研究論文

Management of Daily Charge Level Based on Weather Forecast for a Photovoltaic/Diesel/Battery Power System

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Abstract

A new method for operating a stand-alone photovoltaic/diesel/battery system is presented in this paper. The diesel generator is controlled so that the state of charge (SOC) of the battery may be maintained at a certain daily specified charge level. The battery is discharged when the SOC is higher than the daily specified charge level and charged when lower. A simulation is carried out over one year using the hourly data of electric load, insolation intensity and atmospheric temperature on Kamishima Island, Japan in 1996. Based on next day weather forecasting, the daily specified level is pursued every day so that the fuel consumption is minimum. This method is compared with other operating methods: a conventional operating method maintaining the battery charge level at the full level (FCL) and dynamic programming (DP) operating method. The results show that for diesel generator fuel consumption, this method is better than the FCL, although not to the DP.

Key Words: Photovoltaic/diesel/battery system, Operating method, Simulation, Weather forecast, Battery charge level, Fuel consumption

1. Introduction

Some remote islands in Japan rely primarily on diesel generators for electric power[1]. While being relatively reasonable in cost, stand-alone diesel generator units are generally expensive to operate and maintain, especially in low load factor cases. However, integrating them to a photovoltaic generator and a storage battery becomes cost-effective. Besides being emission free, the energy coming from the sun is available at no cost. The interest in photovoltaic energy form is indeed growing worldwide. From the viewpoint of reducing CO_2 emission, utilization of photovoltaic energy has been positively advanced[2].

Because of the variation of regions, seasons and weather condition, power outputs from photovoltaic generator are unstable and its power density is also low relatively. Furthermore, the supply of this energy source may not coincide with the electric load, so energy storage must provide this missing link[3].

In order to minimize the fuel consumption of diesel generator in photovoltaic/diesel/battery power system, the diesel generator output has to be optimized. The battery has the important role in the system operation. It serves as an energy storage whenever the output of photovoltaic generator is higher than the electric load, otherwise as an energy source. Thus the operating method of the battery will be different in accordance with the purpose. If the battery is used as energy storage, its SOC has to be kept low. On the other hand, if the battery is used as energy source, SOC has to be high.

The new operating strategy called the daily charge level (DCL) is proposed in this paper. The diesel generator is controlled so that SOC of the battery is kept at a daily specified charge level. In this condition, the battery can be as energy storage and also as energy source. If SOC is lower than such specified charge level, the battery is charged. Otherwise, if SOC is higher, the battery is discharged. The daily specified charge level is pursued every day, so that the fuel consumption of diesel generator is minimum. In order to determine the optimum SOC level, the next day weather forecasting is utilized.

A simulation is performed for over one year using the hourly data of electric load, insolation and atmospheric temperature on Kamishima Island, Japan in 1996. DCL method is compared with other methods, i.e., the full charge level (FCL) and the dynamic programming (DP) methods from the viewpoint of fuel consumption.

2. Energy Flows

Energy flows in the photovoltaic/diesel/battery power system are shown in Fig. 1, in which $P_v(t_i)$ is the output of the photovoltaic generator, $P_d(t_i)$ is the output of diesel generator, $P_l(t_i)$ is the electric load, $P_{dl}(t_i)$ is the excess energy dumped to dummy load, and $P_b(t_i)$ is the charge or discharge energy of the battery. $P_b(t_i)$ is positive when the battery is discharged, otherwise is negative. t_i is the hourly time. These flows must satisfy the equation (1).

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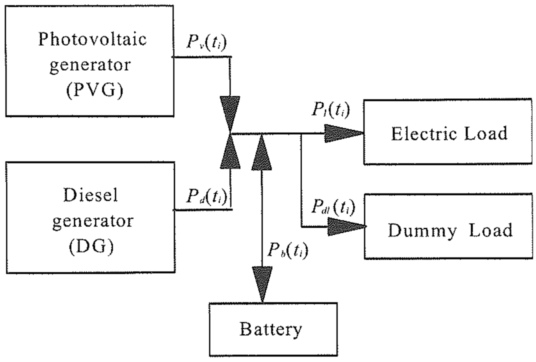

Fig.1. Energy flow in photovoltaic/diesel/battery system.

$$P_v(t_i) + P_d(t_i) + P_b(t_i) = P_l(t_i) + P_{dl}(t_i) \quad (1)$$

3. Electric Loads, Photovoltaic Output, and Natural Energy Supply Ratio

The monthly variations of electric load and photovoltaic generator output at Kamishima Island are shown in Fig. 2. The electric load is high in July and August. Since the yearly electric load energy is 1,538 MWh and the peak load is 393 kW, so the load factor is 46%. The average daily electric load is 4,336 kWh.

The photovoltaic generator (PVG) output is calculated using the equation (2) shown below. The calculation results are in the case that a rated output of PVG is 100 kWp.

Natural Energy Supply Ratio (NESR) is the ratio of PVG output energy to electric load energy. Here, the PVG output energy and electric load energy are calculated based on yearly total energy. The NESR is also taken as parameter (20% – 100%).

4. Output Characteristic of System Components

4.1 Photovoltaic Generator (PVG)

Output of photovoltaic generator $P_v(t_i)$ [kW] is given by the following equation:

$$P_v(t_i) = \varepsilon \cdot A \cdot U(t_i) \cdot (1 - 0.005 \cdot (T(t_i) + 5)) \quad (2)$$

where:

ε : efficiency (15%)
A : area [m^2]
$U(t_i)$: insolation intensity [kW/m^2]
$T(t_i)$: atmospheric temperature [°C]

4.2 Diesel Generator (DG)

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

$$F_d = a \cdot P_d^{\,2} + b \cdot P_d + c \quad (3)$$

where F_d [kg/h] is the hourly fuel oil consumption and P_d [kW] is the output electric power. The coefficients a, b and c are determined by fitting the equation (3) to the characteristic of a commercial DG. The DG output is controlled between 20% and 100% of the rated power. In this study, the rated power of DG is

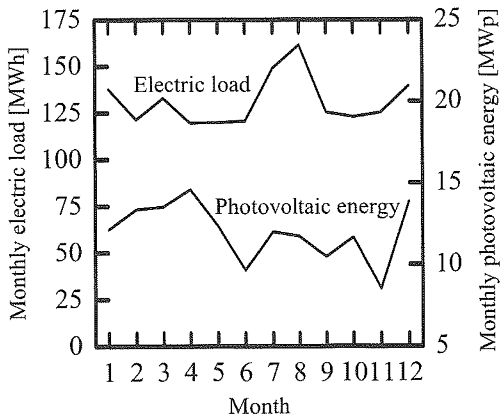

Fig.2. Monthly variation of electric load and photovoltaic energy (PVG size = 100 kWp).

taken as 300 kW, which is lower than peak load (393 kW), and the following values are used as the coefficients a, b and c:

$a = 1\times10^{-5}$ (kg/h)/(kW)^2
$b = 0.224$ (kg/h)/kW
$c = 9.670$ kg/h

4.3 Battery

At present, a lead battery is exclusively used as the energy storage. In the near future, however, a sodium sulfur (NaS) battery will be commercially available[(4)(5)]. The performance of NaS battery is higher than the lead battery. The characteristic of NaS battery is utilized in this study.

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.

5. Operating Method

When the system is operated, it is desirable to reduce the fuel consumption of DG as much as possible. Moreover, when the PVG output exceeds the electric load and then the battery is fully charged, excess energy occurs and it has to be drained away to a dummy load. Therefore, the battery and DG have to be controlled so that the fuel consumption of DG is minimized while the excess energy is suppressed as low as possible.

In this paper, a new operating method that called the daily charge level (DCL) operating method is proposed. In DCL method, the system is operated so that the SOC of the battery is kept at a certain daily specified charge level. When the SOC is higher than such specified charge level, the battery is discharged. On the other hand, when the SOC is lower than specified level, it is charged. The daily specified charge level is determined every day from the electric load and PVG output.

The operation of the system is divided into three scenarios depending on the electric load $P_l(t_i)$, the output of PVG $P_v(t_i)$ and the battery charge level $X(t_i)$, as follow:

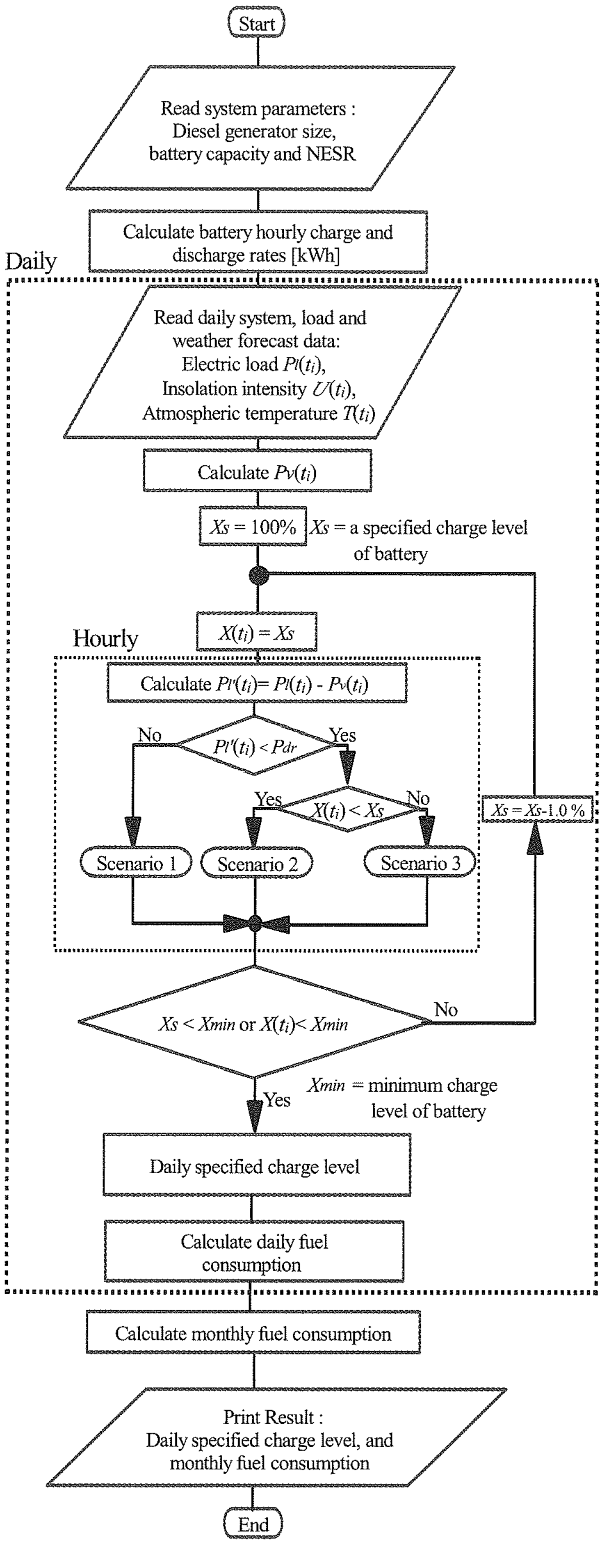

Fig.3. Flowchart of DCL operating method.

Scenario 1: $P_l(t_i) > P_v(t_i) + P_{dr}$
Scenario 2: $P_l(t_i) \leq P_v(t_i) + P_{dr}$ and $X(t_i) \leq X_s$
Scenario 3: $P_l(t_i) \leq P_v(t_i) + P_{dr}$ and $X(t_i) > X_s$

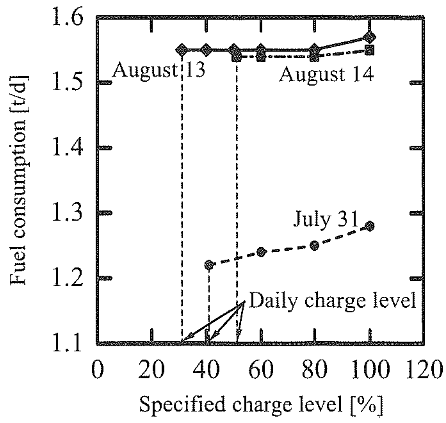

Fig.4. Daily fuel consumption versus specified charge level (Battery capacity = 25%, NSER = 40%).

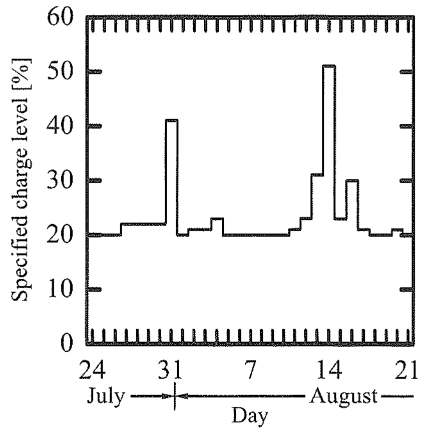

Fig.5. Daily specified charge level [July 24 to August 21] (Battery capacity = 25%, NSER = 40%).

where, P_{dr} : rated output of DG
X_s : daily specified charge level of battery

Scenario 1 : Hourly energy of $\{P_l(t_i) - (P_v(t_i) + P_{dr})\}$ 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 level X_s. The battery hourly discharge rate must be less than or equal to 20% of the battery capacity. In this scenario, when $X(t_i)$ = 100%, the excess energy goes to the dummy load.

Figure 3 shows the flowchart of the DCL operating method. First, the system parameters are read, and the hourly charge and discharge rates of the battery are calculated using them. Next, the system data of hourly electric load, insolation intensity and atmospheric temperature are read and the hourly PVG output is calculated.

In order to determine the daily specified charge level X_s, 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

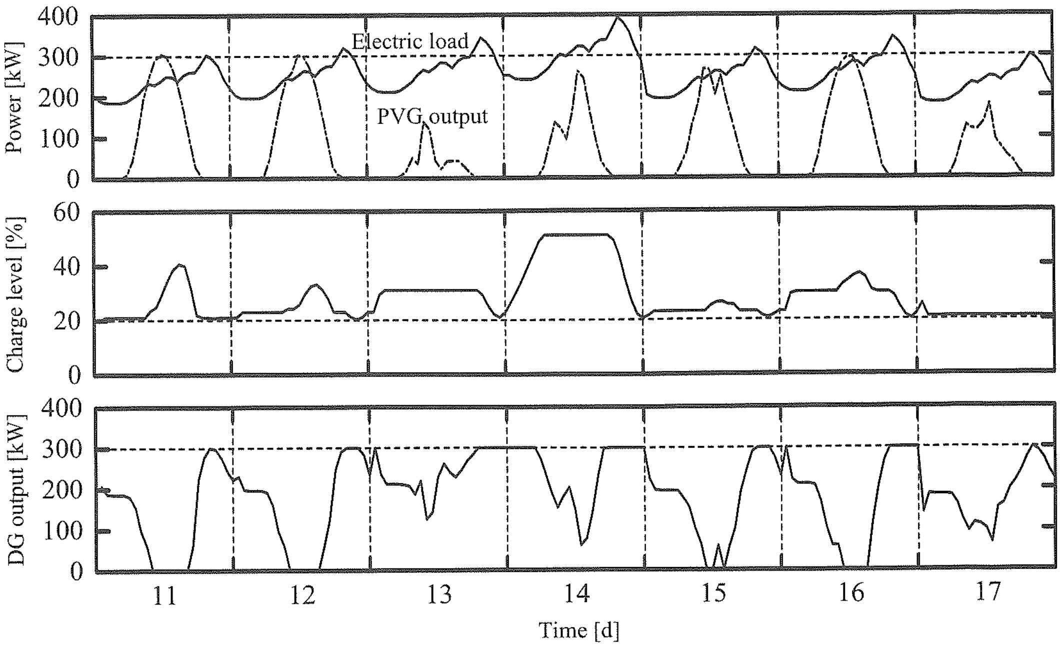

Fig.6. Time series results [August 11 to August 17] (Battery capacity = 25%, NSER = 40%).

scenario 1, 2, and 3. The hourly calculation is repeated until X_s is less than X_{min} or $X(t_i)$ drops below X_{min}, where X_{min} is the minimum charge level that is the margin for prevention of the occurrence of supply shortage caused by inaccuracy of weather forecasting.

In the case the maximum forecasting error ratio of the PVG output $P_v(t_i)$ is ε_{max}, the following electric power $P_s(t_i)$ is the upper limit that should be supplied from the above margin storage of the battery to compensate the forecasting error of $P_v(t_i)$:

$$P_s(t_i) = \begin{cases} \varepsilon_{max} \cdot P_v(t_i) - (P_{dr} - P_d(t_i)) & (\varepsilon_{max} \cdot P_v(t_i) > P_{dr} - P_d(t_i)) \\ 0 & (\varepsilon_{max} \cdot P_v(t_i) \le P_{dr} - P_d(t_i)) \end{cases} \quad (4)$$

The minimum energy that should be stored as the margin in the battery is, therefore, the integral of the above $P_s(t_i)$ over one day, and the minimum charge level X_{min} can be determined for specified ε_{max} through numerical simulations of this relation using already available past weather data. Smaller ε_{max} makes lower X_{min} possible and, therefore, accurate weather forecasting is very important to reduce the fuel consumption.

Since the aim of the present study is not the next day weather forecasting, X_{min} is tentatively selected as 20% in the present study.

Battery durability seems to be a delicate problem for the implementation of this DCL operating method because the SOC of the battery tends to become low in this method. In fact, lead battery is easily degraded by deep discharge and charge cycles. In the present system, however, this problem is not serious because NaS battery is selected and it has very good cycle durability of about 2500 full discharge and charge cycles[5].

6. Results and Discussion

6.1 Daily Specified Charge Level

Figure 4 shows the fuel consumption versus the specified charge level of the DCL operating method, with parameters of a battery capacity of 25% and a NESR of 40%. The fuel consumption versus the specified charge level curves are 365 over one year. Three days, i.e., July 31, August 13 and August 14, are taken as examples. Generally, the fuel consumption decreases as the specified charge level decreases from 100%. However, the specified charge level could not be lower than a certain daily specified charge level, or $X(t_i)$ drops below X_{min}.

The results show that the daily specified charge levels are 41%, 31% and 51% on July 31, August 13 and August 14 respectively. The daily specified charge levels are variables depending on the electric load and PVG output. Figure 5 shows a part of the time series changing of the daily specified charge level with a battery capacity of 25% and a NESR of 40%.

6.2 Time Series Results

Figure 6 shows example of time series results on August 11 to 17. The system parameters are the same as in Fig. 5. This figure reveals the following features. At some hours on August 11, 12, 15 and 16, the PVG outputs are higher than the electric load, so that the DG is idle. The excess energy flows into the battery and thus its SOC increases over the daily specified charge level. At the other time on the same days, the PVG output is lower than the electric load and the SOC of the battery is higher than the daily specified charge level. So, the battery is discharged to the daily specified charge level. Then the deficit power is supplied from DG.

On the other hand, at some hours on August 14, the electric load is so considerably higher than DG capacity. DG is operated at the maximum output. The deficit energy is supplied from the

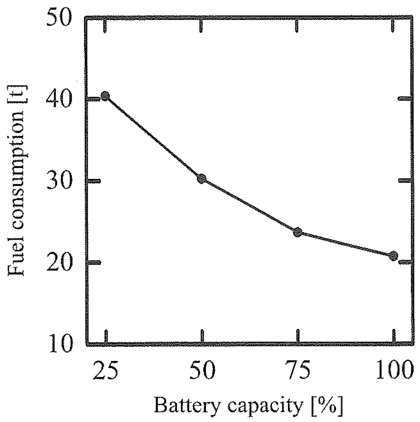

Fig.7. Fuel consumption versus battery capacity [July and August] (NSER = 100%).

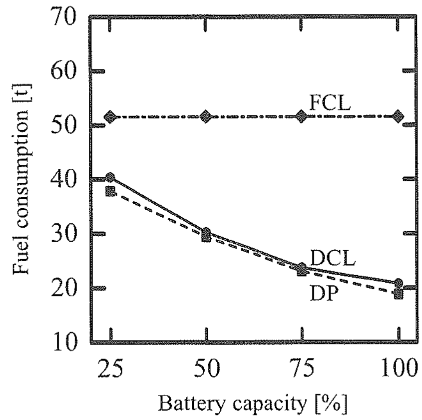

Fig.9. Fuel consumption versus battery capacity for various operating methods [July and August] (NSER = 100%).

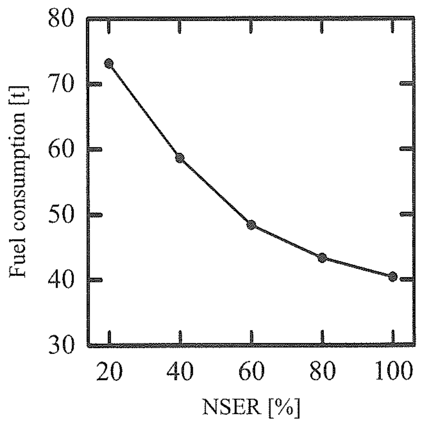

Fig.8. Fuel consumption versus NSER [July and August] (Battery capacity = 25%).

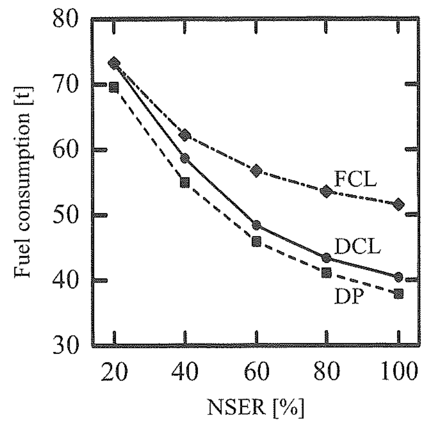

Fig.10. Fuel consumption versus NSER for various operating methods [July and August] (Battery capacity = 25%).

battery, so that the charge level goes down to X_{min}.

6.3 Fuel Consumption

The fuel consumption for every day can be calculated from the time series results of the DG output as shown in Fig. 6 and the equation (3). The parameters are the battery capacity and the natural energy supply ratio (NESR).

Figure 7 shows the fuel consumption versus battery capacity during July to August, where the NESR is 100%. The fuel consumption decreases as the battery capacity increases, because the excess energy (the energy above the electric load) from the PVG is stored more in the battery as the battery capacity is larger. Figure 8 shows the fuel consumption versus NESR during July to August where the battery capacity is 25%. The fuel consumption decreases as the NESR increases. The minimum fuel consumption is reached when NESR is 100%.

7. Full Charge Level and Dynamic Programming Operating Methods

In order to estimate the DCL operating method, it has to be compared with other operating methods. Here, two methods are adopted: the full charge level (FCL) operating method and the dynamic programming (DP) operating method[(4)(6)].

7.1 FCL Operating Method

As mentioned above, the stand-alone photovoltaic/diesel/battery power system has to avoid the shortage of power supply to the electric load. Hence, it is favorable to maintain the battery charge at a full level, i.e., 100%. The FCL operating method is the common operating method and corresponds to the DCL operating method in which the daily specified charge level is set to 100%.

7.2 DP Operating Method

If the hourly data on electric load 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 operating method theoretically gives the lowest fuel consumption.

7.3 Comparison Results

Figure 9 shows the fuel consumption versus battery capacity for three different operating methods (FCL, DCL and DP) during July to August. With any battery capacity, the fuel consumption by DCL and DP methods are lower than the FCL method. The difference is largest with the battery capacity of

100%: the fuel consumptions are 51.5, 20.8 and 18.8 t by FCL, DCL and DP methods, respectively.

Figure 10 shows the fuel consumption versus NESR for FCL, DCL and DP operating methods. When the NESR is 20%, the fuel consumption by DCL is as same as that by FCL but higher than DP. When the NESR is higher than 20%, the fuel consumption with DCL is lower than FCL but not than DP. The difference is largest when the NESR is 100%: the fuel consumptions are 51.5, 40.4 and 37.8 t by FCL, DCL and DP operating methods, respectively.

8. Concluding Remarks

An operating method, DCL operating method, applicable to a stand-alone photovoltaic/diesel/battery power system is introduced in this paper. The output of diesel generator is controlled not only to meet the electric load but also to maintain the battery charge at certain daily specified charge level every day. The daily specified charge levels are obtained at which the fuel consumption is minimum. A simulation is performed over one year using the hourly data of electric load, insolation intensity and atmospheric temperature on Kamishima Island, Japan in 1996.

The DCL operating method is compared with others, i.e., the FCL operating method and the DP operating method. By the simulation results, the fuel consumption of the DCL operating method is lower than that of the FCL operating method but not than the DP.

Forecasting methods for the daily electric load, the insolation intensity[(7)-(9)] and the atmospheric temperature have been developed. Therefore, the DCL operating method may be practically applied.

Our future work is the investigation of the optimum combination of the battery capacity, the NESR and the diesel generator size under given electric load and weather condition.

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