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Compensation for Photovoltaic Generation Fluctuation by Use of Pump System with Consideration for Water Demand

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Abstract – In remote islands, due to expense of existing generation systems, installation of photovoltaic cells (PVs) and wind turbines has a chance of reducing generation costs. However, in island power systems, even short-term power fluctuations change the frequency of grids because of their small inertia constant. In order to compensate power fluctuations, the authors proposed the power consumption control of pumps which send water to tanks. The power control doesn't affect water users' convenience as long as tanks hold water. Based on experimental characteristics of a pump system, this paper shows methods to determine reference power consumption of the system with compensation for short-term PV fluctuations while satisfying water demand. One method uses a PI controller and the other method calculates reference power consumption from water flow reference. Simulations with a PV and a pump system are carried out to find optimum parameters and to compare the methods. Results show that both PI control method and water flow calculation method are useful for satisfying the water demand constraint. The water demand constraint has a little impact to suppression of the short-term power fluctuation in this condition.

Keywords: Solar powered pumping, Island power system, Demand response, Controllable load

1. Introduction

Nowadays, installed capacity of photovoltaic cells (PVs) and wind turbines (WTs) into island power systems has been increasing [1-3]. Because of island system generation's high expense, installation of PVs and WTs has a chance to reduce generation costs. PV cost is reducing rapidly. As of 2013, the cost per MWh of rooftop solar was below retail electricity prices in several countries, including Australia, Brazil, Denmark, Germany, and Italy [4].

However, even short-term power fluctuations of PVs and WTs cause frequency fluctuations in the island grid compared to larger grids because of the small inertia constant and of the weak smoothing effect. Though some of the existing island engine generators have quick response characteristics, their output ranges are limited. Minimum output of existing generators is normally 40 or 50% of the rated power [3]. As it takes several or several tens of minutes for them to start up and connect synchronously to grids, they can't suppress the short-term power fluctuations from large amount of PVs and WTs enough.

In order to suppress such short-term power fluctuations, energy storage systems (ESSs) such as batteries and flywheels are installed into remote island grids [2]. Many researches show that if there is enough capacity of ESSs, they can suppress the power fluctuations of PVs and WTs [5]. However, ESSs are still quite expensive and maintenance of ESSs in remote islands requires more effort.

To compensate the fluctuations with less ESS, power consumption control of the existing load is focused. Many researches propose electric vehicles [6], heat pump equipment [7] and desalination systems to be used as controllable loads. Some of them focus on islands [8-10].

In order to compensate power fluctuations, we have proposed power consumption control of pumps those supply water to tanks for drinking or farming. In such systems, water tanks are intrinsically large in order to prevent the water shortage. Hence control of pumps' power consumption (pump power) doesn't affect water users' convenience as long as tanks hold water. Many researches focus on solar powered pumping systems experimentally [11] and analytically [12]. Over 7000 solar powered water pumping systems are already installed in India [13].

Many of the previous researches focus on stand-alone systems, but there are some researches take notice of grid-connected pumps. High potential of the grid-connected pump control is shown in [14-16]. The authors have focused on the grid-connected system, in which suppression of the power fluctuations of PVs or WTs can be shared with pumps and grids, even if PVs or WTs are remote from the pump system. First, theoretical model of the pump system is proposed [17] and experiments are conducted to obtain basic characteristics [18, 19]. The authors analyzed pressure waves of the system and proposed deadbeat

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control method [20] which enables faster response.

As primary function of the pump system is to supply water, this paper focuses on the water demand constraint. This paper proposes two methods -PI control method and water flow calculation method- to determine the reference of pump power to compensate short-term PV power fluctuations while satisfying water demand. Simulations with a PV and a pump system are carried out to find optimum parameters and to compare the two methods.

2. Simulation Model and Proposed Method

2.1 Target system

Simulation model is constructed based on an actual pump system. Fig. 1 shows the site location, Miyako Island, and appearance of the site. Fig. 2 shows the schematic diagram of the pump system. A power conditioning system (PCS) drives an induction motor (IM) and a centrifugal pump power can be controlled by changing the frequency of the PCS output voltage. The water level difference between the pump and the tank is 42 m. The volume of the tank is 100 m^3 and the distance between the tank and the pump site is about 2km. A PV panel (6.8 kW) located near the pump system and is connected to the grid.

The aim of the pump power control is to suppress short-term power fluctuations of the PV output whereas long-term fluctuations can be suppressed by power conditioning and unit commitment of diesel generators in grids. While suppressing short-term power fluctuations, water level of the tank should be kept within an allowable range. In this study, it is assumed that the pump supplies water only in the daytime and midnight, so the water level at 17:30 should be from 86% to 92% in order not to lack at midnight or overflow. This constraint is called water demand constraint.

Fig. 1. Site location (left) and appearance (right)

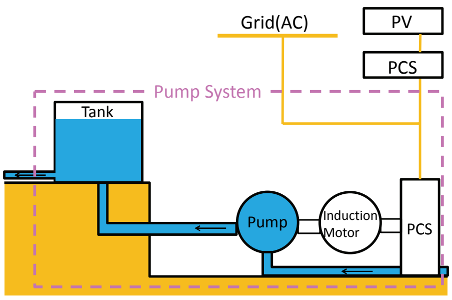

Fig. 2. Schematic diagram of the system

2.2 Simulation model of pump system

Characteristics of the pump system are modelled by use of test results [18]. Fig. 3 shows frequency-power characteristics and frequency-water flow rate characteristics, where dots are measured values and the line is calculated by (1). In (1), P [kW] is the pump power and f [Hz] is the PCS output frequency. To prevent operation under low efficiency, P is controlled between 1.33 kW and 5.75 kW.

Model of frequency-water flow characteristics is the linear interpolation of the measured values expressed by (2) and water flow-pump power characteristic is modelled by (3). Q [m^3/hour] is water flow rate of the pump.

$$P = 0.25f - 9.4 \tag{1}$$

$$Q = f_1(f) = \begin{cases} 1.73(f-42)+2.04 \ (42 \le f < 43) \\ \vdots \\ 0.51(f-59)+16.28 \ (59 \le f < 60) \end{cases} \tag{2}$$

$$P = f_2(Q) = 0.011Q^2 + 0.10Q + 0.86 \tag{3}$$

Fig. 4 shows water per kWh, which indicates efficiency.

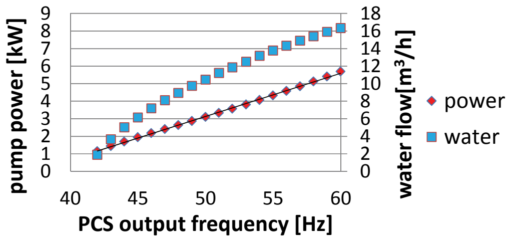

Fig. 3. Pump power and water flow characteristics

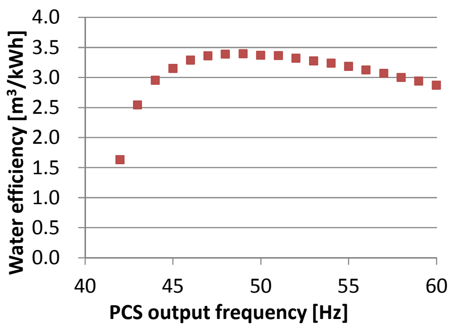

Fig. 4. Efficiency Characteristic

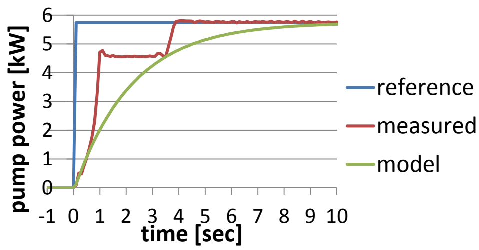

Fig. 5. Pump power step response and its model

From 45 Hz to 59 Hz, the efficiency is higher than that of 60Hz. Hence the power control of the pump rarely increase total power consumption of the pump for water conveyance unless the frequency goes mainly under 45 Hz.

Fig. 5 shows the transient characteristic of the pump power [19] and it is modelled as 2.2 seconds first-order lag. Fig. 5 shows that the model step response is slower than the measured step response, so it is a conservative model.

2.3 Power control without water demand constraint

Fig. 6 shows the block diagram of the simulation without the water demand constraint. Input values are PV output and water demand. The controller calculates the target pump power $\hat{P}$ by use of PV output and its moving average (100 minutes). The constant is equal to 3.25kW, decided by a simulation to minimize the short-term RMS value (defined at section **3.1**) without the water demand constraint. The target frequency $\hat{f}$ is calculated by (1). In the pump system model part, pump power and water flow are calculated by (1) and (2), respectively. The water level $M(t)$ is calculated by integrating water flow and demand, where t [sec] is time of the day.

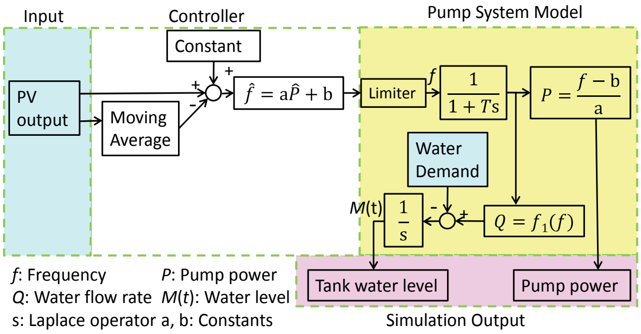

Fig. 6. Block diagram without water demand constraint

2.4 PI control method

Fig. 7 shows the block diagram of the pump power control method with a PI controller for the water demand constraint. Input values of the simulations are PV output, water level target at 17:30 M_{target} [%] (89%) and water demand. The input of the PI controller is the difference between the real-time target water level $M_{tar}(t)$ [%] and actual water level $M(t)$. $M_{tar}(t)$ is calculated by (4). In (4), M_{start} [%] is the initial water level. t_{start} [sec] and t_{target} [sec] is the start and target time of the day, respectively.

$$M_{tar}(t) = \frac{M_{target} - M_{start}}{t_{target} - t_{start}}(t - t_{start}) + M_{start} \tag{4}$$

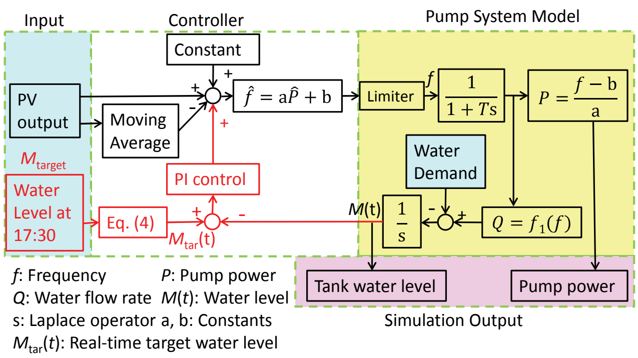

Fig. 7. Block diagram of PI control method

2.5 Water flow calculation method

Water flow calculation method computes the pump power target by calculating reference water flow rate value $\hat{Q}$ [m^3/hour]. In this method, $\hat{Q}$ is calculated by (5) for each time step. The first term of the right side of (5) represents water flow rate for water level increase. Estimated water demand $\hat{Q}_{use}$ is set to 4.5 m^3/ hour, which is the average of the water demand. Fig. 8 shows the concept of the net water flow calculation.

$$\hat{Q} = \frac{M_{target} - M(t)}{t_{target} - t} + \hat{Q}_{use} \tag{5}$$

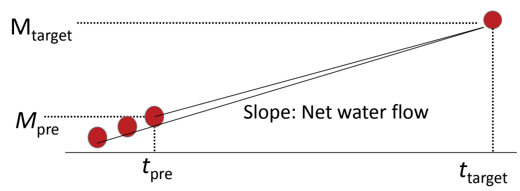

Fig. 8. Conceptual diagram with net water flow calculation

Fig. 9 shows the block diagram of pump power control with the water flow calculation method. Input values are the same as Fig. 7. In Fig. 9, $\hat{P}_{offset}$ [kW] is used instead of the constant used in the controller of other methods in order to send water almost $\hat{Q}$. $\hat{P}_{offset}$ calculated by (6).

$$\hat{P}_{offset} = f_2\left(\hat{Q}\right) \tag{6}$$

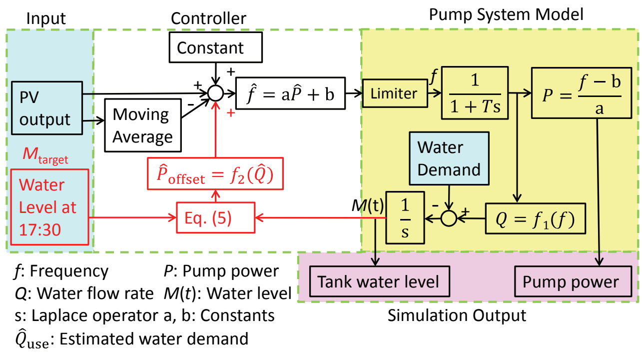

Fig. 9. Block diagram with water flow calculation method

3. Simulation Result and Discussion

3.1 Simulation procedure

Each simulation begins at 5:00 with water level of the tank at 68 % and ends at 17:30. Fig. 10 shows the input data of PV output and water demand. The measured PV generation data is used in the simulation as "PV output". PV generation fluctuates heavily in the cloudy day. The one-month average of the measured water demand is used as “Water Demand”. Simulation sampling time is 1 second.

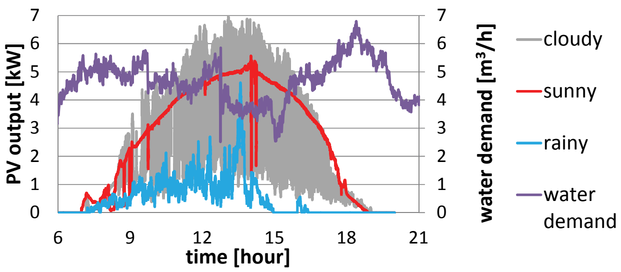

Fig. 10. PV output and water demand

In the case of PI control method, simulations are conducted with various combination of gain K_P [kW/100%] (0 to 25 at 2.5 intervals) and K_I [kW/(100% sec)] (0 to $1.5\text{x}10^{-3}$ at $2.5\text{x}10^{-4}$ intervals). For example, if K_P = 10 kW/100% and the difference between $M_{tar}(t)$ and $M(t)$ is 10 %, 1.0 kW will be compensated. In the cases of water flow calculation method, various control periods (1, 3, 10, 20, 30, 50, 75, 100, 150 and 200 minutes) are used in the simulation. In each method, the objective function is the average of root-mean-square (RMS) values of short-term fluctuations which is defined as current power minus its 20 minutes moving average. The best parameters are defined as those that minimize average of the objective function with three PV data with satisfaction of the water demand constraint in the three PV data.

3.2 Result without water demand constraint

Fig. 11 shows the time-series data without the water demand constraint by use of cloudy PV output. The orange line shows the pump power and the purple line shows the short-term tie-line power flow (RMS value: 0.30kW). Pump power sometimes reach its upper or lower limit as the range of PV output is wider than that of pump power.

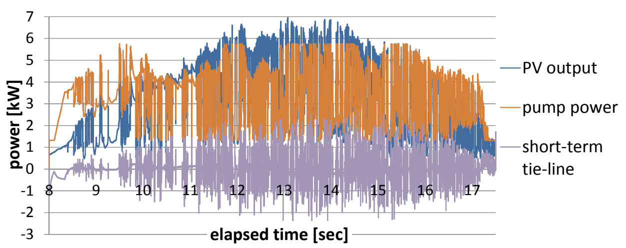

Fig. 11. PV output, pump power and short-term tie-line power without water demand constraint (cloudy)

3.3 Result with PI control method

Fig. 12 shows simulation results with PI control with various parameters. In Fig. 12, the upper graph shows the RMS average of three cases with sunny, cloudy and rainy day PV data, respectively. The lower graph shows the water level at 17:30 of the rainy day. Rainy day water level is shown because it is most difficult to satisfy the constaint at 17:30 in the rainy day. In each graph, legends show the gain K_I. It is shown that the minimum average RMS value, that satisfies the water demand constraint, is 0.23 kW at K_P = 12.5 kW/100% and K_I = $7.5\text{x}10^{-4}$ kW/(100% sec).

Figs. 13-14 show time-series data with PI control method by use of cloudy and sunny and rainy PV output and the best parameters, respectively. Compared with Fig. 11, pump power in Fig. 13 is lower but still reaches its upper limit. This suggests that the control method uses the controllable range effectively. Fig. 14 shows that short-term fluctuations of the tie-line of the sunny and rainy day PV data are small compared to the cloudy data.

3.4 Result with water flow calculation method

Fig. 15 shows simulation results by use of water flow calculation method with various control periods. In Fig. 15, the upper graph shows RMS values by sunny, cloudy, rainy

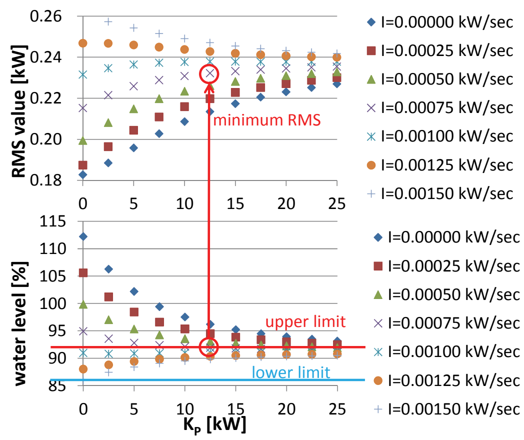

Fig. 12. RMS values and water level with PI method

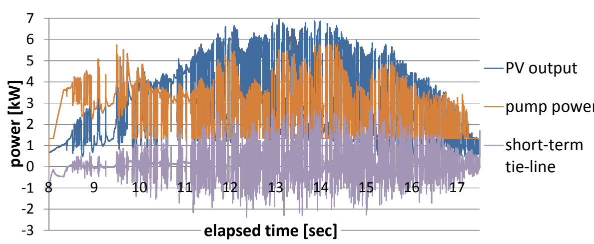

Fig. 13. PV output, pump power and short-term tie-line power with PI method (cloudy)

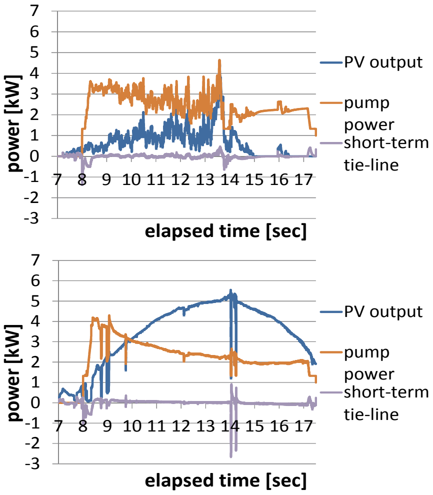

Fig. 14. PV output, pump power and short-term tie-line power with PI method (sunny and rainy)

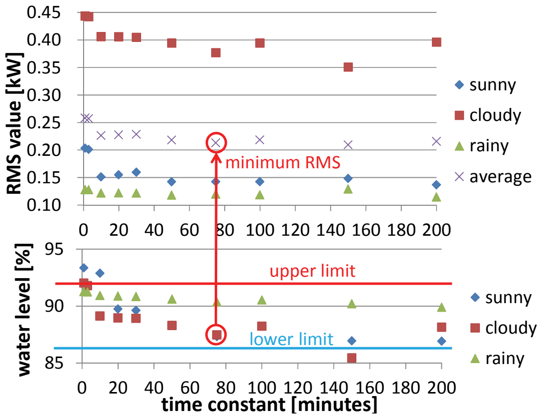

Fig. 15. RMS values and water level with water flow calculation method

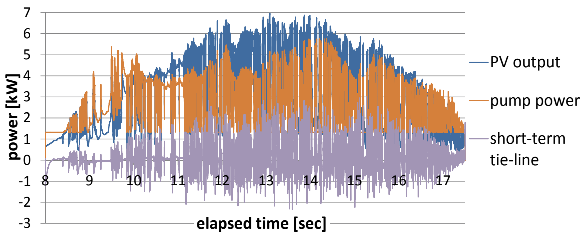

Fig. 16. PV output, pump power and short-term tie-line power with water calculation method (cloudy)

day PV data and their average. The lower graph shows the water levels at 17:30. Horizontal axes are the control periods. The minimum average RMS value that satisfies the water demand constraint is 0.22 kW when the control period is 75 minutes. Compared with Fig. 12 in section 3.3, changes of average RMS values are small according to the parameter. Average RMS values in Fig. 15 are within 0.21 kW to 0.23 kW except when the time constant is 1 minutes.

Figs. 16-17 show time-series data with the water flow calculation method when the time constant is 75 minutes. In Figs. 16-17, waveforms are similar to those of Figs. 13-14, respectively.

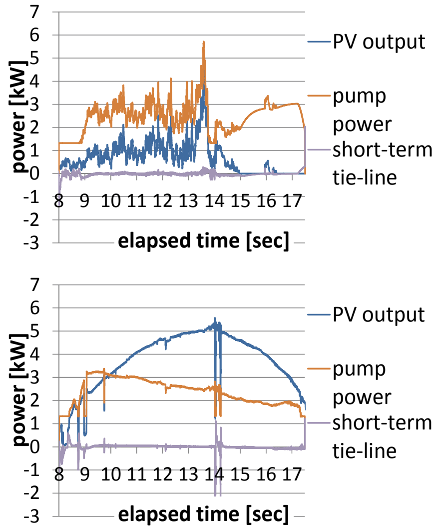

Fig. 17. PV output, pump power and short-term tie-line power with water calculation method (sunny and rainy)

3.5 Discussion

Fig. 18 shows comparison of the time-series water level in the case of cloudy day. Without controls for the constraint, water level exceeds the rated tank capacity (100%). However, by applying PI control method or water flow calculation method, the increase of the water level slows down and the water demand constraint is satisfied.

Fig. 19 shows the comparison of the RMS values with the best parameters. In cloudy case, RMS values become a little worse by applying PI control method or water flow calculation method than that without the water demand

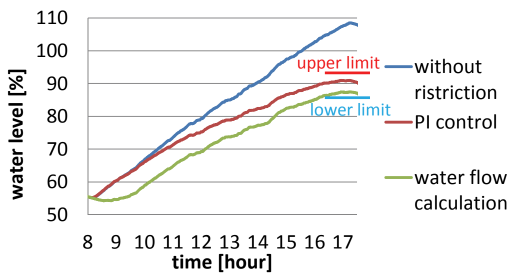

Fig. 18. Comparison of water level (cloudy)

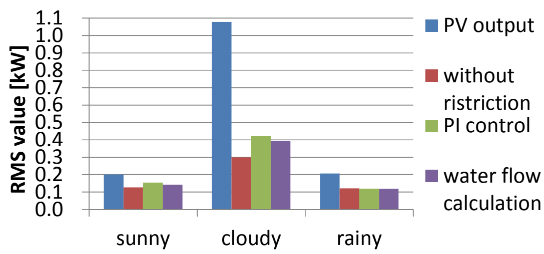

Fig. 19. Comparison of best RMS values

constraint. However, in sunny and rainy cases, the RMS values are almost the same because the pump power rarely reaches the lower limit. Compared to the RMS values of PV output, both controls suppress power fluctuations. In this simulation, RMS values of PI control method and those of the water flow calculation method turned out to be almost same by use of best parameters for each case.

From Figs. 18-19, both the PI control method and the water flow calculation method can suppress the power fluctuations with satisfaction of the water demand. These methods are simple and easy to install to the PCS.

4. Conclusion

This paper shows that power consumption control of the existing pump system can suppress power fluctuations of the PV output to some extent with satisfaction of water for demand. Simulations are made with experimental data of a waterworks pump system driven by a power conditioning system. Both PI control method and water flow calculation method are proposed and are both shown to be useful for satisfying the water demand constraint. The water demand constraint has a little impact to suppression of the short-term power fluctuation in this condition.

Future work includes the simulation by use of more various PV output and water demand data. Another future work is the application of water demand forecast to the water flow calculation method. Estimation of the effect of the power control to system lifetime (e.g., the metal fatigue of water pipes) is important for safety waterworks.

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