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Author(s)	Shirai, Yasuyuki; Minamoto, Sho; Yonemura, Kenta; Rahman, Lutfur, Mohammad
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Output power control of Hybrid off-shore-wind and tidal turbine generation system with battery storage system

Yasuyuki Shirai, Sho Minamoto, Kenta Yonemura and Mohammad Lutfur Rahman
Department of Energy Science and Technology, Graduate School of Energy Science Kyoto University, Japan
E-mail: shirai@energy.kyoto-u.ac.jp

***Abstract*-- Generally, the wind-power output fluctuation is compensated by a rather large capacity battery system. In order to reduce the capacity of the battery, long term fluctuation component should be reduced. We have proposed a hybrid generation system which is composed of large scale off-shore wind farm with small scale tidal generation system (HOTT; Hybrid Off-shore and Tidal Turbine).**

The basic concept of HOTT generation system is to compensate wind power fluctuation by controlling the output of tidal generation system. If the tidal power compensates some long-term portion of the wind fluctuation, the battery capacity can be reduced.

In this study, for coordinating compensation by the tidal generator and the battery, a control system was designed limiting compensating frequency range by using band pass filter and phase compensation. The characteristics of this system was investigated by simulation studies.

***Index Terms*—Offshore Wind generation, Tidal Turbine generation, Hybrid wind and tidal turbine, Power stabilization**

I. Introduction

Recently, Energy problems such as the shortage of fossil fuel and environmental problem such as global warming have attracted the attention in the world. Then, significance of renewable energy is increasing. In this paper, we focus on the offshore-wind generation system and tidal flow generation system.

Large amount of Offshore-wind generation system has been introducing to the electric power grid. Then it comes serious problem that the output fluctuation of wind generation system affects the power system stability. The required battery capacity is increasing especially for long term fluctuation. Tidal flow generation system has the advantage that tidal power has high energy density and has small fluctuation. Whereas, the maintenance and the installation cost is rather high.

Therefore Hybrid Offshore-wind and Tidal Turbine (HOTT) generation system is proposed [1],[2]. The conceptual image of the proposed HOTT generator system is given in Fig.1. Fig. 2 shows the system schematic diagram of the HOTT generation system with the battery energy storage. The large scale off-shore wind farm (synchronous generators) power is converted to DC by a diode rectifier. The small scale tidal turbine with induction generator is connected through a bi-directional converter to DC circuit. And the battery storage system is installed through DC/DC bi-directional converter.

The long term power fluctuation is compensated by controlling bi-directional converter and the tidal induction generator and the short term one is reduced by DC/DC converter control of the battery system.

The hybrid system model was evaluated using PSCAD/EMTDC, and the mathematical models of each component were modified from IEEE models available in PSCAD@EMTDC^{TM} master library [3],[4]. In the proposed system, the induction generator for the tidal turbine can function as a generator to make stable the frequency and active power fluctuations [2]. This research presents the fundamental configuration of the system, the simulation results, and a discussion about the basic operation performance of the proposed system.

Fig. 1. Conceptual image of HOTT.

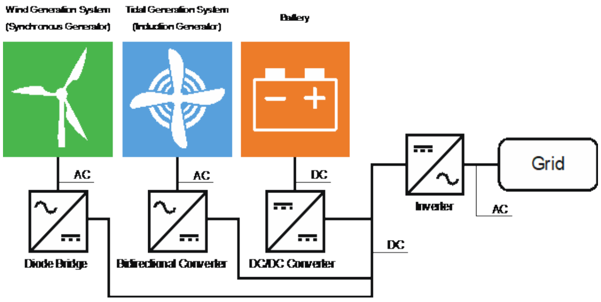

Fig. 2. Conceptual System Schematic of HOTT with Battery.

II. Concept of HOTT Generation System with Battery

A. Offshore-wind Turbine

The simulation model of the offshore wind turbine is shown in Fig. 3 and the parameter of the turbine and generator are listed in TABLE 1. In this model, wind speed, machine rotation speed, and pitch angle are given to the wind turbine module. The wind turbine torque is given to the synchronous generator from the module. Considering the converter efficiency, three phase AC output of the wind synchronous generator is converted to DC by a 6-pulse diode rectifier.

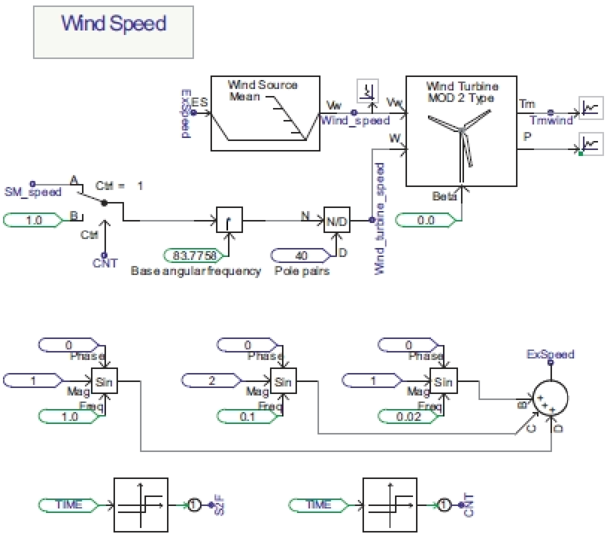

Fig. 3. Simulation model of wind turbine.

TABLE 1
Parameters of wind turbine and generator

Parameters	Value
Generator type	Synchronous machine
Rated power	300 kW
Rated line voltage	400 V
Rotor radius	15 m
Pitch angle	0 ∘
Air density	1.229 kg/m3
Gear Ratio	1
Mechanical Friction and windage	0.05 p.u.
Iron loss resistance	300 p.u.
Moment of inertia	2.0 s

B. Tidal Turbine

The simulation model of the tidal turbine is shown in Fig. 4 and the parameter of the turbine and generator are listed in TABLE 2. To simulate the tidal turbine, we use the same module as wind turbine by changing fluid density, gear ratio and other turbine parameters.

The induction generator is adopted for the tidal system. Three phase AC output from tidal generator is converted to DC by bi-directional insulated-gate bipolar transistor (IGBT) converter. The tidal output power is modulated by controlling the switching frequency of the bi-directional IGBT converter. The rotating magnetic field frequency of the tidal induction generator and the slip of the induction generator are changed to compensate the power fluctuation of the total power of the wind and tidal generators,

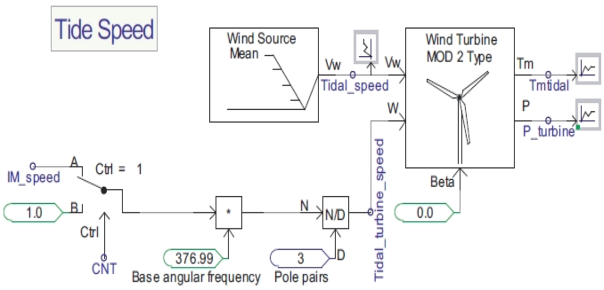

Fig. 4. Simulation model of tidal turbine.

TABLE2
Parameters of tidal turbine and generator

Parameters	Value
Generator type	Induction machine
Rated power	100 kW
Rated line voltage	400 V
Rotor radius	4.5 m
Pitch angle	0 ∘
Sea water density	1026 kg/m3
Gear ratio	180
Stator resistance	0.066 p.u.
First cage resistance	0.298 p.u.
Second cage resistance	0.018 p.u.
Stator unsaturated leakage resistance	0.046 p.u.
Rotor unsaturated mutual resistance	0.122 p.u.
Second cage unsaturated resistance	0.105 p.u.
Moment of inertia	1.0 s

C. Hybrid System Circuit of HOTT with battery

Fig. 5 shows the model circuit of HOTT with Battery on PSCAD/EMTDC. In this system, the induction generator output for the tidal turbine can be modulated to make stable the frequency and the active power fluctuation [2].

Fig. 6 shows the output power fluctuation compensation control block diagram. The input signal is P_{wind}, which is the offshore-wind turbine active power. The fluctuation components of P_{wind} are divided by the filtering unit into three components according to their fluctuation frequency ranges, that is, the higher frequency component is for the

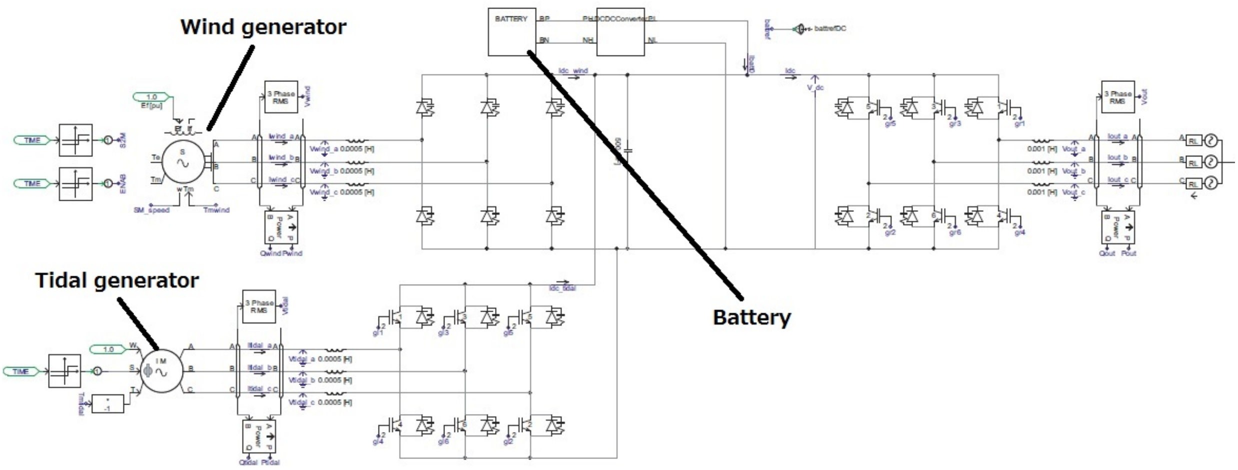

Fig. 5. HOTT with Battery System circuit.

battery compensation output reference, the medium frequency component is for the tidal generator compensation reference.

And then, in order to compensate the phase delay in the tidal generation unit and the filtering unit, the phase compensation circuit has been implemented in the control system.

The tidal generation power is controlled according to the reference by the frequency f_{tidal} of the rotating magnetic field of the induction generator. Figure 7 shows the bi-directional converter control system on PSCAD/EMTDC. The frequency f_{tidal} is controlled by the bi-directional converter of the tidal turbine, which is based on PWM.

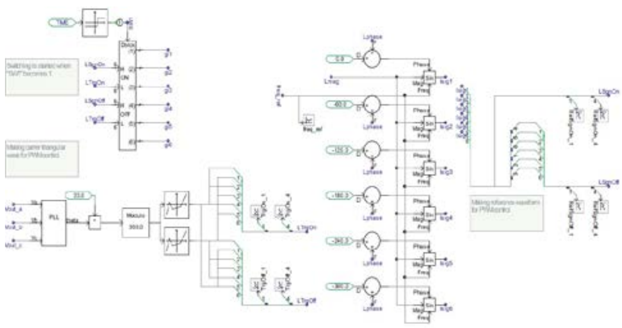

Fig. 7. Bi-directional converter control system.

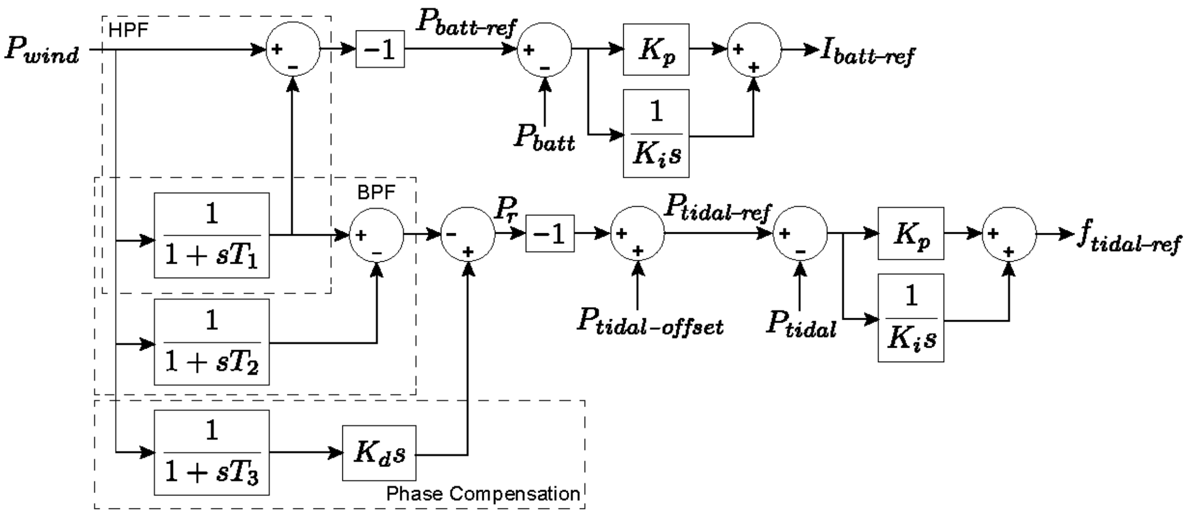

Fig. 6. Output power fluctuation compensation control system.

III. Simulation Results

A. Output power control by the tidal turbine generation

The simulation study was carried out with 8 cases as listed in TABLE 3. Simulation was carried out for 100 seconds, it was started compensation after 15 seconds. In cases 1-4, the wind speed (V_{wind}) was set according to Eq. (1) (Fig.8), which contains DC, 0.1Hz and 1.0Hz components (ratio; 12:1:0.2). In cases 5-8, V_{wind} was set according to Eq. (2) (Fig.9), which contains DC, 0.02Hz and 0.1Hz components (ratio; 12:1:0.5).

The upper cut-off frequency (f_{c1}: related to T_1) and the phase compensation gain (K_d) were set as TABLE 3.

Common parameters, that is the lower cut-off frequency (f_{c2}: related to T_2), the cut-off frequency of the phase compensation function (f_{c3}: related to T_3), the proportional gain and integral gain for PI control (K_p and K_i), the tidal flow speed (V_{tidal}) and the offset (DC component) of the tidal power reference ($P_{\mathrm{tidal\text{-}offset}}$) were set in TABLE 4.

Therefore, the frequency components of the wind power fluctuation between f_{c2} and f_{c1} are compensated by the tidal power control and the higher components than f_{c1} will be compensated by the battery system.

$$V_{wind} = 12 + 0.2\sin(2\pi\cdot 1\cdot t+\phi) + \sin(2\pi\cdot 0.1\cdot t+\phi) \quad (1)$$

$$V_{wind} = 12 + 0.5\sin(2\pi\cdot 0.1\cdot t+\phi) + \sin(2\pi\cdot 0.02\cdot t+\phi) \quad (2)$$

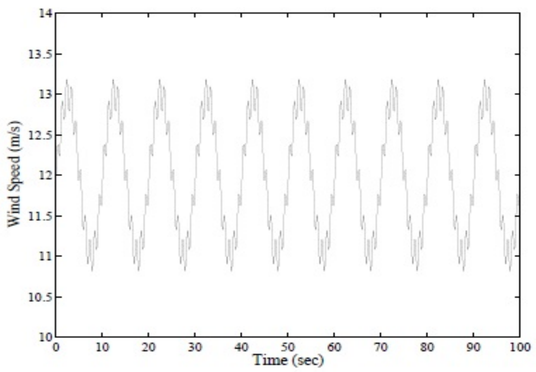

Fig. 8. Wind speed model (Eq. (1))
DC, 0.1Hz and 1.0Hz components (ratio; 12:1:0.2).

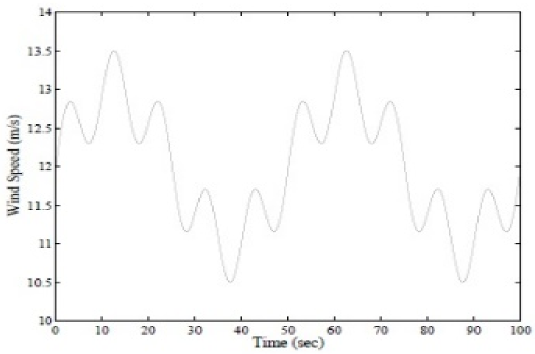

Fig. 9. wind speed (Eq. (2))
DC, 0.02Hz and 0.1Hz components (ratio; 12:1:0.5).

TABLE3
Condition of the simulation

Case	K_d [sec]	V_{wind}
1	0	Eq.(1)
2	0.05	
3	0.12	
4	0.25	
5	0	Eq.(2)
6	0.05	
7	0.12	
8	0.25	

TABLE4
Common condition of the simulation

Parameters	Value
f_{c1}	0.5 Hz
f_{c2}	0.08 Hz
f_{c3}	1.0 Hz
K_p	0.4
K_i	0.2 sec
V_{tidal}	2.0 m/s
$P_{\mathrm{tidal\text{-}offset}}$	20 kW

We defined "Compensation rate" as following to evaluate the control system performance:

$$\text{Compensation rate}(f) = 1 - \frac{A_{\mathrm{total}}(f)}{A_{\mathrm{wind}}(f)} \quad , \quad (3)$$

where $A_{\mathrm{total}}(f)$ and $A_{\mathrm{wind}}(f)$ is amplitude of power fluctuation of f Hz.

Figs. 10, 12 and 13 show the simulation result of wind (blue), tidal (black) and total (red) output powers in case 1, 3 and 4. Fig. 11 shows tidal turbine slip reference in case 1. TABLE 5 shows the result of compensation rate (f = 0.1 Hz) in case 1 - 4.

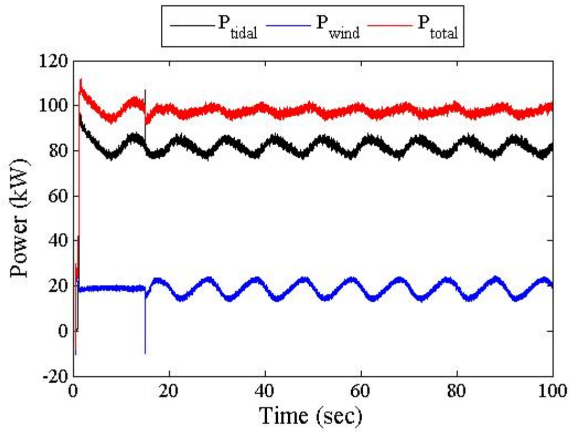

Fig. 10. Output powers of case1.

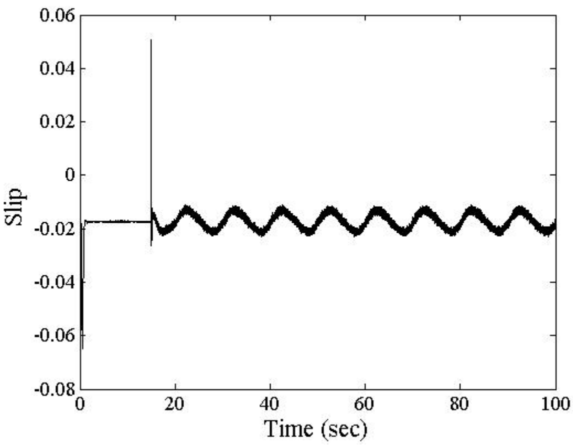

Fig. 11. Tidal turbine slip reference of case 1.

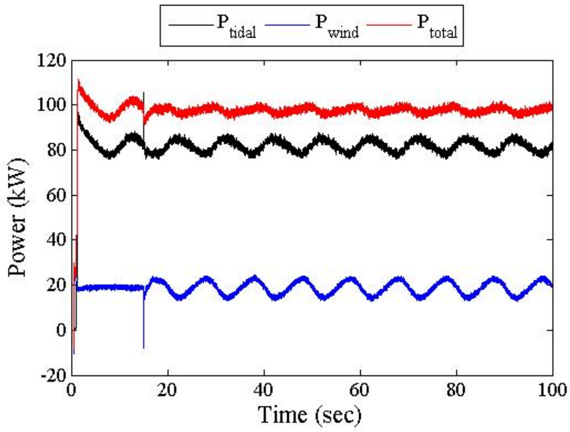

Fig. 12. Output powers of case 3.

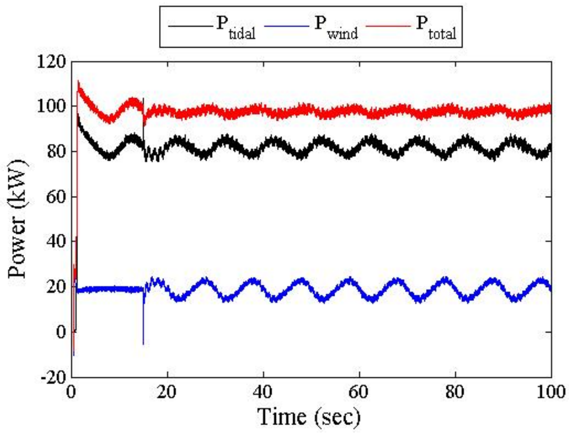

Fig. 13. Output powers of case 4.

TABLE 5
Compensation ratio.

Case	Compensation ratio [%]
1	51.25
2	52.51
3	54.94
4	59.19

Seen from Fig.10, the wind generator power output contains fluctuation (0.1 Hz and 1.0 Hz) caused by the wind speed model Eq.(1) (Fig.8). The tidal generator output is controlled to compensate the fluctuation with the proposed control block, that is, the 0.1Hz component of the tidal compensation power is produced by changing the slip reference (Fig. 11), then the rotating magnetic field given by the bi-directional converter. The total system output is smoothed as shown in red line in Fig.10.

As shown Figs. 10, 12 and 13 and TABLE 5, the compensation ratio is improved as increasing the phase compensation gain K_d. However, 1 Hz fluctuation component of the tidal output come to the surface as in Fig. 13. For actual operation, the gain K_d should be adjusted according to the requirements of the communicating system and the wind conditions.

Figs. 14 and 16 show the simulation result of wind (blue), tidal (black) and total (red) output powers in case 5 and 8. Fig. 15 shows tidal turbine slip reference in case 5. TABLE 6 shows the result of compensation rate (f = 0.1 Hz) in case 5-8.

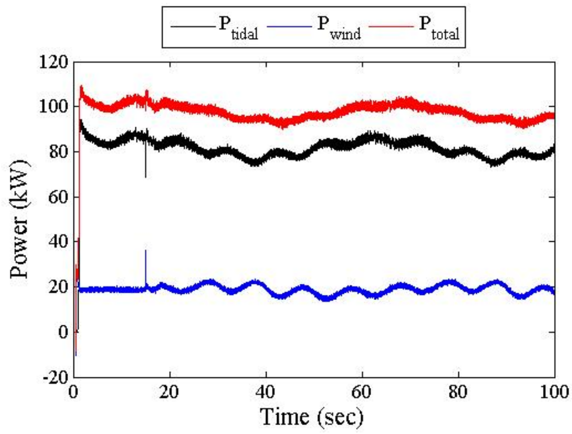

Fig. 14. Tidal turbine slip reference of case 5.

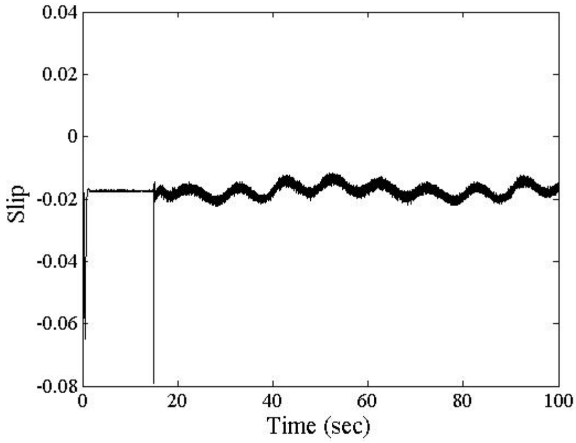

Fig. 15. Tidal turbine slip reference of case 5.

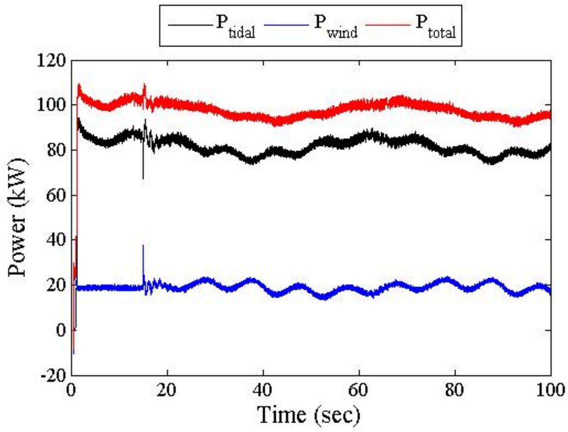

Fig. 16. Output powers of case 8.

TABLE 6
Compensation ratio.

Case	Compensation ratio [%]
5	51.09
6	52.56
7	53.84
8	57.88

Seen from Fig.14, the wind generator power output contains fluctuation (0.1 Hz and 0.02 Hz) caused by the wind speed model Eq.(2) (Fig.9). The total system output is smoothed as shown in red line by the tidal output control according to the slip reference (Fig. 15).

As shown figure 14 and16 and TABLE 6, the compensation ratio is again improved with larger K_d and the tidal generator compensated only 0.1 Hz fluctuation but not 0.02 Hz component which was lower than f_{c2}.

From the above, it was confirmed that compensation frequency sharing for plural or more wind fluctuation components by using bandpass filter (BPF) unit can be done. Besides, the phase compensation is valid for improving compensation ratio, but larger K_d reduce the stability margin in higher frequency component.

IV. Conclusions

We have proposed a hybrid generation system which is composed of large scale off-shore wind farm with small scale tidal generation system (HOTT; Hybrid Off-shore and Tidal Turbine). The basic concept of HOTT generation system is to compensate wind power fluctuation by controlling the output of tidal generation system. If the tidal power compensates some long-term portion of the wind fluctuation, the battery capacity can be reduced.

For the purpose of characterization of output power control of Hybrid off-shore-wind and tidal turbine generation system with battery storage system, some simulation studies were carried out.

There is an upper limit frequency of the fluctuation that the tidal generator can compensate. At the same time, the too much longer term fluctuation compensation may increase the capacity of the tidal turbine. It is necessary to limit compensating frequency range by using band pass filter (BPF). However, a phase delay occurred near the high-frequency cut-off frequency of the BPF, the compensation ratio likely decreased. It was confirmed that the phase compensation control block improves the compensation ratio, but the phase compensation gain K_d should be adjusted according to the requirements of the communicating system and the wind conditions.

In the next step, the cooperative control of the HOTT with battery will be studied under the obtained results.

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