Paper

Comparison of Operating Methods of Battery in a Stand-Alone Photovoltaic/Wind/Diesel/Battery Power System

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A new method for operating a stand-alone photovoltaic/wind/diesel/battery hybrid power system is presented. The system, especially its diesel generator, is controlled so that the battery charge is kept at a specified level. The battery is charged when its present charge level is lower than the specified level and discharged when higher. A simulation is carried out over one year using the hourly data of electric load, insolation, temperature, and wind speed at Kamishima Island, Japan in 1996. This method is compared with other methods: a conventional operating method and a dynamic programming operating method. The results show that in regards to the fuel consumption of diesel generator, the proposed operating method is superior to the conventional method although not than the DP method, and the fuel consumption has a minimum if the PV energy is same as the wind energy.

Keywords : photovoltaic/wind/diesel/battery system, simulation, operating method, battery charge-level, fuel consumption

1. Introduction

Stand-alone diesel generator units, while being relatively reasonable in cost, are generally expensive to operate and maintain especially at low load levels. However, integrating them to a wind turbine generator, a photovoltaic generator and a battery storage becomes cost-effective. Besides being emission-free, the energy coming from the wind and sunrays are available at no cost. In addition, they offer a solution for power supply to remote areas that are not accessible by the utility company, and to developing countries that are poor in fossil-based resources. The interest in renewable energy forms is indeed growing worldwide [1]. From the view point of reducing CO_2 emission, utilization of wind and photovoltaic energies have been positively in 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 power densities are also low relatively [3]. Thus it is limited when they are applied exclusively. In fact, the supply of renewable energies may not coincide with electricity demand. So, the battery must be provided for this missing link [4].

The main purpose of introducing the battery storage is to import/export energy depending upon the situation. The following basic operating strategy is employed [5]:

- The use of electric power generated by the wind turbine generator and photovoltaic generator has priority in satisfying electricity demand over that provided by the batteries or by the diesel generator.
- If the total electric power generated by the wind turbine generators and photovoltaic generator is higher than the demand, the additional electric power will be charged into the battery.
- After charging the battery, the electric power that remains is disposed of.
- If the total electric power generated by the wind turbine generator and the photovoltaic generator is less than the demand, electric power will be discharged from the batteries to supply the demand because once the battery is bought, their major cost would have been committed and their use is given to priority.
- If the battery cannot supply the demand, then electric power has to be drawn from the diesel generator.

A new operating method has been proposed in our previous paper [6]. The diesel generator is so controlled that the battery charge is kept at a specified level: the battery is charged when its level is lower than the specified level and discharged when higher. A minimum specified charge level has been investigated at which the annual fuel consumption of the diesel generator has a minimum.

In the present paper, the new operating method is applied to a photovoltaic/wind/diesel/battery system and the fuel consumption is discussed, where the system parameters are the natural energy supply ratio, the energy ratio of photovoltaic generator to the wind turbine generator, the diesel generator size and the battery size.

2. System Configuration

The system consists of a photovoltaic generator, a wind turbine generator, a diesel generator and a battery.

Energy flows in the stand-alone photovoltaic/wind/diesel/ battery hybrid system are shown in Fig. 1, in which $Ps(t)$ is the output of the photovoltaic generator, $Pw(t)$ is the output of the wind turbine generator, $Pd(t)$ is the output of the battery, $Pl(t)$ is the energy consumed in an electric load and t is the hourly time over one year. These flows must satisfy the equation (1). $Pb(t)$ is positive when the battery is discharged and negative when charged.

$$Ps(t) + Pw(t) + Pd(t) + Pb(t) = Pl(t) \quad (1)$$

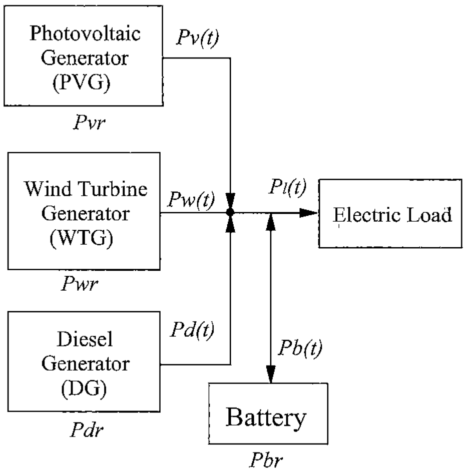


Fig. 1. Energy flows in photovoltaic/wind/diesel/battery systems

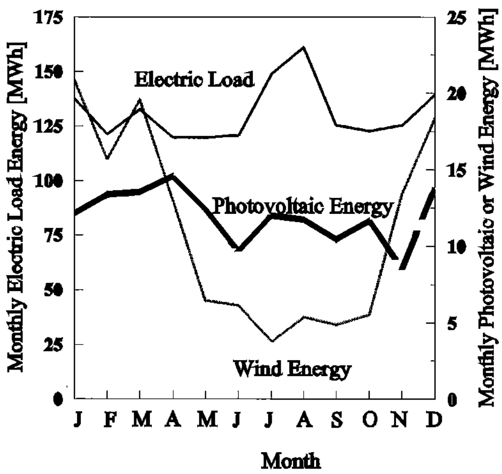


Fig. 2. Monthly variations in electric load, photovoltaic, wind energies (PV size = 100 kWp; WTG size = 100 kW)

The hourly data of electric load, insolation, wind speed, and temperature adopted in this study were recorded at Kamishima Island, Aichi Prefecture, Japan in 1996.

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. 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 photovoltaic generator output is calculated using the equation (2). The characteristics of the wind turbine generator is described by an equation (3). The calculation results of figure (2) are for the case of the rated output of PV as 100 kWp and WTG as 100 kW. The wind energy is higher than the PV energy in January, February, March, November and December, but lower in May, June, July, August, September and October.

4. Characteristics of System Elements

4.1 Photovoltaic Generator (PVG) Output of photovoltaic generator is calculated by the equation 2.

$$Ps = \varepsilon \cdot A \cdot \theta \cdot (1 - 0.005 \cdot (T + 5)) \quad \cdots\cdots (2)$$

Table 1. System parameters

NESR (%)	20 ~ 100
PV/Wind (%/%)	100/0, ~, 50/50, ~, 0/100
Diesel Size (kW)	250, 300, 350, 400
Battery Size (%)	10 ~ 100

NESR. Natural energy supply ratio to the yearly electric load (1,583 MWh).
PV/Wind. Energy Ratio of photovoltaic generator to wind turbine generator.
Battery Size Normalized with the average daily electric load (4,336 kWh).

Where Ps: output of photovoltaic generator (kW)
ε : efficiency (0.15)
θ : insolation (kW/m^2)
A : area (m^2)
T : temperature (°C)

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

$$Pw = \begin{cases} 0 & (v < vc,\ vo \leqq v) \\ Pwr \cdot (v - vr)/(vr - vc) & (vc \leqq v < vr) \\ Pwr & (vr \leqq v < vo) \end{cases} \quad \cdots\cdots (3)$$

Where Pw is the output power, v is wind speed, Pwr is the rated power, vc is the cut-in speed (= 5 m/s), vr is the rated speed (= 12 m/s) and vo is the cut-out speed (= 25 m/s).

4.3 Diesel Generator (DG) The fuel consumption of a diesel generator is calculated using the following equation:

$$Fd = a \cdot Pd^2 + b \cdot Pd + c \quad \cdots\cdots (4)$$

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 (4) to the characteristics of a commercial DG. The output is controlled between 20% and 100% of the rated output. Furthermore, the rated outputs of DG are taken as parameters: 250, 300, 350, and 400 kW.

4.4 Battery Battery capacity is taken as a parameter and figured in percentages. The battery capacity of 100% is equivalent to an average daily electric load (4,336 kWh). Charging and discharging efficiencies are 85% and 100%, respectively. Hourly energy changes are limited to 10% and 20% of the battery capacity when charging and discharging, respectively.

The system parameters are rearranged in Table 1.

5. Specified Charge-Level Operating Method

When the system is operated, it is desirable to reduce the yearly fuel consumption of the diesel generator as much as possible. Moreover, when the output from PVG plus WTG exceeds the electric load and then the battery is fully charged, excess energy occurs and has to be drained away to a dummy load. Therefore, the battery and the DG have to be so operated that the yearly fuel consumption of DG and the excess energy are kept as low as possible.

In this paper, a new operating method that we call the Specified Charge-Level method (SCL method) is proposed. In the SCL method, the system is so operated that the battery is kept at a specified charge-level as long as possible. That level is taken between 20 and 100% of the battery capacity. When the charge-level is lower than the specified level, the DG output has to be increased to charge the battery, and when the charge is higher than the specified level, the DG output has to be decreased to discharge the battery. If the specified level is 20%, the battery cannot be discharged. On the other hand, if the specified level is set to around 100%, the battery cannot be charged. Therefore, the specified level has to be selected appropriately.

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

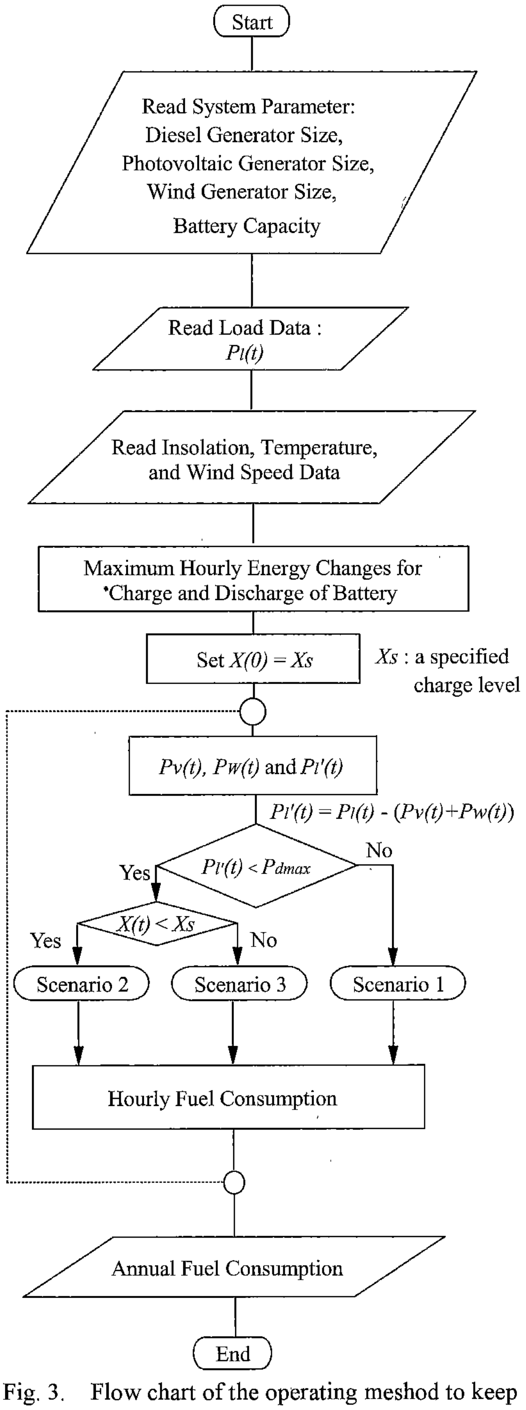


Fig. 3. Flow chart of the operating meshod to keep battery at a specified charge level

Scenario 1: $Pl(t) - (Pv(t) + Pw(t)) > Pdmax$

Scenario 2: $Pl(t) - (Pv(t) + Pw(t)) \leqq Pdmax$ and $X(t) \leqq Xs$

Scenario 3: $Pl(t) - (Pv(t) + Pw(t)) \leqq Pdmax$ and $X(t) > Xs$

Where, $Pdmax$: the rated output of diesel generator

Xs: a specified charge-level of battery

Scenario 1: Energy of $\{Pl(t) - (Pv(t) + Pw(t)) - Pdmax\}$ is supplied from the battery. The hourly energy change must be less than 20% of the battery capacity.

Scenario 2: DG supplies energy to the battery so that its charge level is elevated to the specified level. The hourly energy charge must be less than 10% of the battery capacity.

Scenario 3: The battery is discharged so that its charge level is lowered to the specified level. The hourly energy discharge must be less than 20% of the battery capacity.

A Flow chart of the SCL method is shown in Fig. 3. First, data on the electric load, insolation, atmospheric temperature and wind speed are read. Next, the initial charge level, X(0), and a specified level, Xs, are read. Then the output of PVG and WTG are calculated. The diesel generator and the battery are operated comparing X(0) with Xs such as in scenarios 1, 2, and 3. The calculation is repeated hourly, and finally the annual fuel consumption is obtained.

6. Full Charge-Level and Dynamic Programming Operating Methods

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

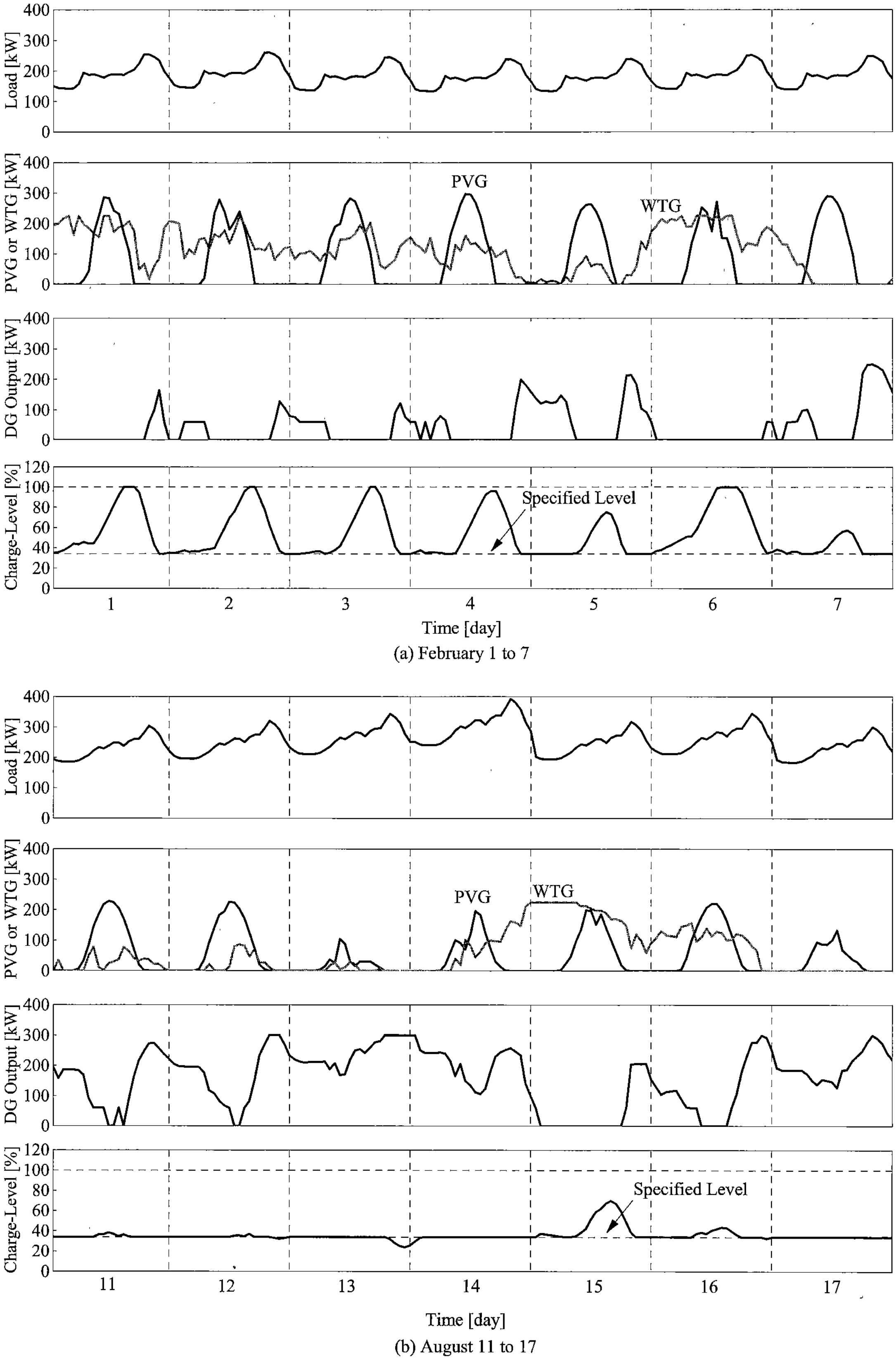
6.1 Full Charge-Level (FCL) Operating Method In the full charge-level (FCL) operating method, the battery is mainly to assist PVG and WTG. Therefore, the battery is kept fully charged. This operating method corresponds to the SCL method in which the specified charge-level is set to 100%.

6.2 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 applied to operate the system. In this DP method, the estimated value is the annual fuel consumption, the control variable is the output of DG, and the state variable is the battery charge-level. The DP method gives the lowest annual fuel consumption of any operating methods, although it is not a practical operating method to use.

7. Results and Discussion

7.1 Time Series Result Figure 4 shows examples of time series results calculated with the parameters of DG size, battery size, PV/Wind ratio, NESR and specified charge-level at 300 kW, 25%, 50/50, 60%, and 34%, respectively. Figure 4 (a) shows these parameters for February and (b) those for August. In regard to electric load, February is lower than August, while in regard to PVG and WTG, February is higher than August.

In February, when the power generated by PV plus WTG is larger than the electric load, DG stops and the charge increases from the specified level to the 100% level. On the other hand, when the power generated by PVG plus WTG is smaller than the electric load, the battery discharges, i.e., the charge decreases from 100% to the specified level. And when the charge reaches the specified level, DG begins to operate. On the sixth day the charge reaches 100%, so the PVG output plus



(a) February 1 to 7

(b) August 11 to 17

Fig. 4. Time series example of operating method (diesel size = 300 kW, PV/wind = 50/50, NESR = 60%, battery size = 25%, specified charge-level = 34%)

WTG output minus the electric load is referred to as excess energy.

In August, the electric load is larger than the PVG plus WTG output during the whole week except on the fifteenth day. The charge is kept at the specified level by controlling the DG output. The charge is always below 100%, so no excess energy occurs.

7.2 Fuel Consumption and Excess Energy If the simulation parameters are given, the annual fuel consumption and excess energy are calculated from the annual time series result as shown in Fig. 4.

Figure 5 shows the annual fuel consumption versus the specified charge-level for various battery sizes. Diesel generator size, natural energy supply ratio, and PV/Wind are 300 kW, 50%, and 50/50, respectively. If the battery size is 50% or less, the fuel consumption increases as the specified charge-level increases. With a battery size of 100%, the fuel consumption is constant with the specified charge-level of 20 to 70%, while it increases sharply as the specified charge-level increases from 80 to 100%.

It is shown that the fuel consumption decreases as the specified level decreases if the battery size is constant. If the battery size is 10%, the specified level could not be kept below 50%. Otherwise, the hybrid system could not supply power to the electric load. In other words, there is a specified level at which fuel consumption has a minimum value. Here, we call it the minimum specified level. If the battery size is 10%, the minimum specified level is 50%, and if a battery size is 25% the minimum specified level is 30%. Thus, if parameters (battery size, DG size, etc.) are given, the minimum specified level could be obtained from the annual simulations.

Figure 6 shows the annual excess energy versus the specified charge-level for various battery sizes, parameters being same as Fig. 5. The excess energy increases as the specified level increases and the battery size decreases. With these parameters, the dependence of the excess energy on the specified level and the battery size are quite the same as those for fuel consumption. If one of the parameters, for example, NESR, takes higher value (70~100 %), the dependence of the excess energy becomes slightly different from those of the fuel consumption.

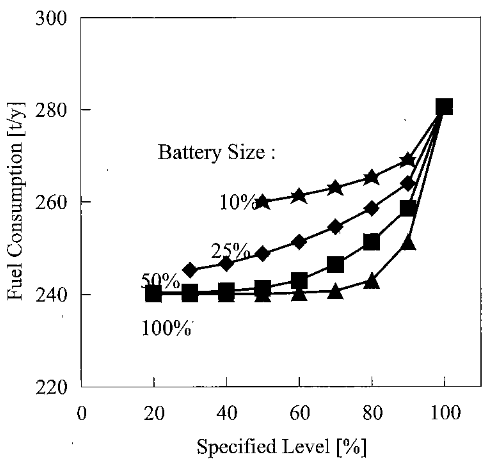


Fig. 5. Annual fuel consumption versus specified level (diesel size = 300 kW, PV/wind = 50/50, NESR = 50%)

7.3 Minimum Specified Charge Level Figure 7 shows the minimum specified charge level versus the battery size for various diesel generator sizes. NESR and PV/Wind are 50% and 50/50, respectively. If the diesel generator size is 300 kW, the minimum specified level increases sharply as the battery size decreases from 50% to 10%. If the diesel generator size is 350 and 400 kW, the minimum specified charge-level is almost 20% constant, the minimum charge-level of the battery.

In these cases, the battery is not used effectively but diesel generator almost compensates for the power shortage in relation to the electric load such as Fig.4 (b). The minimum specified charge-level is influenced by system parameters, so it should be determined for every set of system parameters.

7.4 Comparison With Other Operating Methods
Figure 8 shows examples of time series results of different operating methods: FCL (Full Charge-Level operating method, see Section 6.1), MSCL (Minimum Specified Charge-Level operating method) and DP (Dynamic Programming method, see Section 6.2). Time series data for the electric load, PVG and WTG outputs are same as in Fig. 4. From the time series results, it is clear that in regard to the charge-level; (1) in February,

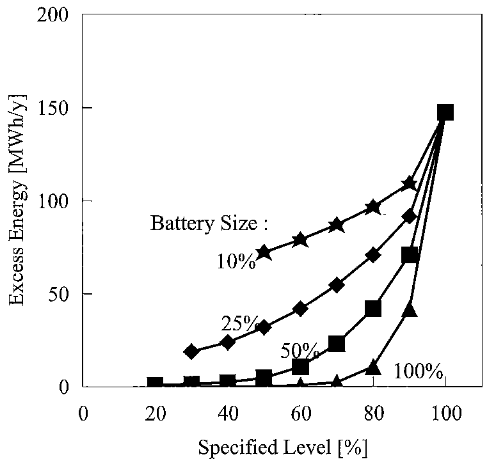


Fig. 6. Annual excess energy versus specified level (diesel size = 300 kW, PV/wind = 50/50, NESR = 50%)

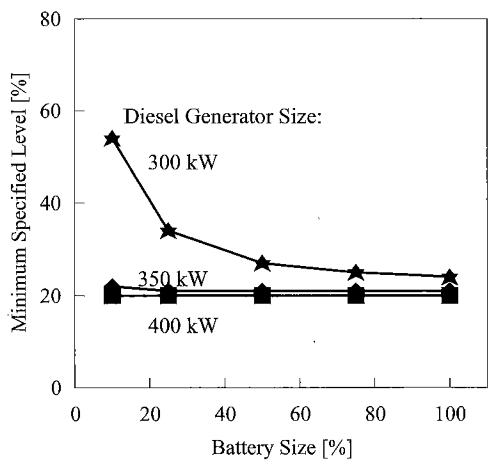


Fig. 7. Minimum specified level versus battery size (NESR = 50%, PV/wind = 50/50)

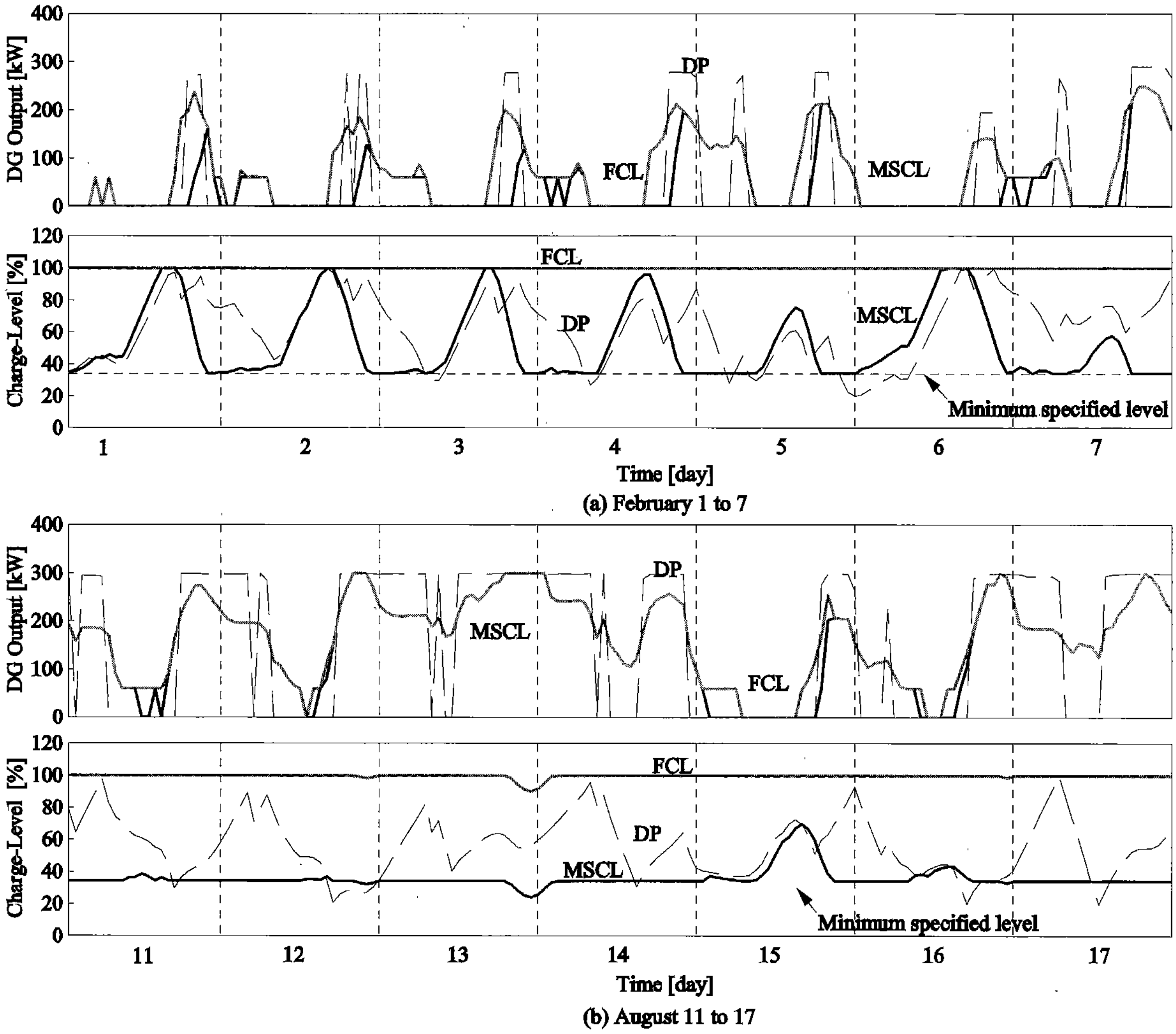


Fig. 8. Time series example of MSCL, FCL, and DP operating method (diesel size = 300 kW, PV/wind = 50/50, NESR = 60%, battery size = 25%)

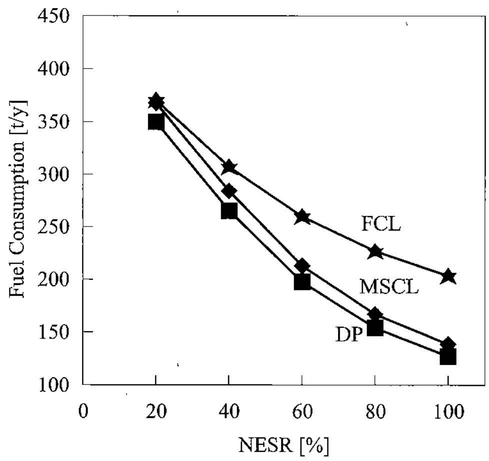


Fig. 9. Comparison of various operating methods : fuel consumpton versus NESR (diesel size = 300 kW, battery size = 25%, PV/wind = 50/50,)

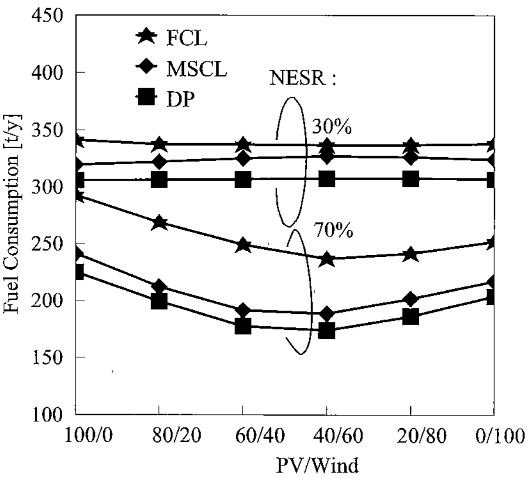


Fig. 10. Comparison of various operating methods : fuel consumpton versus PV/wind (diesel size = 300 kW, battery size = 25%)

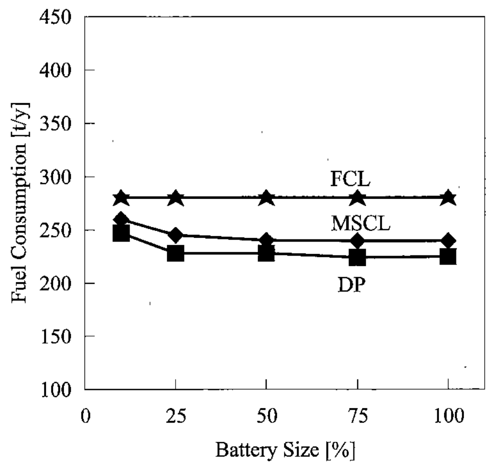


Fig. 11. Comparison of various operating methods : fuel consumpton versus battery size (diesel size = 300, kWPV/wind = 50/50, NESR = 50%,)

FCL is constant at 100%, DP changes dynamically between 20% and 100%, MSCL changes periodically between the minimum and maximum level, (2) in August, behavior of FCL and DP are same as in February. However, MSCL is almost kept at the minimum specified level except on the fifteenth day.

Figure 9 shows the annual fuel consumption versus the NESR for three different operating methods: FCL, MSCL and DP. For every operating method, the fuel consumption decreases as the NESR increases. The decreasing rates of MSCL and DP are higher than that of FCL.

Figure 10 shows the annual fuel consumption versus the PV/Wind for the three kinds of operating methods. Two values (30% and 70%) are selected as the NESR. If the NESR is 30%, the fuel consumption does not depend on the PV/Wind. On the other hand, if the NESR is 70%, the fuel consumption depends on the PV/Wind, and the fuel consumption has a minimum at a certain value of the PV/Wind. The value is about 40/60. This is because the annual time series pattern of PTG plus WTG output is most similar to that of electricity load. Here, also, the MSCL tends to be the same as that of DP.

Figure 11 shows the annual fuel consumption versus the battery size for the three kinds of operating methods. The fuel consumption does not depend on the battery size. The fuel consumption of MSCL and DP are lower than that of FCL.

8. Concluding Remarks

A new operating method which has been developed for a stand-alone wind/diesel/battery system is applied to a stand-alone photovoltaic/wind/diesel/battery system. In the new operating method, the diesel generator is controlled so that the energy stored in the battery is kept at a specified charge-level. The specified charge-level is set between 20 to 100% of the battery capacity. The purpose of the operating method is to minimize the fuel consumed by the diesel generator.

A simulation is carried out over one year using the hourly data of electric load, insolation, air temperature and wind speed. The fuel consumption is calculated from the time series result of the diesel generator output.

The system parameters are the natural energy supply ratio (NESR), the ratio of PV energy to wind turbine energy (PV/Wind), the diesel size and the battery size.

Generally, fuel consumption decreases with the specified level. However, the specified level cannot be lowered than a certain level, because blackout occurs. Here, the certain level is called the minimum specified charge-level and the SCL operating method with the minimum specified charge- level is called the MSCL operating method.

The MSCL operating method is compared with the other two operating methods (Full Charge Level operating method, in which the energy stored in the battery is kept fully condition and Dynamic Programming operating method). The results are as follows: (1) If the diesel generator size is less than the peak load, e.g., 300 kW, the minimum specified level increases as the battery size decreases; (2) Fuel consumption of diesel generator by MSCL or DP is less than FCL; (3) The fuel consumption greatly decreases if NESR increases; (4) If NESR is high, e.g., 70%, the fuel consumption has a minimum at a PV/Wind of 40/60; and (5) the fuel consumption does not depend on the battery size.

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