

The micro grid system was operated under only DC voltage stabilization control without optimal SOC management. The DC bus voltage, power generation and consumption, and the dependence of electrical energy on the charge/discharge of battery during one day are shown in **Fig. 5**. For this verification, the condition was set with unstable power generation by renewable energy and demand pattern with sharp fluctuations in which a balance between the supply and demand of electric power is difficult to maintain. **Figure 5** shows that the DC bus voltage was maintained constant irrespective of sharp fluctuations in the generation and consumption of electric power. This means that the RF battery achieved a balance between the supply and demand of electric power by appropriately controlling the amount of charge/discharge.

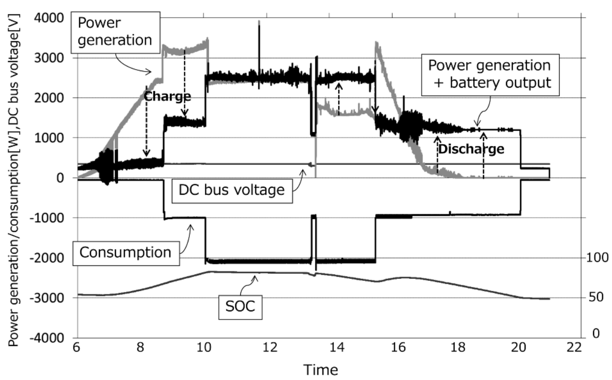


Fig. 5. Result of DC bus voltage stabilization control

4-2 Effects created by optimal SOC management

Figure 6 shows the results obtained by optimal SOC management during three weeks from June 24 to July 13, 2013. This figure shows that the SOC being full or empty could be avoided for three weeks regardless whether the system was operated under bad weather conditions or when introducing to visitors. During the first week from June 24 through June 28, the system was operated under restricted power consumption due to a small SOC and poor power generation. Only the television and floor lighting 1 were turned on according to the order of priority. During the second week from July 1 through July 6, the weather improved and the electrical loads consumed a relatively large amount of electric power. However, since the system consumed a large amount of electric power for introducing the system to visitors, operation of the electrical loads was slightly restrained. During the third week from July 9 through July 13, sunny days continued. Since the photovoltaic generators could produce sufficient electric power, the micro grid system did not restrain power consumption. During the period from July 11 through July 13, however, the system restrained the operation of generators since the battery had a sufficient amount of SOC.

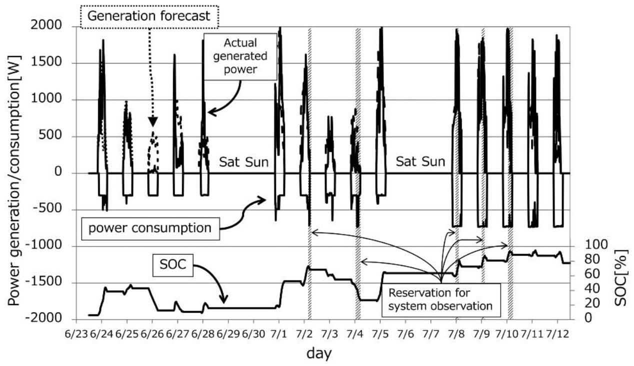


Fig. 6. Results of long-term system operation by optimal SOC management

4-3 Effect of short cycle re-planning in optimal SOC management

Optimal management of SOC for one day is discussed in this section. **Figure 7** shows the generation/consumption of electric power according to the plan that was established at 0:00 a.m. on July 15, 2013 and the same data obtained after re-planning the optimal management at intervals of 15 minutes. For this day, the forecast at 0:00 a.m. showed sufficiently large power generation throughout the day. Accordingly, the electrical loads were planned to maximally consume electric power and satisfy the demand pattern. However, due to an unexpectedly large electric power generation forecast error, the SOC at 8:00 p.m. would have dropped to approximately 30% if the original plan had been carried out without any change. In contrast, re-planning at 15-minute intervals could predict that the SOC would decrease. As a result, the original plan was revised so that the system would start restraining the power consumption of the electrical loads at around 11:00 a.m. based

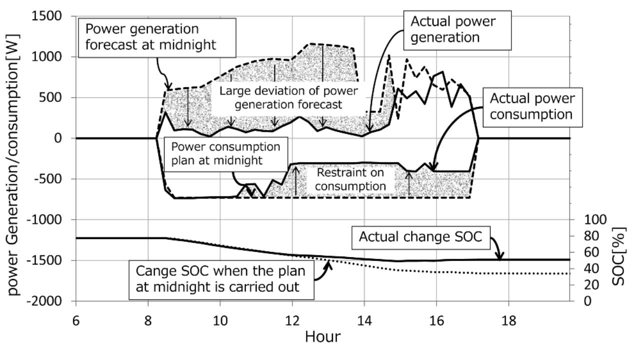


Fig. 7. Results of system operation on July 15, 2013

on a decrease in the SOC. Thus, the new plan prevented the battery from remarkably reducing the SOC. This result verified that, when planning for optimal operation of a generator which depends on renewable energy whose available quantity is difficult to forecast with a high level of accuracy, it is effective to handle the forecast error by reviewing and revising the original system operation plan using a short cycle.

5. Conclusions

We developed an EMS that can achieve a balance of supply and demand of electric power with highest stability in an isolated micro grid system, which is independent of the commercial transmission grid and uses only renewable energy to produce electric power.

A micro grid system equipped with the newly developed EMS has been in full time operation since April 1, 2013 until today (March 31, 2014) while preventing the SOC being full or empty.

Technical Terms

*1 Smart grid: A power supply network in which the flow of electricity is controlled from both its supplier and consumer sides to optimally balance the supply and demand. The smart grid helps save energy, reduce cost, and enhance the credibility and transparency of renewable energy power generation.

*2 Micro grid (small-scale power generation system or distributed power network): A power system equipped with small-capacity generators, such as gas/diesel generators, photovoltaic generators, wind turbine generators, and fuel cells. This system is constructed in a power demand district to meet the power demands in the district. Compared with a remotely located large-scale centralized electric power generation system, a micro grid reduces the transmission facility construction cost and minimizes energy transmission loss. Locating the electric power generation facilities within the power demand district makes it possible to construct a cogeneration system to use heat, a by-product of electric power generation, thereby enhancing energy utilization efficiency.

References

(1) N. Ayai, T. Hisada, T. Shibata, H. Miyoshi, T. Iwasaki, K. Kitayama, "DC Micro Grid System," SEI Technical review, No.75, pp.132-136 (2012)

(2) Y. Ishigaki, T. Okumura, T. Hisada, N. Ayai, K. Kitayama, I. Matsusue, H. Miyoshi, "Development of DC Micro Grid (1) – Autonomous Distributeed Power Supply System –" Annual Conference of Power & Energy Society, 132, pp.06-5-6 (2012)

(3) K. Toya, Y. Abiko, I. Takashi, "Development of DC Micro Grid (4) – Concentrator Photovoltaic –" Annual Conference of Power & Energy Society, 135, pp.06-11-12 (2012)

(4) K. Saitou, Y. Abiko, K. Toya, K. Mori, Y. Kogetsu, T. Iwasaki, "Development of Concentrator Photovoltaic System," SEI Technical Review, No. 76, P.23-26 (2013)

(5) T. Shigematsu, "Redox Flow Battery for Energy Storage," SEI Technical Review, No.73, P.4-13 (2011)

(6) Y. Abiko, K. Hirotsu, Y. Ishigaki, J. Itoh, T. Iwasaki, Y. Kimura, K. Saitou, K. Toya, and K. Yamagishi, "CPV Power Generation Estimation Based on Weather Forecast Information" 9. International Conference on Concetrator Photovoltaic Systems, Poster Session 2 P32, Miyazaki, Japan (April 2013)

(7) T. Okumura, Y. Ishigaki, T. Hisada, N. Ayai, "Development of DC Micro Grid (2) – DC Bus Control –" Annual Conference of Power & Energy Society, 133, pp.06-7-8 (2012)

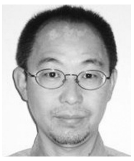
Contributors (The lead author is indicated by an asterisk (*).)

Y. ISHIGAKI*
- Power system R&D center

Y. KIMURA
- Power system R&D center

I. MATSUSUE
- Infocommunications and Social Infrastructure systems R&D Center

H. MIYOSHI
- Group Manager, Infocommunications and Social Infrastructure systems R&D Center



K. YAMAGISHI
- General Manager, Power system R&D center