研究論文

An Operating Method for Fuel Savings in a Stand-Alone Wind/Diesel/Battery System

Yusuf ISMAIL * Yoshishige KEMMOKU *

Hirofumi TAKIKAWA * Tateki SAKAKIBARA *

Abstract

A new method for operating a stand-alone wind/diesel/battery system is presented in this paper. The system, especially its diesel generator, is controlled so that a given constant battery charge level may be maintained, i.e., the battery is charged when the charge is lower than the constant level and discharged when higher. A simulation was carried out over one year using the hourly data of electric load and wind speed on Kamishima Island, Japan in 1996. This method was compared with other methods; a conventional operating method maintaining the battery at the fully charged level and a dynamic programming operation method (DP method). The results show that for diesel generator fuel consumption, this method is superior to the conventional method, although not to the DP method, and that for excess energy this method is much better than the conventional method and as good as the DP method.

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

1. Introduction

Many stand-alone wind/diesel/battery systems have been installed on remote islands [1-4]. It is required to operate the system so that the fuel consumption of the diesel generator is minimized without causing any blackout, in order to reduce the primary energy consumption and the fuel cost during the system running. In such operation[5-8], the battery has the role of storing surplus energy or of assisting a wind turbine generator. If the battery is used to store surplus energy, the battery charge level has to be kept low. On the other hand, if the battery is used to assist a wind turbine generator, its charge has to be kept high. Thus, the operating method of the battery differs with the purpose for which it is used.

A new method of operation is investigated in this paper. The diesel generator is so controlled that the battery charge level is kept constant between the minimum (20%) and maximum level (100%) of battery capacity. Here, this is called the CCL method. In this method, the battery is charged when its level is less than constant, and discharged when it exceeds it. A simulation was performed for over one year using the hourly data of electric load and wind speed on Kamishima Island, Japan in 1996. The most suitable battery charge level was pursued, i.e., the level at which fuel consumption is lowest.

The CCL method is compared with other methods[8] from the viewpoints of annual fuel consumption and excess energy.

2. System Configuration

Energy flows in the stand-alone diesel/wind/battery system are shown in figure 1, in which $Pw(t_i)$ is the output energy from a wind turbine generator (WTG), $Pd(t_i)$ is the output energy from a diesel generator (DG), $Pb(t_i)$ is the output energy from a battery, $Pl(t_i)$ is the energy consumed in an electric load, and t_i is the hourly time over one year (i = 1, 2, ・・・, 8760). They have to satisfy the following equation. $Pb(t_i)$ is positive when the battery is discharged and negative when charged.

$$Pw(t_i) + Pd(t_i) + Pb(t_i) = Pl(t_i) \qquad (1)$$

3. Electric Load and Wind Energy

The hourly data of electric load and wind speed adopted in this study were recorded on Kamishima Island, Aichi Prefecture, Japan in 1996. Their monthly variations are shown in figure 2. The electric load is high in July and

* Dept.of Electrical and Electronic Engineering, Toyohasi University of Technology
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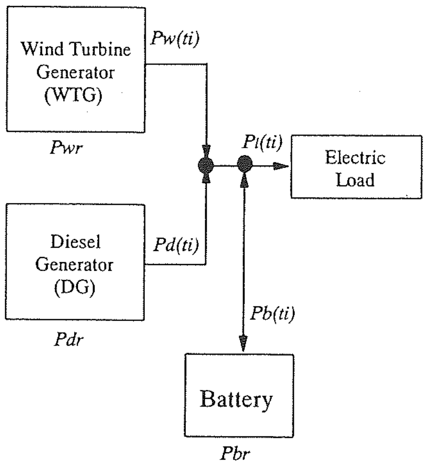


Fig. 1 Energy Flows in Wind/ Diesel/Battery System

August. Since the annual electric load energy is 1,583 MWh and the peak load is 393 kW, the load factor is 46%. The average daily electric load is 4,336 kWh.

The wind energy calculations are made by matching the power-wind speed characteristics of a commercial wind turbine generator with hourly wind speed data from over one year. The characteristics of the wind turbine generator are described by an equation (2). The calculation result is for a case in which the rated output of WTG is 250 kW. The wind energy is high in January, February, March, November and December.

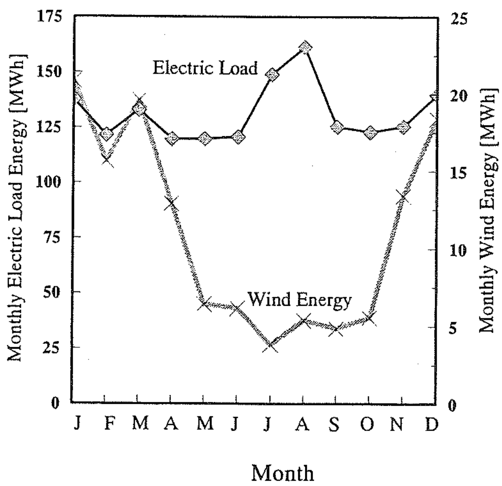


Fig. 2 Monthly Variations in Electric Load, and Wind Energy used in this Simulation

4. Characteristics of System Elements

4.1. Wind Turbine Generator (WTG)

Output-wind speed characteristics (Pw-v characteristics) of WTG are given by the following equation [9]:

$$Pw = \begin{cases} 0 & (v < vc,\ vo \leqq v) \\ Pwr \times (v - vc)/(vr - vc) & (vc \leqq v < vr) \\ Pwr & (vr \leqq v < vo) \end{cases} \quad (2)$$

where Pwr is the rated output of WTG, vc is the cut-in wind speed, vr is the rated wind speed and vo is the cut-out wind speed. Here, Pwr = 250 kW, vc = 5 m/s, vr = 12 m/s, vo = 25 m/s.

4.2. Diesel Generator (DG)

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

$$Fd = \mathrm{a} \times Pd^2 + \mathrm{b} \times Pd + \mathrm{c} \quad (3)$$

where Fd is the fuel consumption of DG and Pd is the output of DG. The coefficients a, b and c are determined by fitting the equation (3) to the characteristics of a commercial DG. The lowest output is assumed to be 20% of the rated output. The rated outputs are taken as parameters; 250, 300, 350, and 400 kW. Figure 3 shows the characteristic of a rated output of 400 kW; those of other rated outputs are almost the same.

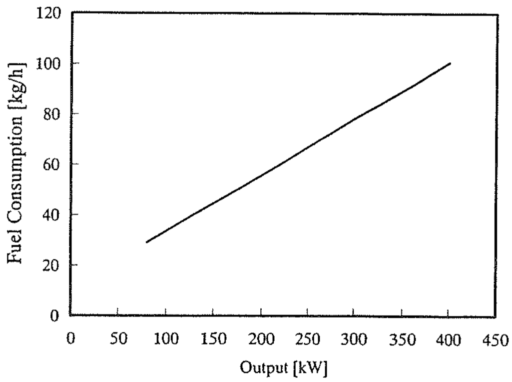


Fig. 3 Fuel Consumption versus Output of a Diesel Generator (rated output : 400 kW)

4.3. Battery

Battery capacity is taken as a parameter and figured in percentages. The entire 100% of battery capacity is equivalent to an average daily electric load (4,336 kWh).

Range of charge level of the battery is assumed to be from 20% to 100% of battery capacity, supposing that the battery can be used to the utmost limit.

The charging efficiency changes with the state of charge, the charge current (or charging hourly energy change)and the temperature. However, if the charge current is controlled to 10% or less of battery capacity, it may be assumed that their effections on the charging efficiency are small. Therefore, charging and discharging efficiencies are assumed to be 85% and 100%, respectively, for simplification of the model.

Hourly maximum charging and discharging energy changes are also limited to 10% and 20% of battery capacity, respectively.

5. Operating Method

It is a self-evident truth that blackouts are never induced by stand-alone wind/diesel/battery systems. Under that circumstance, it is technically desirable to reduce fuel consumption and excess energy to as low a level as possible. The fuel is consumed in DG. In the event, that the output from WTG exceeds the electric load and the battery charge level is maximum, then the excess energy is drained away. Therefore, the battery and the DG have to be so operated that the system may meet these requirements. Here the WTG is assumed to be uncontrollable.

In this paper, a new operating method which we call the Constant Charge-Level method (CCL method) is proposed. In this method, the system is so operated that the battery charge is kept at a constant level as long as possible. That level is between 20 and 100% of battery capacity. When the charge level is lower than the constant level, the output of DG has to be increased to charge the battery, but when the charge level is higher than the constant level, the output of DG has to be decreased to discharge the battery. Should the charge level drop to less than a 20% level, a blackout would occur. On the other hand, when the charge level rises to around the 100% level, WTG would generate some excess energy. Therefore, the constant level has to be selected appropriately.

The operation of the system is divided into three scenarios depending on $Pl'(t_i)$ which is the defference of electric load, $Pl(t_i)$, and the output of WTG, $Pw(t_i)$, and the battery charge level, $X(t_i)$, as follows:

Scenario 1: $Pl'(t_i) > Pd_{max}$

Scenario 2: $Pl'(t_i) \leqq Pd_{max}$ and $X(t_i) \leqq Xc$

Scenario 3: $Pl'(t_i) \leqq Pd_{max}$ and $X(t_i) > Xc$

where, Pd_{max}: maximum output of diesel generator (= rated output)

Xc: constant battery charge level

Scenario 1:

Energy of $\{Pl'(t_i) - Pd_{max}\}$ is supplied from the battery. If the energy is greater than P_{dismax} which is maximim battery discharge energy, then a blackout occurs. Here, P_{dismax} is the smaller one among $\{(X(t_i) - 20)/100 \cdot C_B\}$ and $\{20/100 \cdot C_B\}$, where C_B is the battery capacity [kWh] and is battery capacity [%] times daily electric load [kWh].

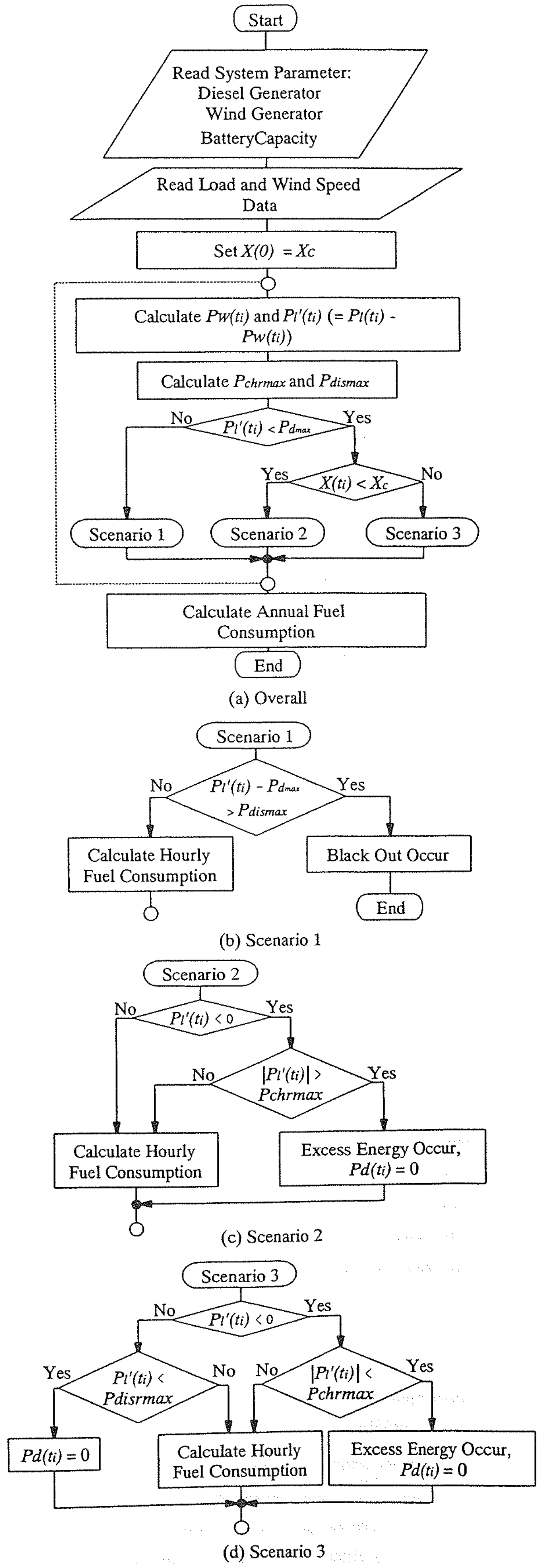


Fig. 4 Flow Chart of Method to Maintain Constant Battery Charge Level

Scenario 2:

DG supplies energy to the battery so that its charge level is elevated to the constant level. If $Pl'(t_i)$ is negative and $|Pl'(t_i)|$ is greater than P_{chrmax} which is maximim battery charge energy, then excess energy occurs and DG supplies no energy. Here, P_{chrmax} is the smaller one among {(100-$X(t_i)$)/100 ·C_B} and {10/100 ·C_B}.

Scenario 3:

The battery is discharged so that its charge level is lowered to the constant level. The discharged energy must be less than P_{dismax}. If $Pl'(t_i)$ is greater than P_{chrmax}, then DG supplies no energy. However, if $Pl'(t_i)$ is negative, the battery is charged. Moreover, if $|Pl'(t_i)|$ is greater than P_{chrmax}, then excess energy occurs and DG supplies no energy.

A flow chart of the CCL method is shown in figure 4. First, data of the electric load and wind speed are read. Next, the initial charge level, $X(0)$, and the constant level, Xc, are read. Then the output of WTG is calculated, and the diesel generator and the battery are operated comparing $X(0)$ with Xc such as in scenarios 1, 2, and 3. The calculation is repeated hourly, and finally the annual fuel consumption is obtained.

The system parameters are as follows. The rated output of WTG: 250 kW. The rated output of the diesel generator: 250, 300, 350, and 400 kW. The battery capacity: 10% to 100% of the average daily electric load (4,336 kWh).

6. Result and Discussion

6.1. Time Series Results

Figure 5 shows examples of time series results in which the rated output of DG, the battery capacity, and the constant battery charge level are 250 kW, 50% and 80%, respectively. Sometimes in winter (figure(a)), the WTG generates much energy so that the battery charge is higher than the constant level. In summer it generates no energy for several days, so the battery charge falls below the constant level.

6.2. Fuel Consumption and Excess Energy

Figure 6 shows annual fuel consumption and annual excess energy as functions of the battery constant charge level for different rated outputs of DG, the battery capacities being 25% (a) and 100% (b). There is no curve for a rated DG output of 250 kW in case of the battery capacity being 25% (figure(a)) since then a blackout would occur. Figure 6(a) shows the following tendencies. Fuel consumption is almost constant at constant levels from 20% to 90% and increases as the constant level rises from 90% to 100%. It also increases as the rated power of DG increases. Excess energy increases little by little as the constant level rises from 20% to 90%, and it does not depend on the rated output of DG. However, it increases dramatically as the constant level rises from 90% to 100%, and increases with the rated output of DG.

Figure 6(b) exhibits the same tendency as figure 6(a). In figure 6(b), curves of a rated DG output of 250 kW are added. The reason is that there is no blackout for a rated DG output of 250 kW in case of a battery capacity of 100%.

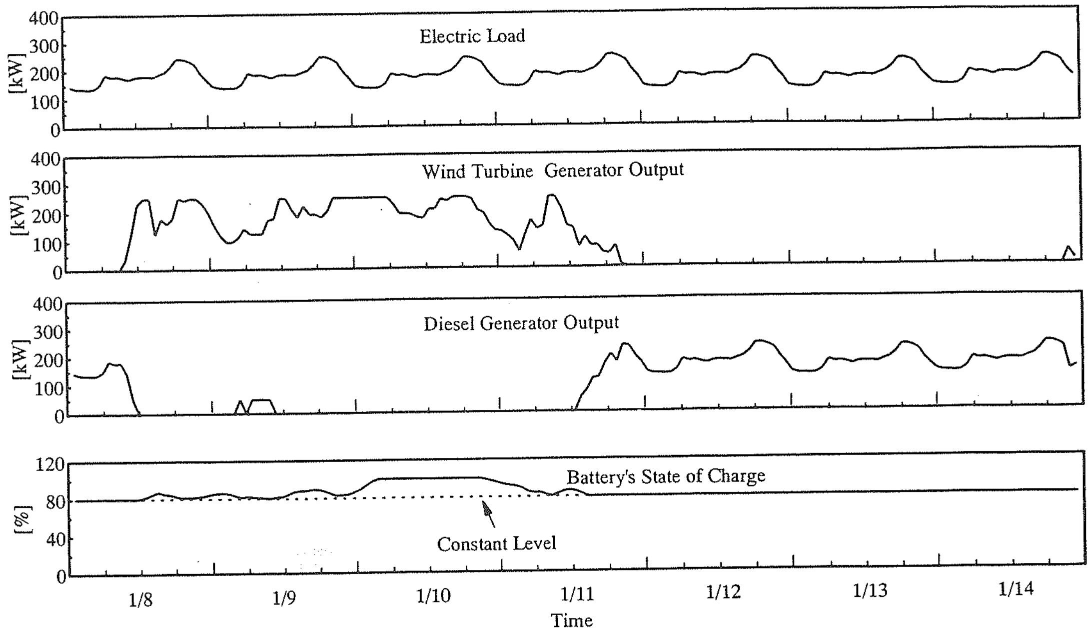
6.3. Optimum Constant Level

As for fuel consumption versus a constant level curve of figure 6, a blackout occurs at a constant level below 41% in case of a rated DG output of 250 kW. It is generally desirable that the constant level is as low as possible because then the battery capacity could be minimized. The minimum constant level above which blackouts never occur is here called the "optimum constant level". Such a level is obtainable from the simulation according to the flow chart of figure 4 if the battery capacity and the rated output of DG are specified. Figure 7 shows the optimum constant charge level as a function of battery capacity for different rated outputs of DG. When the rated output of DG is 400 kW, the optimum constant level remains at 20%, and rises to 21% if the rated output of DG is 350 kW. However, when the rated output of DG is 250 or 300 kW, the optimum constant level decreases with battery capacity.

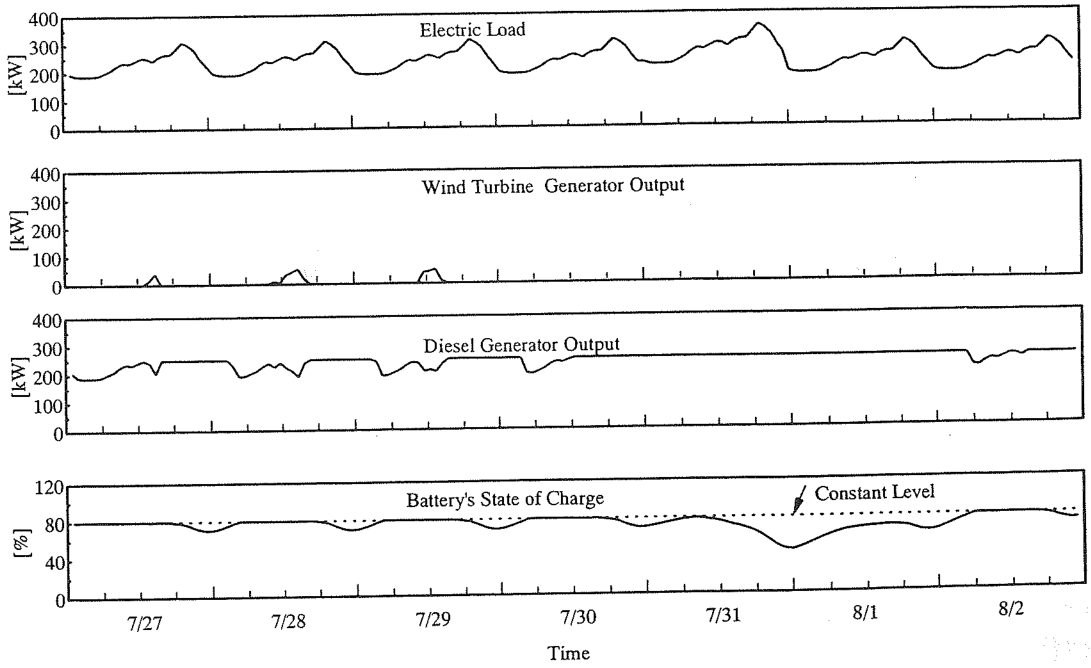
Figure 8 shows fuel consumption and excess energy as functions of battery capacity for different rated outputs of DG in case of the constant level being set to the optimum. We call this the Optimum Charge-Level (OCL) method. It becomes evident from this figure that (1) fuel consumption does not depend on battery capacity but increases with the rated output of DG, although a blackout occurs when battery capacities fall below 50% in case of the rated DG output of 250 kW; and (2) excess energy decreases sharply to zero as battery capacity increases from 10% to 25%. It can be concluded that a battery capacity of 50% is sufficient for a rated DG output of 250 kW, and a battery capacity of 25% is sufficient for rated DG outputs above 300 kW.

6.4. Comparison with Other Operating Methods

In order to evaluate the OCL method, it has to be compared with other operating methods. Here, two alternative methods are adopted: full charge-level operation and dynamic programming.



(a) Winter



(b) Summer

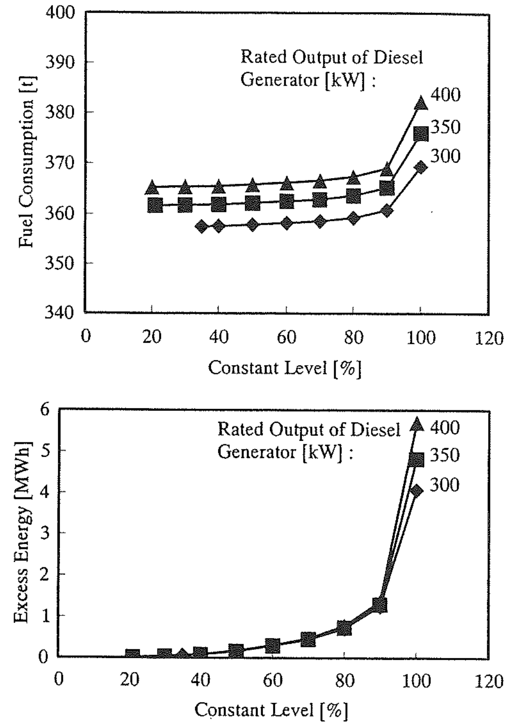
Fig. 5 Example of Time Series Results

6.4.1. Full Charge-Level Operating Method (FCL method)

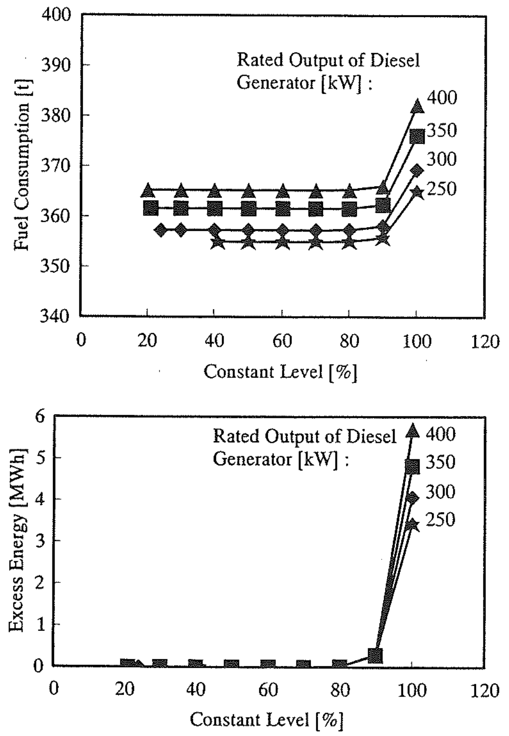
As mentioned above, the stand-alone wind/diesel/ battery system must avoid blackouts. Hence, it is favorable to maintain the battery at a fully-charged level, i.e., 100%. This operating method corresponds to the CCL method in which the constant level is set to 100%.

6.4.2. Dynamic Programming Operating Method (DP method)

If the hourly data of electric load and wind speed are known for one full year, the dynamic programming (DP) method could be applied to the operating method of the wind/diesel/battery system. In this DP method, it is necessary to know a priori the hourly data of electric load and wind



(a) Battery Capacity : 25%



(b) Battery Capacity : 100%

Fig. 6 Annual Fuel Consumption and Excess Energy Versus Constant Level of Battery's State of Charge

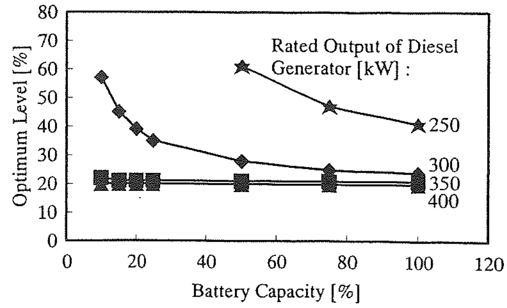


Fig. 7 Optimum Level of Battery's State of Charge

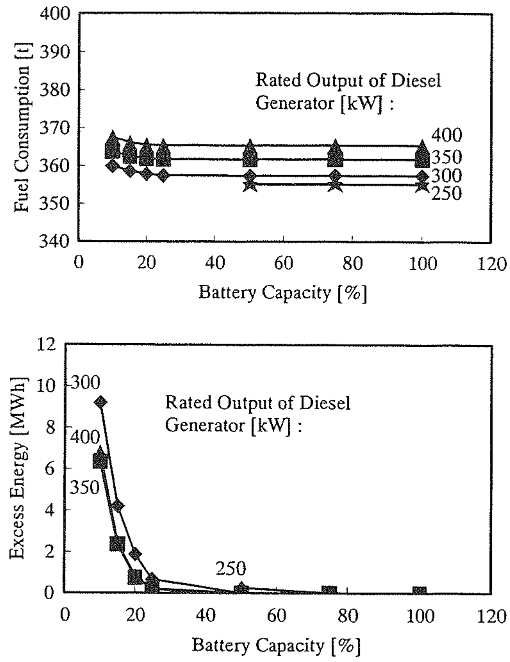
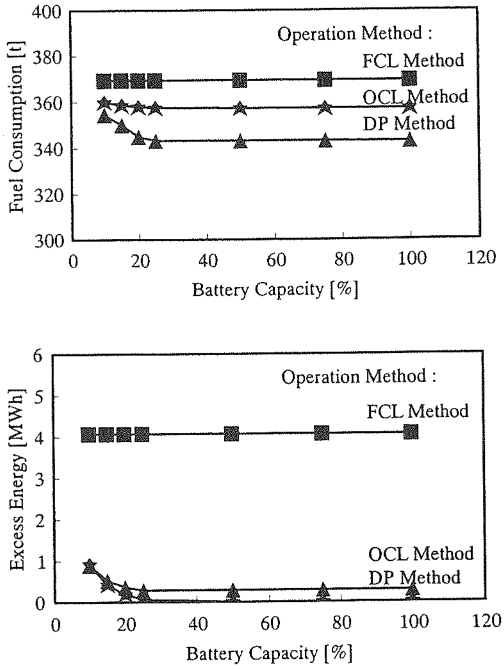


Fig. 8 Fuel Consumption and Surplus Energy Versus Battery Capacity of the System Operated at the Optimum Level

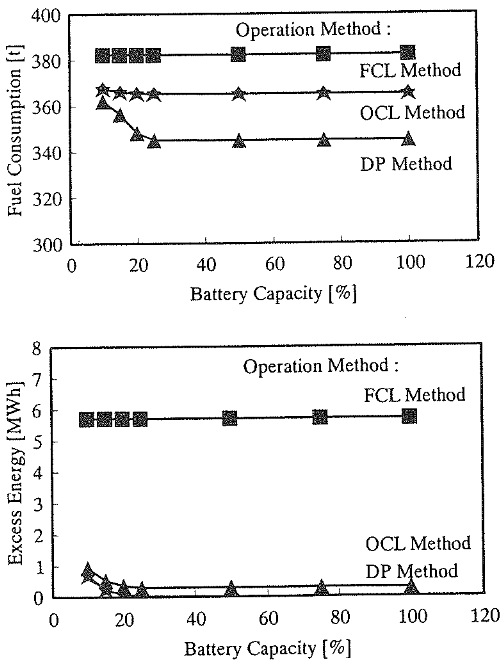
generated output through the year before the system operation. Therefore, this DP methos is not practical.

6.4.3. Comparison

Figure 9 shows annual fuel consumption and excess electric energy as functions of battery capacity for different operation methods, the rated output of DG being 300 kW in figure (a) and 400 kW in figure (b), respectively. It is evident from figure (a), that the fuel consumption of the OCL method is lower than that of the FCL method by 12 t (3%), although higher than that of the DP method by 14 t (4%). The excess energies are 4.1 MWh with FCL, 0.3 MWh with OCL, and 0 MWh with DP, respectively. In a comparison of figures (a) and (b), the fuel consumption in figure (b) turns out to be higher than that in figure (a), and the excess energy in figure (b) is higher than that in figure (a) for the FCL method. It is concluded from figure 9 that the OCL method is superior to the FCL method although inferior to the DP method.



(a) Rated Output of Diesel Generator : 350 kW



(b) Rated Output of Diesel Generator : 400 kW

Fig. 9 Comparison of This Operation Method with Other Operation Methods ;
OCL Method: Optimum Charge Level Operation Method;
FCL Method : Full Charge Level Operation Method;
DP Method : Dynamic Programming Operation Method.

7. Concluding Remarks

A new operating method applicable to a stand-alone wind/diesel/battery system is investigated in this paper. The output of the diesel generator is controlled so that the battery charge may be maintained at a constant level. 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 value of the daily electric load. Parameters are the outputs of the diesel generator (250 to 400 kW), the battery capacity (10 to 100%), and the constant battery charge level (20 to 100%). The optimum value of the constant level is pursued, at which the fuel consumption is at a minimum without causing any blackout.

A Simulation results show that (1) fuel consumption is constant at below 90%, and it increases as the constant level rises above 90%, (2) excess energy is scarce at constant levels below 90% while it increases abruptly as the constant level exceeds 90%, (3) fuel consumption and excess energy increase with the rated output of DG, (4) the optimum value of the constant level decreases with the battery capacity and the rated output of DG, (5) when the system is operated maintaining the battery charge at the optimum level, fuel consumption is constant and not dependent on battery capacity while it decreases with the rated output of DG, and excess energy decreases greatly as battery capacity falls below 20%.

From the results mentioned above, the optimal battery capacity and DG can be found. For example, a battery capacity of 25% and a rated DG output of 300 kW fit the electrical needs of Kamishima Island.

This operating method is compared with others, i.e., FCL method and the dynamic programming method. FCL method sets the constant battery charge level at 100% of the CCL method. The results show that fuel consumption with the OCL method ranges between the FCL and the dynamic programming method, and excess energy with the OCL method is the same as with the dynamic programming method.

Both the CCL and OCL methods are applicable to any circumstances, if the hourly data of electric load and wind speed for over one year or more are known.

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