研究論文

Variable Charge Level Operating Method for a Stand-Alone Photovoltaic/Wind/Diesel/Battery System

Yusuf Ismail [*1] Yoshishige Kenmoku [*2] Hirofumi Takikawa [*1] Tateki Sakakibara [*1]

Abstract

A new operating method for a stand-alone photovoltaic/wind/diesel/battery system is presented. The Variable Charge Level (VCL) operating method is proposed as an improvement of our previous operating method, i.e., Minimum Specified Charge Level (MSCL) operating method. The diesel generator is controlled so that the battery charge may be maintained at a minimum specified level. In the MSCL operating method, the minimum specified charge level is constant over one year. In the new operating method, the minimum specified level is changed monthly, weekly or daily. A simulation was carried out over one year using the hourly data of electric load, insolation and wind speed on Kamishima Island, Japan in 1996. This method is compared with the MSCL and Dynamic Programming (DP) operating methods. The results show that, in terms of diesel generator fuel consumption, this method is superior to MSCL, although not to the DP.

Key Words : photovoltaic/wind/diesel/battery system, yearly simulation, operating method, battery charge level, fuel consumption.

1. Introduction

Stand-alone diesel generator units, while relatively reasonable in cost, are generally expensive to operate and maintain especially at low levels. However, integrating them with a photovoltaic generator, wind turbine generator, and storage battery becomes cost-effective. Besides being emission-free, energy from the sun and wind are available at no cost. In addition, they offer a power supply solution to remote areas not accessible to the utility companies. The interest in photovoltaic and wind energy forms is indeed growing worldwide [1]. From the viewpoint of reducing CO_2 emission, utilization of photovoltaic and wind energies has been positively advanced [2].

Because of the variation of regions, seasons and weather conditions, power outputs from these two kinds of energy sources are very unstable, and their power densities are also relatively low [3]. Furthermore, the supply of these energy sources may not coincide with the electric load, so energy storage must provide this missing link [4].

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A diesel generator operating method for hybrid power systems has been proposed in our previous papers. The Specified Charge Level (SCL) operating method was proposed for the hybrid power system [5], and the MSCL operating method has also been developed [6].

In the SCL operating method, the diesel generator is operated so that the charge of the storage battery may be held at a specified level as long as possible. As described in section 6, the fuel consumption of the DG decreases as the specified charge level decreases. However, shortage of energy supply occurs when the specified charge decreases to less than a certain level. The level is called the minimum specified charge level. In the MSCL operating method, the DG is operated so that the charge of the storage battery may be held at a minimum specified charge level as long as possible. Since the minimum specified charge level can be varied monthly, weekly and even daily, the fuel consumption of DG could be reduced more and more. This paper proposes an improved MSCL operating method called the Variable Charge Level (VCL) operating method.

A simulation is performed for over one year using the hourly data of electric load, insolation intensity, wind speed, and atmospheric temperature on Kamishima Island, Japan in 1996. The VCL operating method is then compared with the

MSCL and the Dynamic Programming (DP) operating methods from the viewpoints of yearly fuel consumption.

The system parameters are the Natural Energy Supply Ratio (NESR), the energy ratio of photovoltaic generator to wind turbine generator (PV/Wind), and the battery size. The diesel generator selected is a 300-kW model.

2. Energy Flows

Energy flows in the photovoltaic/wind/diesel/battery hybrid system are shown in Fig. 1, in which *Pv(ti)* is the output of the photovoltaic generator, *Pw(ti)* is the output of the wind turbine generator, *Pd(ti)* is the output power of the diesel generator, *Pl(ti)* is the energy consumed in an electric load, *Pdl(ti)* is the excess energy dumped to the dummy load, and *Pb(ti)* is the charge or discharge energy of the battery. *Pb(ti)* is positive when the battery is discharged, and otherwise negative. *ti* is the hourly time. These flows must satisfy equation (1).

$$Pv(ti) + Pw(ti) + Pd(ti) + Pb(ti) = Pl(ti) + Pld(ti) \qquad (1)$$

3. Electric Load, Photovoltaic and Wind Energies

The monthly variations in electric load, photovoltaic and wind energies at Kamishima Island are shown in Fig. 2. The electric load is high in July and August. The average daily electric load is 4,336 kWh. Since the yearly electric load energy is 1,583 MWh and the peak load is 393 kW, the load factor is 46%.

The photovoltaic generator and wind turbine generator output are calculated using equation (2) and (3), respectively. The results in Fig. 2 are calculated for the case of a rated output of PVG of 100 kWp and WTG of 100 kW. The wind energy is higher than the photovoltaic energy in January, February, March, November and December, but lower in May to October.

4. Characteristics of Components

4.1 Photovoltaic Generator (PVG)

The output of the photovoltaic generator *Pv(ti)* (kW) is given by the following equation:

$$Pv(ti) = \varepsilon \cdot A \cdot U(ti) \cdot (1 - 0.005 \cdot (T(ti) + 5)) \qquad (2)$$

Where ε : efficiency (0.15)

A : PV panel area (m^2)

$U(ti)$: insolation intensity (kW/m^2)

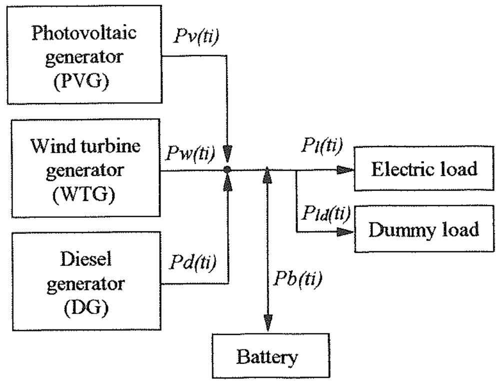


Fig. 1. Energy flows in photovoltaic/wind/diesel/battery system

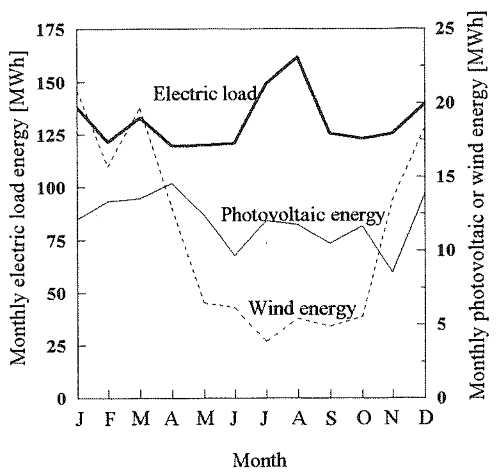


Fig. 2. Monthly variations in electric load, photovoltaic, wind energies (PVG rating = 100 kWp ; WTG rating = 100 kW)

$T(ti)$: atmospheric temperature (°C)

4.2 Wind Turbine Generator (WTG)

Output - wind speed characteristics (Pw - v characteristics) of WTG is given by the following equation [7]:

$$P_{w(ti)} = \begin{cases} 0 & (v_{(ti)} < v_c,\ v_o \leqq v_{(ti)}) \\ P_{wr} \cdot (v_{(ti)} - v_c)/(v_r - v_c) & (v_c \leqq v_{(ti)} < v_r) \\ P_{wr} & (v_r \leqq v_{(ti)} < v_o) \end{cases} \qquad (3)$$

Where $v_{(ti)}$ is wind speed, P_{wr} is the WTG rating, v_c is the cut-in speed (= 3 m/s), v_r is the rated speed (= 12 m/s) and v_o is the cut-out speed (= 25 m/s).

4.3 Diesel Generator (DG)

The fuel consumption of the diesel generator is calculated using the following equation:

$$F_d = a \cdot P_d^{\,2} + b \cdot P_d + c \qquad (4)$$

where F_d is the fuel consumption of DG and P_d is the output of DG. The coefficients a, b and c are determined by fitting

Table 1. System Parameters

NESR (%)	20, 40, 60, 80, 100
PV/Wind ratio (%/%)	100/0, 75/25, 50/50, 25/75, 0/100
Battery capacity (%)	15, 25, 50, 75, 100

NESR: Natural energy supply ratio to the yearly electric load

PV/Wind ratio: Energy Ratio of photovoltaic generator to wind turbine generator.

Battery capacity : Normalized with the average daily electric load.

equation (4) to the characteristics of a commercial DG. Here, a = 1×10^{-5}, b = 0.224, and c = 9.670. The output is controlled between 20% and 100% of the rated output. In this paper, the rated output of DG is taken as 300 kW, which is lower than the peak load (393 kW).

4.4 Battery

At present, a lead battery is exclusively used as the storage battery. In the near future, however, a Sodium Sulfur (NaS) battery or a redox flow battery will be commercially available [4]. In this paper, this type of battery is assumed as the storage battery. Although its performance is higher than the lead battery, its detailed characteristics have not been published.

The battery capacity is taken as a parameter and expressed in percentages. The capacity of 100% is equivalent to an average daily electric load. Charging and discharging efficiencies are 85% and 100%, respectively. Battery hourly charge rates are limited to 10% and 20% of the battery capacity when charging and discharging, respectively.

The system parameters are presented in Table 1.

5. Operating Method

Basically, the VCL operating method is the same as the MSCL operating method. The difference is in the time interval for determining the minimum specified charge level. In the MSCL operating method [6], the minimum specified level is constant during a year. On the other hand, in the VCL operating method, the minimum specified charge levels are obtained based on three time intervals, i.e., monthly, weekly, or daily. So, there are three kinds of VCL operating methods called VCL-monthly, VCL-weekly, and VCL-daily. The operation of the system is divided into three scenarios depending on the electric load, $P_{l(ti)}$, the output of PVG, $P_{v(ti)}$, the output of WTG, $P_{w(ti)}$, and the battery charge level, $X_{(ti)}$, as follows:

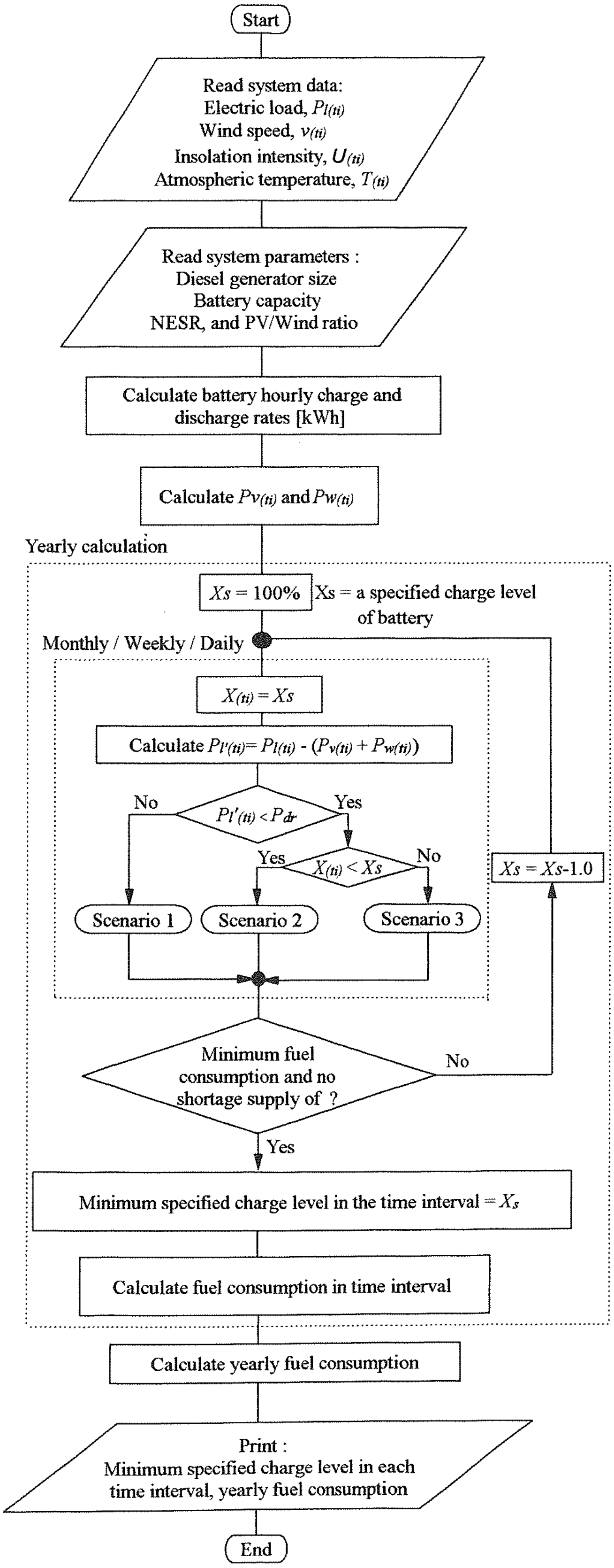


Fig. 3. Flowchart of Variable Charge Level operating method for a stand-alone photovoltaic/wind/diesel/battery power system

Scenario 1: $P_l(t_i) > P_v(t_i) + P_w(t_i) + P_{dr}$

Scenario 2: $P_l(t_i) \leqq P_v(t_i) + P_w(t_i) + P_{dr}$ and $X(t_i) \leqq X_s$

Scenario 3: $P_l(t_i) \leqq P_v(t_i) + P_w(t_i) + P_{dr}$ and $X(t_i) > X_s$

Where, P_{dr} : rated output of diesel generator

X_s : specified charge level of battery

Scenario 1: Hourly energy of $\{P_l(t_i) - (P_v(t_i) + P_w(t_i) + P_{dr})\}$ is supplied from the battery. The battery hourly discharge rate must be less than 20% of the battery capacity, or the system could not meet the electric load.

Scenario 2: DG supplies energy to the battery so that its charge increases to the specified level, X_s. The battery hourly charge rate must be less than or equal to 10% of the battery capacity.

Scenario 3: The battery is discharged so that its charge decreases to the specified charge level, X_s. The battery hourly discharge rate must be less than or equal to 20% of the battery capacity. In this scenario, if $X(t_i)$ = 100%, the excess energy generated goes to the dummy load.

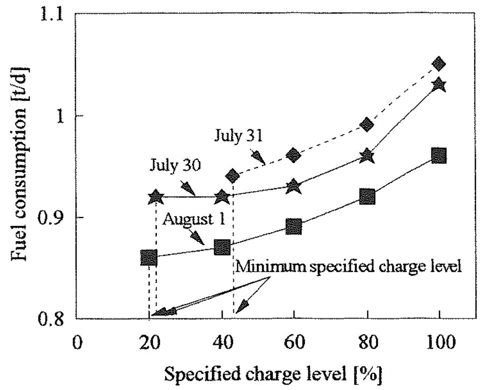
Fig. 3 shows the flowchart of the VCL operating method. First, the system data are read, i.e., electric load, wind speed, insolation intensity, and atmospheric temperature. The battery hourly charge and discharge rates are calculated after reading the system parameters. Next, the outputs of PVG and WTG are calculated.

In order to determine the minimum specified charge level in each time interval, the initial specified charge level is set at 100%. The diesel generator and the battery are operated comparing $X(t_i)$ with X_s such as in scenarios 1, 2, and 3. The hourly calculation is repeated until the minimum specified charge level is found. Finally, the yearly fuel consumption is calculated as the sum of the fuel consumption at each time interval.

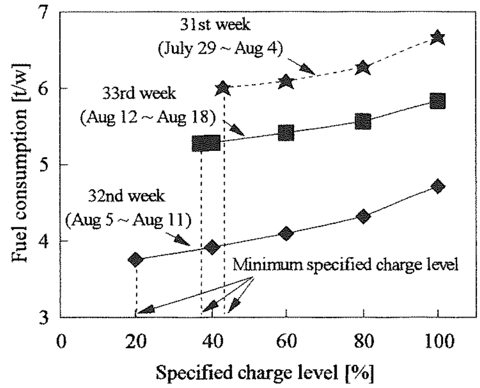
6. Results and Discussion

6.1 Minimum Specified Charge Level

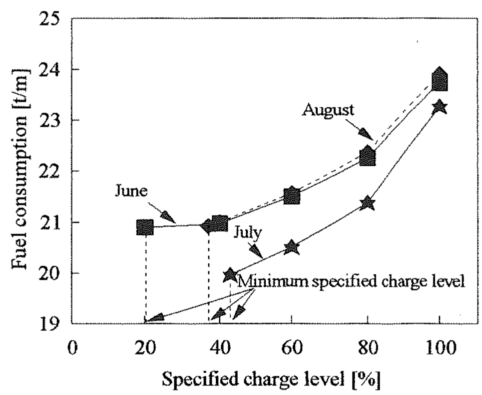
Fig. 4 shows the fuel consumption versus the specified charge level of the VCL and the MSCL operating methods, with parameters of a battery capacity of 15%, a NESR of 100%, and a PV/Wind ratio of 50/50. The fuel consumption versus the specified charge level curves are 365 in case of the VCL-daily operating method, against about 52 curves in the case of the VCL-weekly, 12 in the case of the VCL-monthly operating method, and only one in the case of the VCL-yearly operating method. Generally, the fuel consumption decreases as the specified charge level decreases from 100%. However, the specified charge level could not be



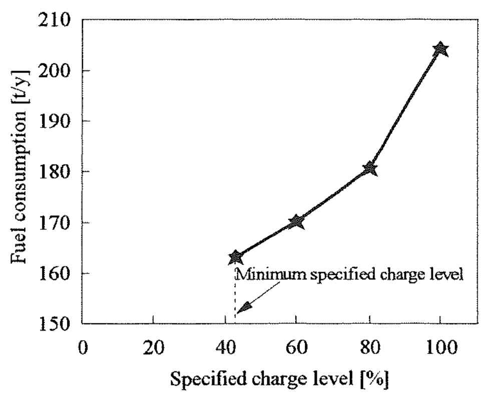
(a) VCL-daily operating method



(b) VCL-weekly operating method



(c) VCL-monthly operating method



(d) VCL-yearly operating method or Minimum Specified Charge Level operating method

Fig. 4. Fuel consumption versus specified charge level obtained by the variable charge level operating method (Battery capacity = 15%, NESR = 100%, PV/Wind ratio = 50/50)

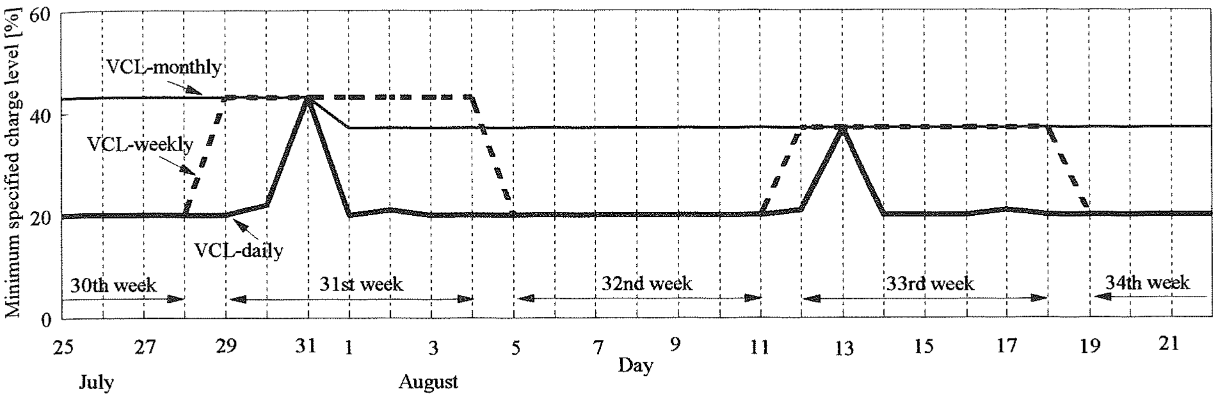


Fig. 5. Time series results of the minimum specified charge level (Parameters are same as Fig. 4)

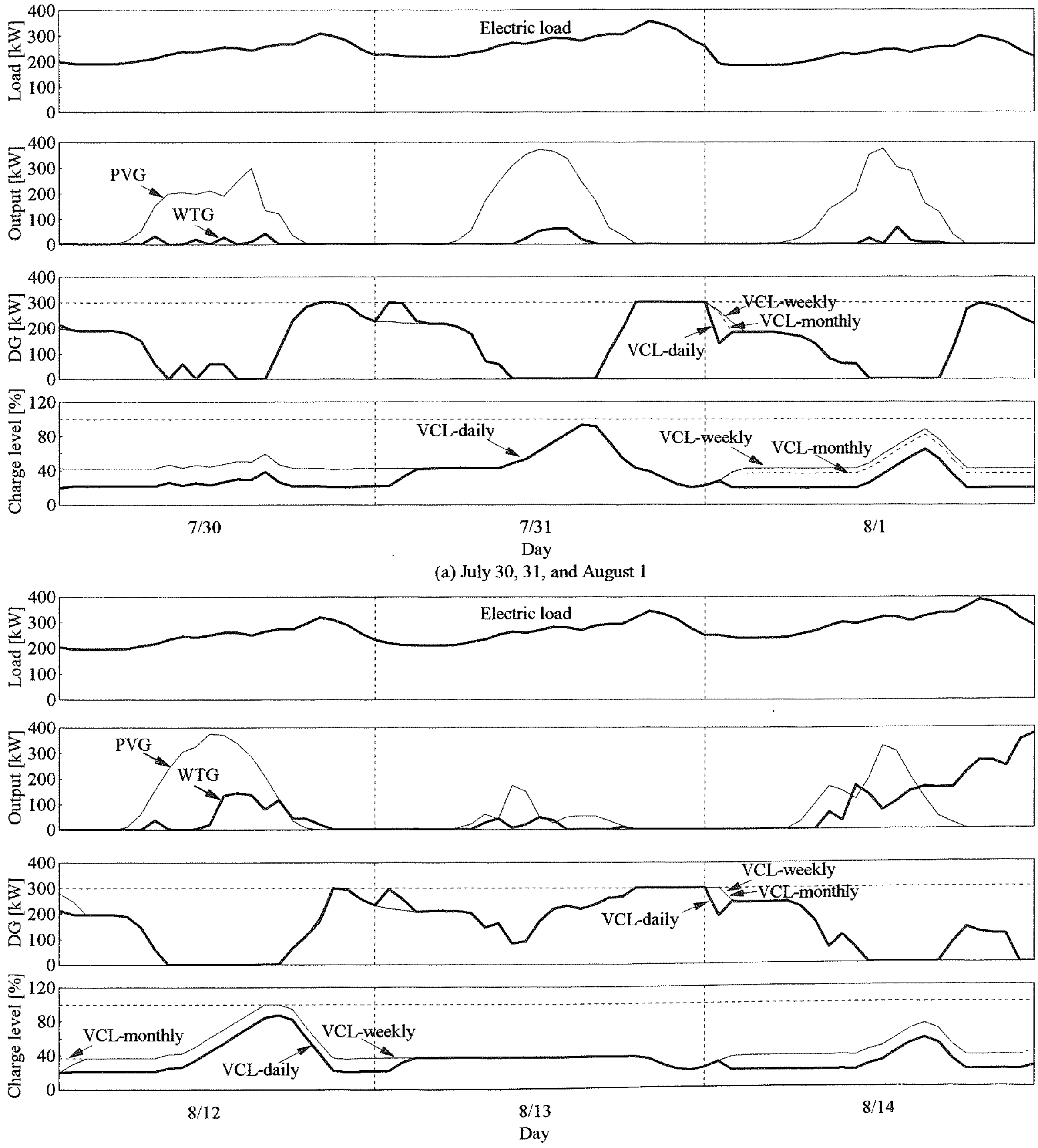


Fig. 6. Time series results of VCL-daily, weekly, and monthly operating methods.

lower than the minimum specified charge level, or the a supply shortage occurs.

The result of the VCL-daily operating method (Fig. 4(a)) shows that the minimum specified charge levels are 43, 22, and 20% on July 31, July 30, and August 1, respectively. The result of the VCL-weekly operating method (Fig. 4(b)) shows that the minimum specified charge levels are 43, 37, and 20% at the 31st, 33rd, and 32nd weeks, respectively. The result of the VCL-monthly operating method (Fig. 4(c)) shows that the minimum specified charge levels are 43, 37, and 20% in July, August, and June, respectively. On the other hand, the result of the VCL-yearly operating method (Fig. 4(d)), i.e., the MSCL operating method, shows that the minimum specified charge level is only 43%.

As mention above, the minimum specified charge level changes daily, weekly, or monthly. Fig. 5 shows a part of the time series change in the minimum specified charge level. The minimum specified charge level of VCL-daily operating method is 43% on July 31 and 37% on August 13 and 20% on other days. The minimum specified charge level of VCL-weekly operating method is 43% at the 31st week, 37% at the 33rd week, and 20% at other weeks. The minimum specified charge level of VCL-monthly operating method is 43% in July, 37% in August and 20% in other months. The distinctive feature is that on July 31 the minimum specified charge level takes the same value of 43% with the VCL-daily, VCL-weekly, and VCL-monthly operating methods. On August 13, the minimum specified charge level also takes the same value of 37%. In other words, the minimum specified charge level of the VCL operating methods is basically determined by the VCL-daily operating method.

6.2 Time Series Results

Fig. 6 shows an example of time series results of 3 days for July and August. The system parameters are the same as in figure 4. Fig. 6(a) reveals the following features. The PVG output is sufficient to meet the load in daytime, so the DG stops. With regard to the charge level of battery, on July 31 the VCL-daily, weekly, and monthly levels are the same, while on August 1 they are different because the minimum specified charge levels are different at 20, 37, and 43% with the VCL-daily, weekly, and monthly, respectively. Fig. 6(b) reveals the following features. The PVG plus WTG output is not enough to meet the load all day on August 13, so the DG operates. With regard to the charge level of battery, on August 12 and 14 the VCL-weekly and monthly levels are almost equal while the VCL-daily level is different because the minimum specified charge level of VCL-weekly and monthly are both 37%, where as that of VCL-daily is 20%.

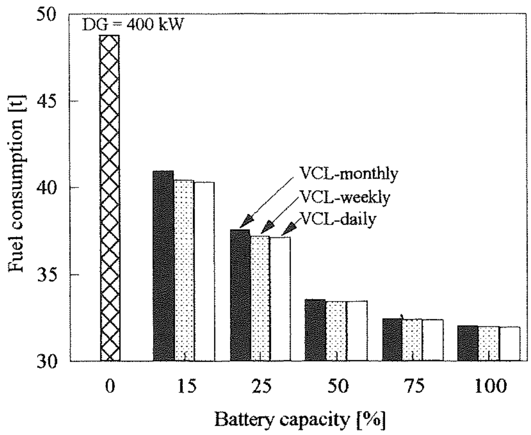


Fig. 7. Fuel consumption versus battery capacity during July to August (NESR = 100%, PV/Wind ratio = 50/50)

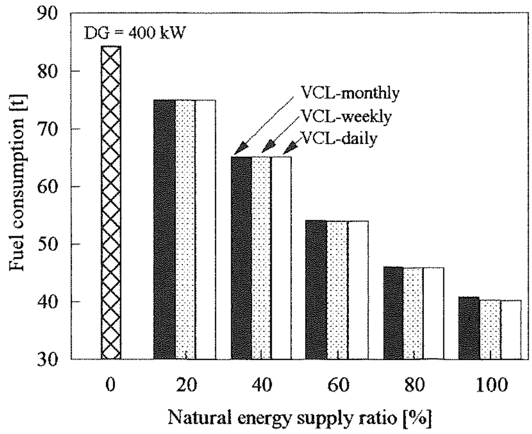


Fig. 8. Fuel consumption versus natural energy supply ratio during July to August (NESR = 100%, PV/Wind ratio = 50/50)

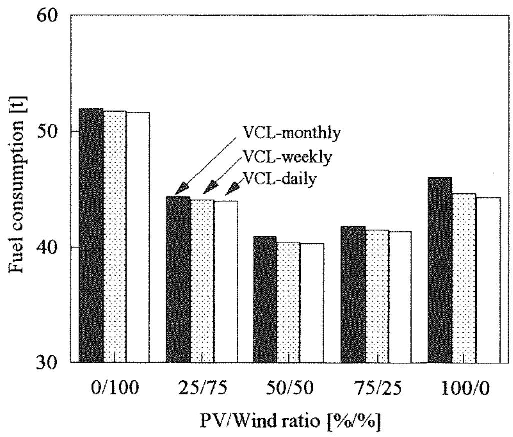


Fig. 9. Fuel consumption versus PV/Wind ratio during July to August (Battery capacity = 15%, NESR = 100%)

6.3 Fuel Consumption

The fuel consumption for a time period can be calculated from the time series results of the DG output as shown in Fig. 6 and equation (4). The parameters are the battery capacity, NESR, and PV/Wind ratio. Fig. 7 shows the fuel consumption versus the battery capacity for different VCL operating methods, where the NESR is 100% and the PV/Wind ratio is 50/50. The fuel consumption for July and August decreases as the battery capacity increases, because

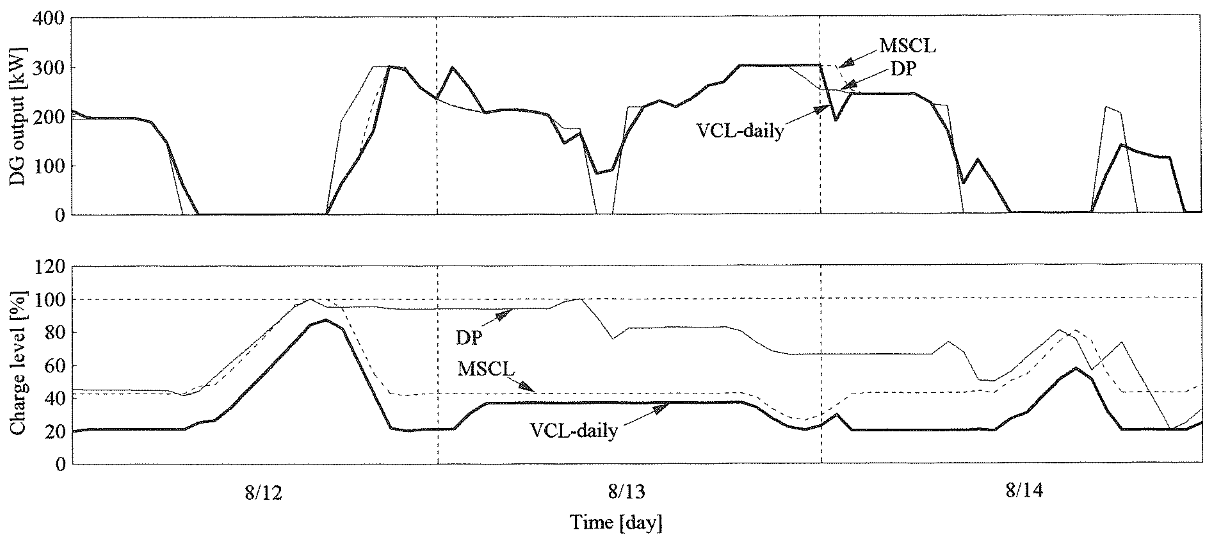


Fig. 10. Time series results of various operating methods (Battery capacity = 15%, NESR = 100%, PV/Wind ratio = 50/50)

the excess energy (energy above the electric load) from the PVG plus PWG is stored more in the battery as the battery capacity is larger. The fuel consumption of the VCL-daily operating method is slightly lower than those of the VCL-weekly and monthly operating methods with battery capacities of 15 and 25%.

Fig. 8 shows the fuel consumption versus the NESR for different VCL operating methods, where the battery capacity is 15% and the PV/Wind ratio is 50/50. The fuel consumption decreases as the NESR increases, because the DG energy to be generated is lower with increase in the NESR. If the NESR is lower than 60%, the fuel consumption is the same with VCL operating methods. On the other hand, if the NESR is higher than 80%, the fuel consumption with the VCL-daily operating method is slightly lower than with the other operating methods.

Fig. 9 shows the fuel consumption versus the PV/Wind ratio, where the battery capacity is 15% and the NESR is 100%. The fuel consumption takes a minimum at a PV/Wind ratio of 50/50. An understandable explanation for this is that the time series profile of the PVG plus WTG output best matches the time series profile of the electric load at about 50/50 of the PV/Wind ratio. Here, the fuel consumption of the VCL-daily operating method is lower than those of the VCL-weekly and monthly operating methods.

7. Minimum Specified Charge Level and Dynamic Programming Operating Methods

In order to estimate the VCL operating methods, they must be compared with other operating methods. Here, two methods are chosen: the Minimum Specified Charge Level (MSCL) operating method and the Dynamic Programming (DP) operating method.

7.1 MSCL Operating Method

The MSCL operating method is described in references (5) and (6) in detail, where the minimum specified charge level is determined by the flowchart like Fig. 3 for a time interval of one year. Therefore, the MSCL operating method is the same as the VCL-yearly operating method. The minimum specified charge level is 43% as shown in Fig. 4(d), that is, constant during the year.

7.2 Dynamic Programming (DP) Operating Method

If the hourly data on electric load, insolation, temperature and wind speed are known for one full year, the dynamic programming (DP) method could be available as the system operating method. In the DP method, the estimated value is the annual fuel consumption, the control variable is the DG output, and the state variable is the battery charge level. The DP method theoretically gives the lowest fuel consumption.

8. Comparison

Fig. 10 shows the time series results of the DG output and the battery charge level for the MSCL, VCL-daily, and DP operating methods. The system parameters are same as in Fig. 4. In regard to the DG output, there is not a large difference among the three operating methods. However, in terms of the battery charge level, there are indeed differences. The charge level of the MSCL operating method changes with time at around a charge level of 43%, which is the minimum specified charge level with the MSCL operating method. The

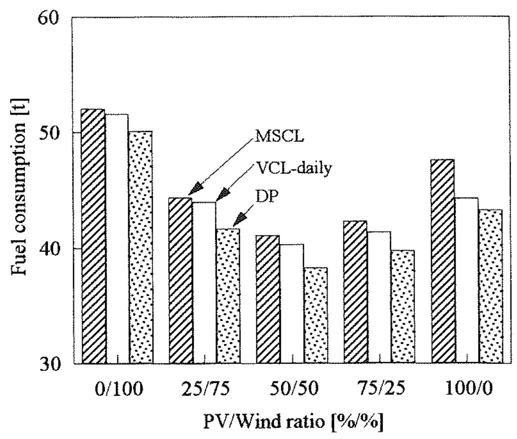


Fig. 11. Fuel consumption versus PV/Wind ratio for various operating method during July to August (Battery capacity = 15%, NESR = 100%)

charge level of the VCL-daily operating method changes with time at a charge level of 20% which is the minimum specified charge level with the VCL-daily operating method. On the other hand, the charge level of the DP operating method fluctuates with time between 20% and 100%, because there is no minimum specified charge level with this method.

Fig. 11 shows the fuel consumption versus PV/Wind ratio for the three different operating methods during July to August. With any operating method, the fuel consumption is lowest at a PV/Wind ratio of 50/50. And with any PV/Wind ratios, the fuel consumption is highest with the MSCL operating method, followed by the VCL-daily and the DP. The difference is largest with a PV/Wind ratio of 100/0: the fuel consumptions are 47, 44, and 43 t with MSCL, VCL-daily, and DP, respectively.

9. Concluding Remarks

An operating method applicable to a stand-alone photovoltaic/wind/diesel/battery system is improved in this paper. The output of the diesel generator is controlled so that the battery charge may be maintained at a specified level for certain time period, i.e., monthly, weekly and daily. The minimum specified charge is introduced as the specified charge level, at which the fuel consumption is minimum for each time period. A simulation was performed over one year using the hourly data of electric load and wind speed on Kamishima Island, Japan in 1996. The battery capacity is normalized with an average daily electric load. Parameters are the PV/Wind ratio (100/0 to 0/100), the battery capacity (10 to 100%), and the natural energy supply ratio (20 to 100%). The diesel generator size is selected as 300 kW, which is lower than the peak load.

Simulation results show that the VCL-daily method gives the lowest fuel consumption compared to the VCL-weekly and the VCL-monthly methods. Those numerical values in case of parameters (battery capacity = 15%, NESR = 100%, PV/Wind ratio = 100/0) are 44.3, 44.8, and 46.0 t with the VCL-daily, VCL-weekly, and VCL-monthly, respectively.

The VCL-daily operating method is compared with the MSCL and DP operating methods. The results show that the fuel consumption with the VCL-daily is lower than with the MSCL operating method but not the DP method. Those numerical values in case of parameters (battery capacity = 15%, NESR = 100%, PV/Wind ratio = 100/0) are 44.3, 47.6, and 43.3 t with the VCL-daily, MSCL and DP methods, respectively.

In order to practically apply the VCL, MSCL, and DP operating methods, the hourly data on electric load, insolation intensity, wind speed, and atmospheric temperature have to be given a priority for each time period, i.e., one year's data are forecast for the MSCL and DP operating methods, one month's data for VCL-monthly, one week's data for the VCL-weekly operating method, and one day's data for the VCL-daily operating method.

Forecasting methods for the daily electric load, insolation intensity, and wind speed have been developed [9-10]. Therefore, the VCL operating method may be practically applied. However, a new method in which uncertainty of forecasting the electric load and weather condition are also considered, has to be developed for determining the minimum specified charge level with which the fuel consumption has a minimum.

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