Power Control Method using Time Delay Compensation Scheme Based on Smith predictor for Flywheel Power Leveling System

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Abstract— **This paper introduces the performance of a power leveling system with a 3.0-MJ, 9500-r/min flywheel energy storage. In term of the cost reduction, this system uses low cost flywheel and the general purpose products. Therefore, the time delay of the measurement device limits the control performance. In order to overcome this problem, the time delay compensation scheme based on Smith predictor is applied in the control in order to improve the control performance of the power regeneration. As a result, the overshoot of the regeneration power is eliminated by applying the compensation. In addition, the effectiveness of the power leveling control in a prototype is evaluated by experiment. As a result, it is confirmed that the power fluctuation is reduced by 84.6 %.**

I. INTRODUCTION

Renewable energy systems, especially a wind turbine and a photovoltaic cell, are generated power fluctuation due to the meteorological conditions. Therefore, these systems require energy buffers such as electric double layer capacitors (EDLC), batteries, or flywheels to suppress the power fluctuations. For example, the battery can be realized a high energy density at low cost. However, one of the problems in the battery energy storage has a short life time. In particular, the lifetime depends on ambient and the number of charge and discharge time. In addition, the battery cannot cope with rapid charge and discharge by a large internal resistance. The replacement cost for the batteries is very expensive. On the other hand, the EDLC has a high charge and discharge efficiency. Moreover, the rapid charge and discharge is possible because the internal resistance is very small. However, similar to the battery, the lifetime is decreased due to the influence of the ambient temperature. On the other hand, the flywheels has some advantages: (i) environmental friendly, (ii) low maintenance cost, (iii) long lifetime due to no chemical structure, and (iv) the charge and discharge characteristic of high cycle are excellent. Additionally, the kinetic energy which stored in the flywheel is proportional to the square of the rotational speed. For this reason, ultra high speed rotation using magnetic bearings have been studied in order to achieve high energy density [1-6]. The magnetic bearing to hold the rotating shaft without mechanical contact has been studied. However the cost of the flywheel energy system becomes expensive.

This paper presents how to achieve low cost flywheel system with a control method of the regeneration power for the power leveling system. The flywheel system is configured from commercial products; which consist of a transducer, a general purpose inverters and an inexpensive microcomputer without the specific device. Moreover, instead of the magnetic bearing, the normal ball bearing is used to degrade the cost. However, the inexpensive power detection device has a long delay time. As a result, the control becomes unstable due to long delay time. In this paper, in order to improve the response performance of the regenerative power, the time delay compensation scheme based on the Smith predictor [7][8] is applied to the proposed flywheel system. The constitution of this paper is follows: at first, the proposed flywheel system is introduced. Next, the principle of the power control method which includes the time delay compensation scheme based on the Smith predictor is discussed. Finally, the proposed control method is demonstrated by the prototype flywheel energy storage system.

II. PROTOTYPE FLYWHEEL SYSTEM

Fig. 1 shows the photograph of the proposed flywheel system of which has the specification as shown in Table 1. The general purpose ball bearings is used to reduce the costs and to improve the performance because the rotational speed is suppressed within 9500 r/min. Moreover, the outward form of the flywheel is 569×511×600 mm. Therefore, the energy density is 17.2 kJ/dm^3. On the other hand, the energy density of the EDLC is 36.0 kJ/dm^3 [9]. Therefore, it is approximately twice of the prototype system.

Fig. 2 shows the block diagram of the prototype flywheel system including the accessories parts. Inexpensive power meters which has a long dead time is applied in this system. Additionally, the rotational speed command of the flywheel is controlled by an inexpensive PIC microcontroller. In addition, the vacuum pump and the oil cooler are implemented to reduce the windage loss and heat generation. As mechanical features, the vacuum is kept by a small vacuum pump because the flywheel has been stored in a sealed container. In this structure, it is possible to reduce the windage loss which occurs at high speed rotation region. Furthermore, over temperature of the bearing and the motor can be prevented by the oil cooler.

Note that this flywheel system assumes that several numbers of flywheels are used in one system in order to increase energy capacity. Therefore, an oil pump and a vacuum pump can be used for some flywheels.

III. POWER CONTROL METHOD WITH SMITH PREDICTOR

In the flywheel system, when induction machine is operated as a generator during deceleration, kinetic energy is converted into the electrical energy. On the other hand, during acceleration, the electrical energy is stored as kinetic energy, which is working as a motor. In general, inexpensive general purpose inverter can only provide speed command. Therefore, the charging and discharging power is controlled by the speed of the flywheel.

The kinetic energy of a body of revolution is expressed by (1).

$$E = \frac{1}{2} J\omega^2 \quad \text{...} (1)$$

where, J is the moment of inertia[kgm^2] and ω is the angular velocity of the body revolution[rad/s]. In addition, the speed command ω^* which shown in Fig. 2 can be obtained by transforming (1).

On the other hand, the output power of the flywheel can be obtained by differentiating the both sides of (1) from the relation between the rotational kinetic energy and power. Thus, the output power is expressed by (2).

$$P = J\omega \frac{d\omega}{dt} \quad \text{...} (2)$$

Accordingly, the regenerative power of the flywheel is proportional to the product of the rotational angular velocity and angular acceleration. The speed command value for the regenerative power of the flywheel is given by (3).

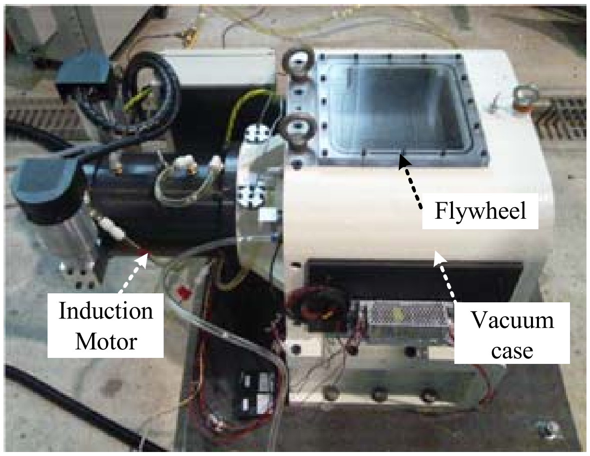
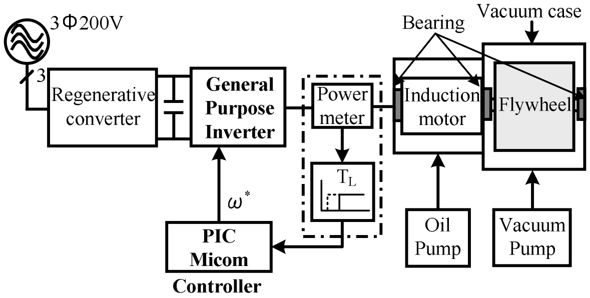


Fig. 1. Photograph of the prototype Flywheel System. This system adopts general purpose ball bearings in order to reduce costs and improve performance because the rotational speed is suppressed within 9500 r/min.

Table 1. Specification of the Flywheel unit.

Rated voltage	200V
Rated current	126A
Rated rotation speed	9500rpm
Accumulated energy	3.0MJ
Outward form	569×511×600mm
Energy density	17.2kJ/dm^3
Weight of the FW	241kg
Diameter of the FW	45cm



Inverter	**FRENIC5000G11**
Controller	**PIC16F887**
Sampling Time	**20ms**
Delay Time T_L	**400ms**

Fig. 2. Configuration of the Flywheel system. In this system, the vacuum pump and the oil cooler are implemented to reduce the windage loss and heat generation.

$$\omega^{*} = \frac{1}{J}\int \frac{P^{*}}{\omega_o}\,dt \tag{3}$$

where, ω_o is the rotational angular velocity of the previous sampling time and P^{*} is the output of the PI controller.

Furthermore, the discrete system of equation (3) is given by (4).

$$\omega_n = \omega_{n-1} + \frac{1}{J}\frac{P^{*}}{\omega_{n-1}}\Delta t \tag{4}$$

where, ω_{n-1} is the speed command value of the previous sampling time and Δt is the sampling time of the controller.

In this system, the regenerative power is obtained from an inexpensive power meter that the sampling time is 400 msec. In such a system, the control may become unstable by setting a high proportional gain to improve the response. In this paper, the control performance is improved by the Smith delay time compensation scheme.

Fig. 3(a) shows the block diagram of the typical feedback control system. Note that the change of the rotational angular velocity is sufficiently slower than the processing time of the control system. Therefore, the rotational angular velocity of the previous sampling time is treated as a constant value ω_o. The characteristic equation of this control system is given by (5).

$$1 + C(s)G(s)e^{-T_L S} = 0 \tag{5}$$

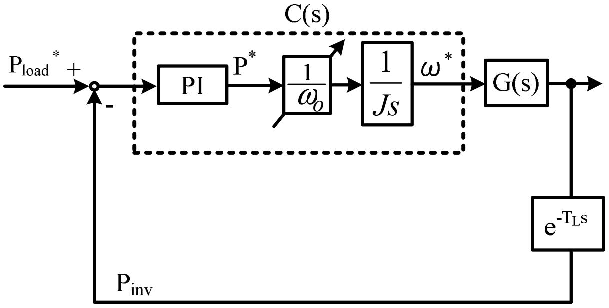
In a typical feedback control system, the system becomes unstable due to the phase lag. This is caused by the delay time element.

Fig. 3(b) shows the block diagram with the Smith predictor to power control. This compensation eliminates the effect of delay time by estimating the output of the controlled object *G(s)* after the lapse of delay time. The characteristic equation is given by (6).

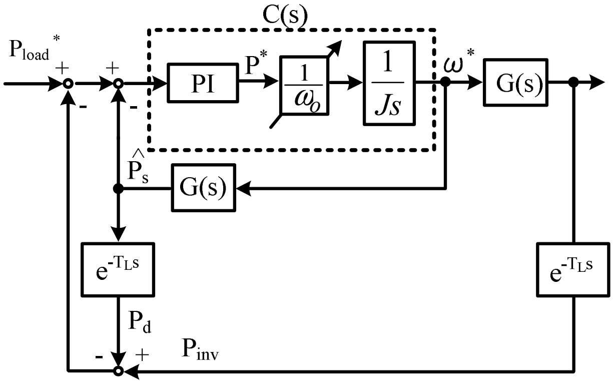
$$1 + C(s)G(s) = 0 \tag{6}$$

Therefore, the control performance can be improved from this equation. In other words, the delay time element has been removed from the characteristic equation.

In this control system, the speed command $\omega^{*}_{\wedge}$ is obtained by (2) from the estimation of the output power P_s. Note that P_{inv} is detected value of the power meter and P_d is the output power after the lapse of dead time. In addition, P_s is calculated by the inertia J and the rotation speed command ω^{*} from (1).



(a) Without smith predictor.



(b) With smith predictor.

Fig. 3. Block diagram of time delay compensation scheme based on Smith predictor. This compensation eliminates the effect of delay time by estimating the output of the controlled object *G(s)* after the lapse of delay time.

IV. SIMULATION AND EXPERIMANTAL VERIFICATION

Fig. 4 illustrates the simulation results of the regenerative power from the flywheel system with and without the Smith predictor. The simulation conditions are as follows; the steady rotation speed is 6000 r/min and the load is changed from 0.0 kW to 2.0 kW. From the simulation results, a large overshoot occurs when the Smith predictor is not applied. By contrast, the overshoot does not occur when the Smith predictor is applied. Therefore, it is confirmed that the response performance is improved by the Smith predictor.

Next, the effectiveness of the Smith predictor is verified by the experiment.

Fig. 5 shows the step response of the output power. Note that the experimental conditions are similar to the simulation.

In addition, the gain of PI controller is determined by the limit sensitivity method [10]. The inverter used in the experiment is FRENIC5000G11 (Fuji Electric), the microcontroller is PIC16F887 (Microchip Technology), and the sampling time is 20msec.

According to Fig. 5(a), an overshoots is approximately 500 W because the power measurement system has delay time. On the other hand, it is confirmed that the overshoots does not occur by using Smith predictor in Fig. 5(b). From these results, the effectiveness of the compensator is confirmed by simulations and experiments.

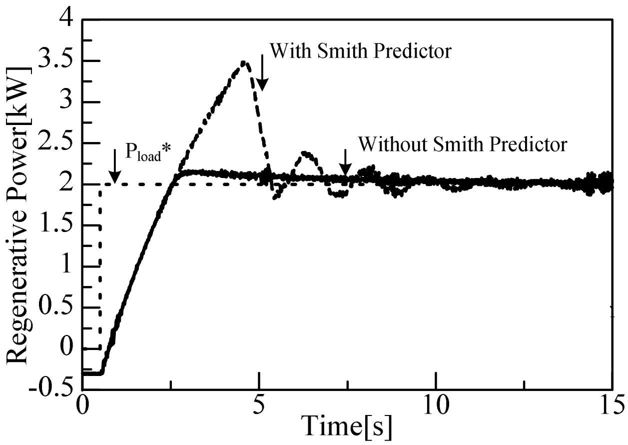
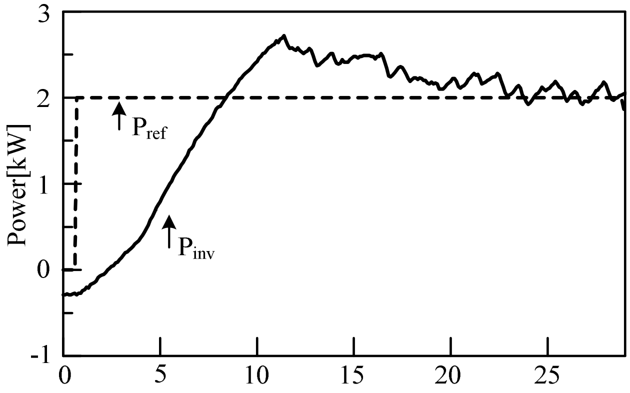
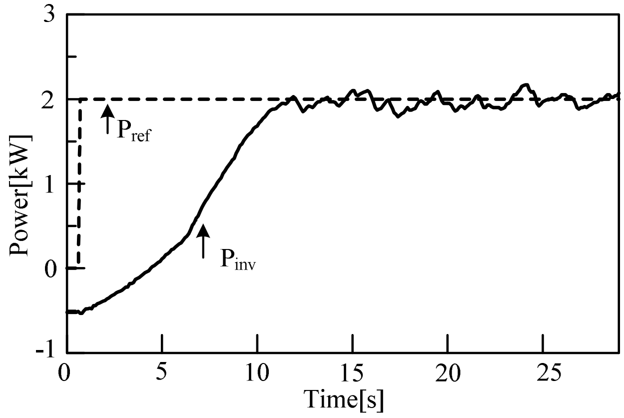


Fig. 4. Step response of the regeneration power on the simulation results. The simulation conditions are as follows; the steady rotation speed is 6000 r/min and the load is changed from 0.0 kW to 2.0 kW.



(a) Without Smith compensation scheme.



(b) With Smith compensation scheme.

Fig. 5. Step response of the regeneration power on the experimental results. The experimental conditions are as follows; the steady rotation speed is 6000 r/min and the load is changed from 0.0 kW to 2.0 kW.

Next, the prototype flywheel system is evaluated by loss analysis.

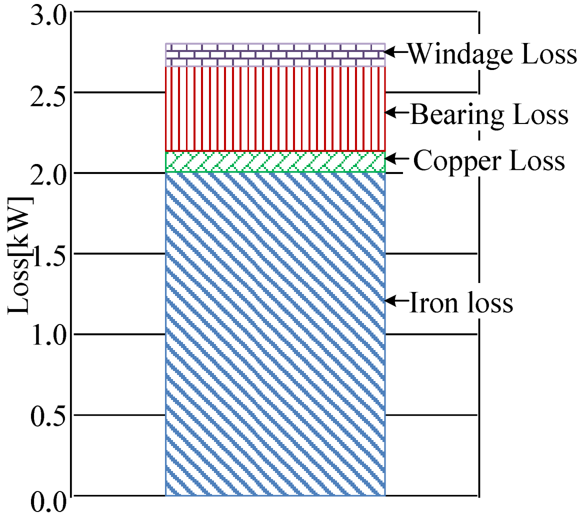


Fig. 6. Analytical results of the steady state losses. In this experiment, the rotation speed is 9500 r/min, the vacuum case is kept at 800 Pa.

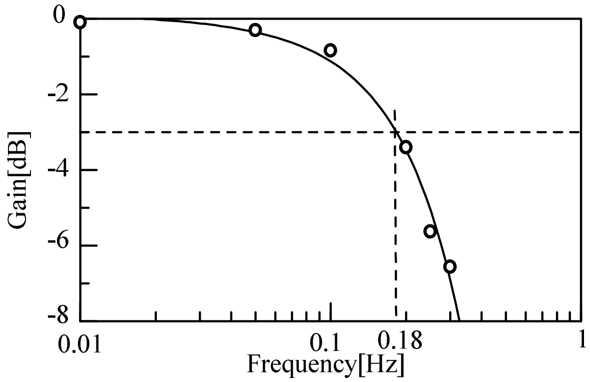
Fig. 6 shows the analytical result of the steady state losses. In this experiment, the rotation speed is 9500 r/min, the vacuum case is kept at 800 Pa. As a result, the flywheel losses in the steady state are as follows; the bearing loss is 19 %, the iron loss is 76 % for the induction motor. From the analysis, it is confirmed that the motor loss is dominant in the standby mode. Therefore, it is necessary to reduce the motor loss to improve the efficiency of the flywheel system.

Fig. 7 shows the frequency characteristics of the prototype system. From the results, frequency response after applying the Smith predictor is 0.18Hz. Power generation system using renewable energy power generator varies greatly depending on weather conditions. In the change of the amount of solar radiation and wind direction are short period fluctuations and long-term fluctuations are combined. Therefore, the prototype system can be applied to compensate for power fluctuations which is several tens of seconds [11][12].

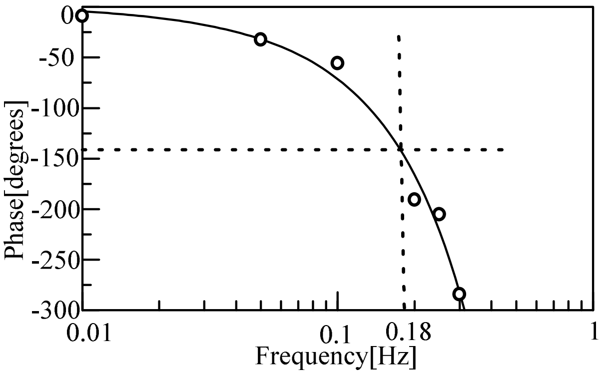
V. VERIFICATION OF POWER LEVELING CONTROL

Fig. 8 shows the power leveling control system. Note that the rotation speed is 5500 r/min at steady state. In the experiment, the power fluctuation is reproduced by a step-down chopper. In addition, the flywheel power command value is extracted from a high pass filter (HPF) that cutoff frequency is set to 0.0025 Hz. The prototype system is intended to compensate for a short cycle of the power fluctuation. Therefore, the cutoff frequency of the HPF is set to low frequency.

Fig. 9(a) shows the power fluctuation pattern which uses a part of generation power by PV panels. From this figure, the generation power of the solar cell has a rapid power fluctuation of approximately 2 kW.



(a)Gain characteristic.



(b)Phase characteristic.

Fig. 7. Bode diagrams of the proposed control system. It is confirmed that the response frequency of the prototype flywheel system is 0.18Hz.

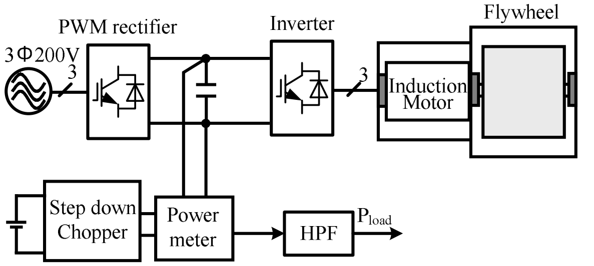
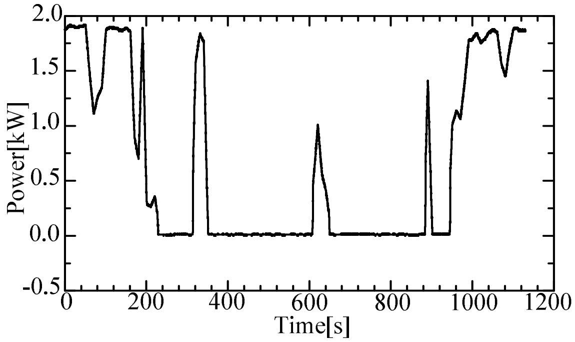


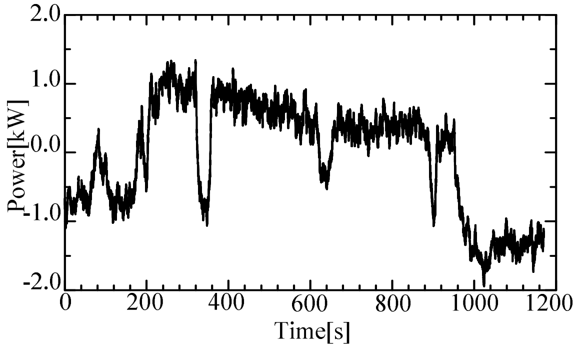
Fig. 8. Configuration of the experimental system for the power fluctuation compensation. By using the step down chopper, this system simulates the power fluctuations which caused PV.

Fig . 9(b) shows the output power of the flywheel and Fig. 9(c) shows the grid power. From these results, the fluctuation of generated power is compensated by the output power of the flywheel. Therefore, the sudden fluctuations due to power fluctuation does not occur on the grid power.

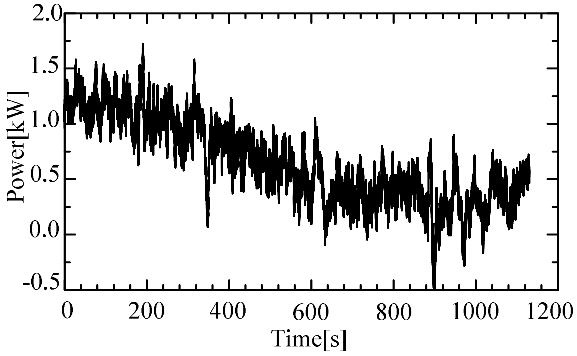
Fig. 9(d) shows the rotation speed of the flywheel. As a result, it is confirmed that the sudden speed variation does not occurs. According to the Fig. 9(c), the high frequency ripple occurs in the grid power. This ripple is caused by the influence of the power detection delay time. This problem can



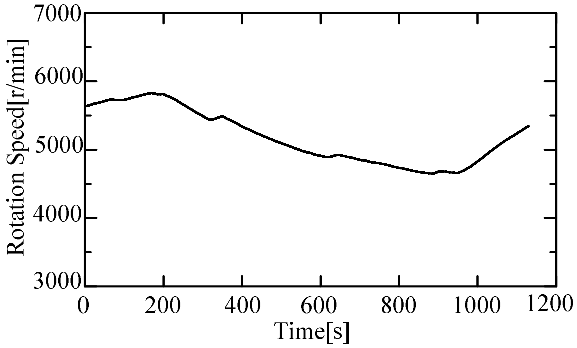
(a)Fluctuation pattern



(b) Output power of the Flywheel



(c) Grid power



(d)Rotation speed

Fig. 9. Experimental results of the power fluctuation compensation control when applying Smith predictor. (Rotation speed is 5500r/min)

be improved by the optimization of the control gain.

Fig. 10 shows the harmonic analysis of the fluctuation pattern and the grid power. The experimental conditions are similar to Fig. 9. As the result, it is confirmed that the fluctuation pattern has large frequency component between 0.01 Hz and 0.004 Hz. By contrast, the grid power fluctuations over 0.004 Hz is reduced 84.6 % by the power leveling control.

VI. CONCLUSION

This paper discussed a low cost power leveling system with a 3.0 MJ, 9500 r/min flywheel energy storage by a combination of the general purpose products.

As a result, in the regenerative power control, the overshoot of regeneration power was improved by using Smith predictor. In addition, the effectiveness of the power leveling control in the prototype was evaluated by experiment. From the harmonic analysis, it is confirmed that the power fluctuation is reduced by 84.6 %.

In future work, the design method of the low loss flywheel system is established.

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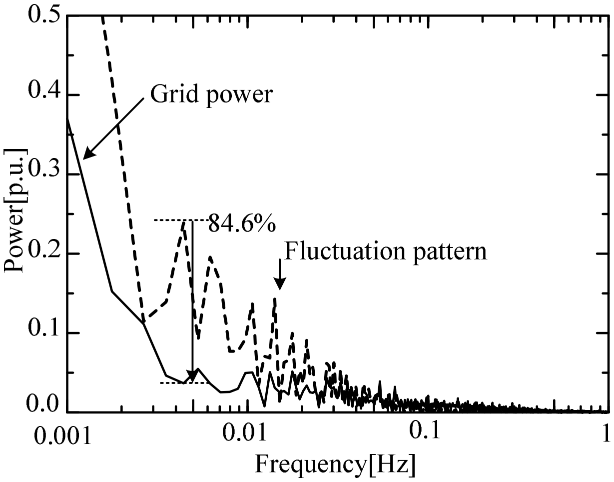

Fig.10. Harmonic analysis during the power fluctuation compensation. The experimental conditions are similar to Fig. 9.

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