GRID-CONNECTED PHOTOVOLTAIC SYSTEMS WITH BATTERY STORAGES CONTROL BASED ON INSOLATION FORECASTING USING WEATHER FORECAST

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This paper reports an insolation forecasting method and simulation results of a control method of grid-connected photovoltaic systems with battery storages. First, it predicts the global irradiance every one hour by using weather forecast every three hours, and corrects the prediction accuracy by 14 kinds of weather change patterns. Second, it estimates tomorrow's photovoltaic generated power from the insolation forecasting, and calculates the best amount of charge to the battery from the utility grid every night. Simulation results show that providing with battery and using weather forecast are effective in cost, energy efficiency, and dependence on the utility grid.

Keywords: AE-PV system, grid-connected, battery control, insolation forecasting

INTRODUCTION

Most of the photovoltaic (PV) systems for residences spreading rapidly are grid-connected type. Usually, since this system has no electricity storage, the difference between generated and used electric power is processed by electric power flow of the utility grid. In the future so that the PV systems may spread further, it is necessary to develop "Autonomy-Enhanced" PV (AE-PV) system technologies with electricity storage functions that less depends on the utility grid [1]. The authors propose new control method of grid-connected PV systems with battery storages.

OUTLINE OF CONTROL METHOD

The control method of proposal contains the technology of two steps in the PV system configuration shown in **Fig.1**. The technology of first step predicts insolation by using weather forecast announced by the Japan Meteorological Agency (JMA). The technology of second step controls battery storage charging or discharging based on the tomorrow's insolation forecasting.

INSOLATION FORECASTING

Weather and irradiance

The authors investigated the past weather (Fair, Cloudy, and Rain) every three hours of 10 years from 1994 through 2003 based on precipitation and cloud cover observed in the JMA Tokyo point.

The irradiance observed every one hour in the same 10 years and the same point are categorized by the weather, date, and time. And they are calculated the mean value at each category. Base estimation is defined as the calculated mean value of days moving average. **Fig.2** shows one example of the base estimation in the categories of time from 9 to 10 o'clock.

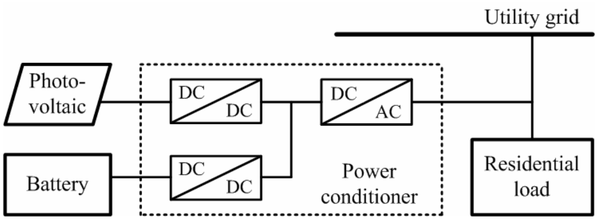

Fig.1: PV system configuration

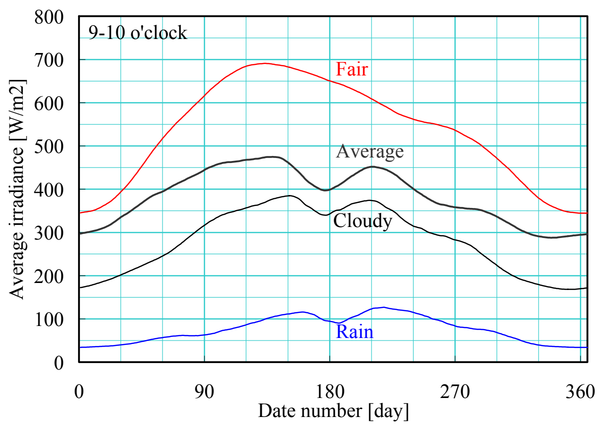

Fig.2: Base estimation (9-10 o'clock)

Weather change pattern

There must be difference between the cloudy close to fair and the cloudy close to rain. Then the observed irradiance are categorized by 14 kinds of weather change patterns, and calculated the mean values at each category. Weather change pattern correction factor is defined as the calculated mean value divided by the base estimation. **Table 1** shows the categories and the correction factors of the weather change patterns. The predicted global irradiance every one hour is estimated by the product of the base estimation and the correction factor.

Table 1: Weather change pattern categories and correction factor

Categories	Fair			Cloudy						Rain				
	1-1	1-2	1-3	2-1	2-2	2-3	2-4	2-5	2-6	3-1	3-2	3-3	3-4	3-5
Correction factor	1.054	1.016	0.884	1.467	1.343	1.224	0.937	0.714	0.598	1.341	1.195	0.983	0.793	0.768
Appearance frequency [times/10years]	14524	4511	6147	620	4173	2667	9794	1648	2676	611	975	958	1029	735
Contained weather change pattern	11111	11112	112	121	122	12221	12223	22223	123	131	331	133	13331	33333
		11113	113		221	12222	22222	32222	223	132	332	233	13332	
		21111	211			22221	32221	32223	321	231			13333	
		31111	311						322	232			23331	
Fair: 1		21112	212						323				23332	
Cloudy: 2		21113	213										23333	
Rain: 3		31112	312										33331	
		31113	313										33332	

Results

Insolation forecasting results are shown in **Fig.3** and **Fig.4**. Estimation error ratio (***Err****rat*) is defined as the following equation.

$$Err_{rat} = \frac{\sum_i |Irr_{est_i} - Irr_{msr_i}|}{\sum_i Irr_{msr_i}} \quad (1)$$

$Irr_{est\ i}$ is the predicted global irradiance. $Irr_{msr\ i}$ is the measured global irradiance. In **Fig.3** and **Fig.4**, the result of using weather forecast contains misses of weather forecast. The method of insolation forecasting decreases the prediction error to the half.

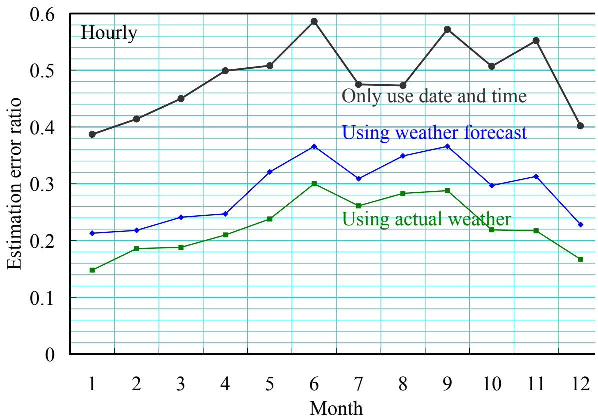

Fig.3: Insolation forecasting result (Hourly)

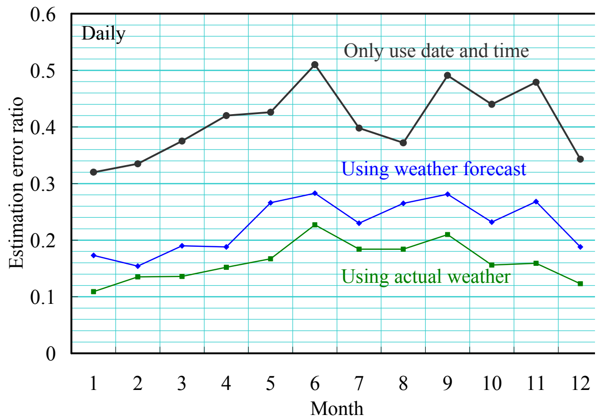

Fig.4: Insolation forecasting result (Daily)

BATTERY CONTROL

Control method

The battery control method calculates the best amount of charge from the utility grid every night. Charging during midnight has advantages in cost because midnight power is cheap. However, it is not good that the battery is charged full, because it has to compensate demand/supply power gap during day time. Then, the method calculates PV power by using insolation forecasting, and calculates demand/supply power gap by using demand forecasting. Therefore, it can calculate the best amount of charge.

The method also schedules equalizing charge plan based on the tomorrow's demand/supply power gap in order to keep the battery's health.

Simulation model

The effect of the control method of proposal is confirmed by the simulation.

- Solar cell model A standard I-V curve is made by the equation (2) based on the equivalent circuit of a solar cell. The curve is converted into various conditions by the following equations of (3) and (4) [2].

$$I = I_{ph} - I_0 \left[\exp\left\{ q\left(\frac{V + R_s \cdot I}{nkT} \right) \right\} - 1 \right] - \frac{V + R_s \cdot I}{R_{sh}} \quad (2)$$

$$I_2 = I_1 + I_{sc}\left(\frac{E_2}{E_1} - 1 \right) + \alpha \left(T_2 - T_1 \right) \quad (3)$$

$$V_2 = V_1 + \beta \left(T_2 - T_1 \right) - R_s \left(I_2 - I_1 \right) - K \cdot I_2 \left(T_2 - T_1 \right) \quad (4)$$

- Battery model The authors also propose a battery simulation model shown in **Fig.5**. This model is reported in the references of [3].

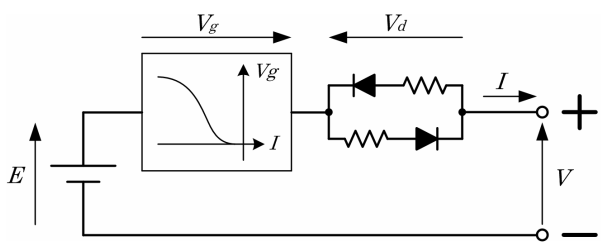

Fig.5: Equivalent circuit of battery

- Power conditioner model Electric power is lost with three converters shown in **Fig.1**. The input power of converter is shown by the quadratic expression of the output power.

Conditions

In this simulation, reverse power flow to the utility grid is limited in order to less depend on the utility grid. If the PV excess power is larger than the permissible reverse power when the battery is charged full, the excess power is summed up to the PV limiting loss.

Installed PV array rated power is decided as annual demand electric energy divided by 1000 hours. The battery capacity is variable.

The simulation uses the irradiance data and the residential power consumption data measured in Tokyo every minute during one year, and also uses the weather forecast announced every day by the JMA.

Results

The simulation results are shown in **Fig.6 to 9**. Battery capacity ratio is defined as the battery capacity divided by the average daily electric energy consumption. Reverse power limiting factor is defined as the permissible reverse power divided by the PV array rated power. PV limiting loss ratio is defined as the PV limiting loss divided by the PV ideal energy.

Fig.6 and **Fig.7** show that using forecast has advantages in both of PV limiting loss and electric bill. If the demand forecasting error will decrease by increasing number of demands such as AE-PV clusters [1], using forecast will have more advantages.

Fig.8 and **Fig.9** show that installing battery has advantages in hard limiting of reverse power. In addition, the effect of increasing battery capacity weakened when the battery capacity ratio exceeded the half.

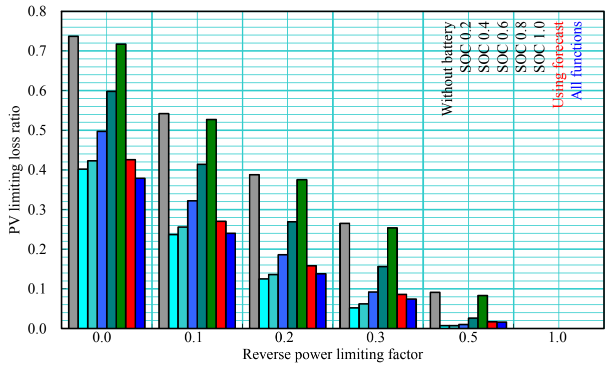

Fig.6: PV limiting loss ratio

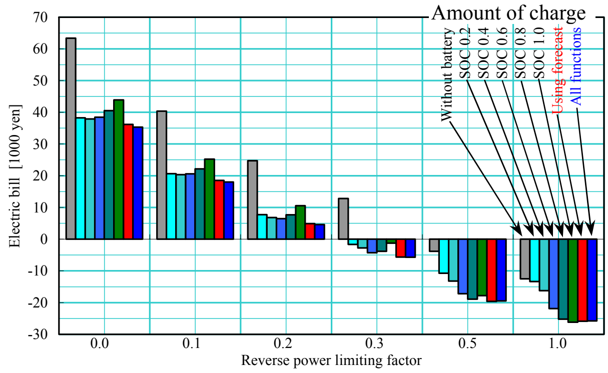

Fig.7: Electric bill

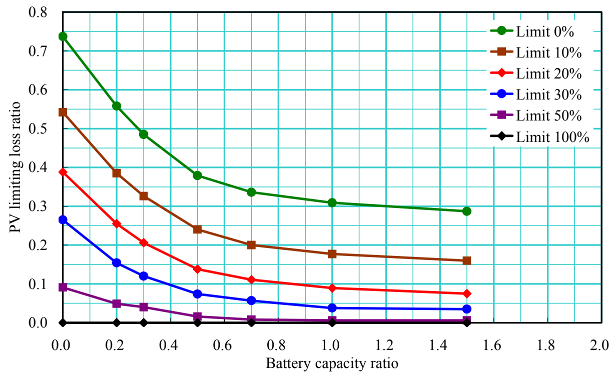

Fig.8: PV limiting loss ratio

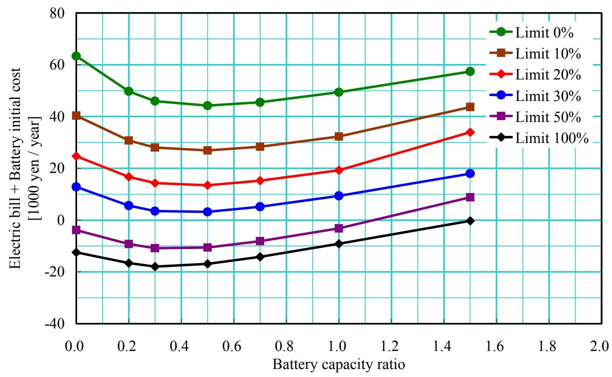

Fig.9: Electric bill added Battery initial cost

CONCLUSIONS

To develop AE-PV system that less depends on the utility grid, the authors propose the insolation forecasting method and the battery control method.

In the PV system limiting reverse power flow, it was confirmed that using weather forecast is effective. In addition, the effect of providing with battery weakened when the battery capacity exceeded the half of average daily electric energy consumption.

The authors are studying the battery control method based on the forecasting in the AE-PV clusters. This work is being supported by NEDO under the Ministry of Economy, Trade and Industry.

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