International Journal of Control and Automation
Vol. 10, No. 2 (2017), pp.383-394
http//dx.doi.org/10.14257/ijca.2017.10.2.32

Coordinated Frequency Control of FESS and BESS in Microgrid based on Model Predictive Control Strategy

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Abstract

This study deals with the frequency control in microgrid (MG) using flywheel energy storage system (FESS) and battery energy storage system (BESS), in which the FESS is a rapid response energy storage system (ESS) with low energy density whereas BESS is a slow response ESS with high energy density. In MG system, the FESS should respond firstly to the disturbance in MG system due to its rapid response characteristic then the BESS should compensate gradually for the disturbance due to its high energy density. Owing to characteristics of FESS and BESS, the coordinated frequency control based on model predictive control (MPC) is proposed in this study. A comparison study of MPC and PI control for frequency regulation in MG system is presented to evaluate the effectiveness of the proposed control strategy.

Keywords: *Model predictive control, microgrid, coordinated frequency control, flywheel energy storage system (FESS), battery energy storage system (BESS)*

1. Introduction

The increasing penetration of renewable energy sources (RESs) into microgrid (MG) offers many advantages of environments and economics, but also poses the negative impacts on frequency regulation of microgrid [1–3]. Particularly, frequency control MG in the islanded operation mode is more difficult than the grid-connected mode due to the lack of synchronization with the upstream utility grid. The frequency deviation from the nominal value is unavoidable in islanded MG system due to the penetration of RESs with the main characteristics of low inertia, uncertainties, and intermittent nature [4].

To improve the frequency performance and stability of islanded MG system, energy storage systems (ESSs) such as flywheel energy storage system (FESS), superconducting magnetic energy storage (SMES), electrical double-layer capacitor (EDLC), and battery energy storage system (BESS) have been introduced into MG system [5–8]. The ESSs with the characteristics of low energy density, high power density, and rapid response time such as FESS, SMES, and EDLC are suitable for short-term operation. Meanwhile, the BESSs, which have characteristics of high energy density, low power density and slow response time due to the chemical process, are suitable for long-term operation [9]. Various control strategies along with such ESSs have been proposed for frequency regulation in the islanded MG system [10–12]. Multiple ESSs can be used in islanded MG system to improve efficiency of MG system. For the islanded MG system with the penetration of multiple ESSs, owing to the characteristic of each ESS, coordination control strategies are required to share power between each ESSs effectively [13–15]. Coordinated control algorithm for distributed multiple ESSs to mitigate the voltage and frequency fluctuation has been presented in [13]. The novel frequency and voltage control strategy based on droop control scheme for islanded MG system based on multiple ESSs has been proposed to enhance the system dynamic stability and current sharing among ESSs [14,15].

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ISSN: 2005-4297 IJCA

Recently, MPC has gained attention in MG application, which can offer several advantages such as intuitive concepts, ease to handle MIMO system and constrains, and robustness against uncertainties [16]. Coordinated frequency control of wind generations and plug-in hybrid electric vehicles (PHEVs) using MPC presented in [17] could be used for MG system with high penetration of wind generation. Multiple MPCs-based frequency regulation, in which several MPCs can be chosen according to the change of operating conditions, has been presented in [18,19]. A compound control strategy based on an MPC for generators and a distributed leader-following consensus control strategy for multiple energy storage units has been proposed in [20]. However, the application of MPC for coordination frequency control of multiple ESSs has not been studied in previous literatures. This study proposes the coordinated frequency control of FESS and BESS for the islanded MG system by using a centralized model predictive control (MPC) strategy. MPC operation is based on online receding horizon control strategy, in which the control signal of FESS and BESS are made by solving an optimization problem over a finite time horizons for islanded MG system. A comparison study of MPC and PI regulator for frequency control in islanded MG system is presented in this study to evaluate the effectiveness of the proposed control strategy.

The rest of this paper is arranged as follows. Section 2 presents the test islanded MG system and the design process of MPC-based frequency control. Simulation results are shown in Section 3. The main conclusions are summarized in Section 4.

2. MPC-based Coordinated Frequency Control

2.1. Test islanded MG System

The typical islanded MG system, which consists of a diesel generator (DG), wind turbine generations (WTG), a domestic load, FESS, and BESS, is shown in Figure 1. The FESS connects to the MG bus through an AC/AC converter while the BESS uses a DC/AC converter. The islanded MG that is disconnected from the utility grid should regulate stably its frequency and voltage. The DG supplies the main power to the domestic load while WTG generates its maximum capability. Both FESS and BESS can either supply or absorb power to compensate the fluctuation in wind generation. The DG is responsible for primary frequency control in the islanded MG system whereas FESS and BESS are in charge of secondary frequency control. The centralized controller based on MPC, which measures frequency deviation of the islanded MG system, is proposed for both FESS and BESS.

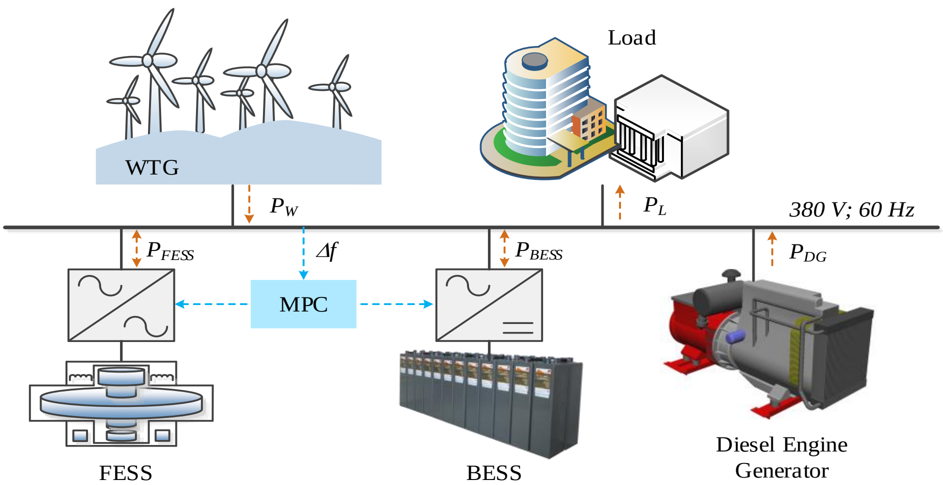

Figure 1. Typical Islanded MG Configuration with FESS and BESS

The frequency response of the islanded MG system is evaluated by using the linearized model shown in Figure 2. The DG, which consists of turbine, governor, and speed control, is represented as the first order transfer functions including inertia constant H and load damping D. Owing to the gradual change in wind speed, WTG is modelled by the first order transfer function with high time constant (T_W) whereas FESS and BESS are modelled by the first order transfer functions with small time constant (T_B and T_F). The system parameters, which are adopted from [21], are shown in Table 1.

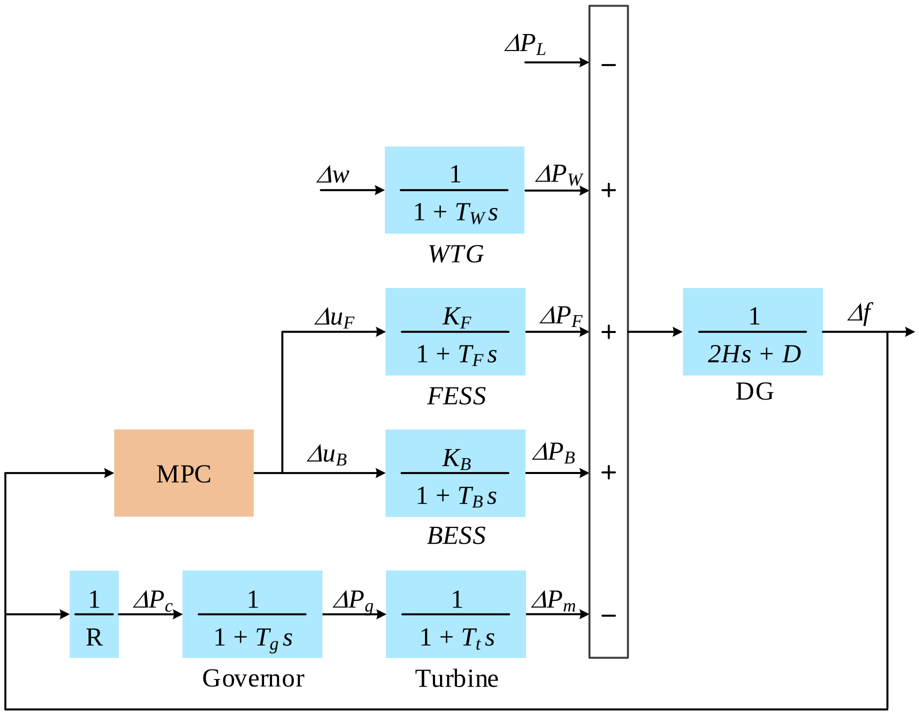

Figure 2. Linearized MG Model

Table 1. System Parameters

Parameters	Value	Parameters	Value
D	0.012	T_W	1.5
$2H$	0.2	T_B	0.1
T_g	0.08	T_F	0.1
T_t	0.4	K_B	-3/100
R	3	K_F	-1/100

The state-space dynamic model of the islanded MG shown in Figure 2, which is used for designing the MPC-based secondary frequency control, is given by (1).

$$\dot{x} = Ax + Bu$$
$$y = Cx \qquad (1)$$

where: $$x^T = [\Delta P_B \quad \Delta P_F \quad \Delta P_W \quad \Delta P_g \quad \Delta P_m \quad \Delta f \quad \Delta w \quad \Delta P_L] \qquad (2)$$

$$u = [\Delta u_B \quad \Delta u_F] \qquad (3)$$

$$A = \begin{bmatrix} -\frac{1}{T_B} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_F} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_W} & 0 & 0 & 0 & \frac{1}{T_W} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_g} & 0 & \frac{1}{R.T_g} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{T_t} & -\frac{1}{T_t} & 0 & 0 & 0 \\ -\frac{1}{2H} & -\frac{1}{2H} & \frac{1}{2H} & 0 & -\frac{1}{2H} & -\frac{D}{2H} & 0 & -\frac{1}{2H} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

$$B^T = \begin{bmatrix} \frac{K_B}{T_B} & \frac{K_F}{T_F} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (5)$$

$$C^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (6)$$

Here, x and u are the state vector and control signal vector, respectively; y is the output vector; Δu is the control increment; A, B, and C are the system matrices.

2.2. Design MPC for Coordination Control

The operation of MPC strategy is based on the state measurements to predict the future values of control signals. The objective of MPC is to find the sequence of control signals to minimize the error between the actual output of plant and reference signal. Figure 3 shows the operation principle of MPC strategy for many sampling instants, in which the integer k represents the current instant.

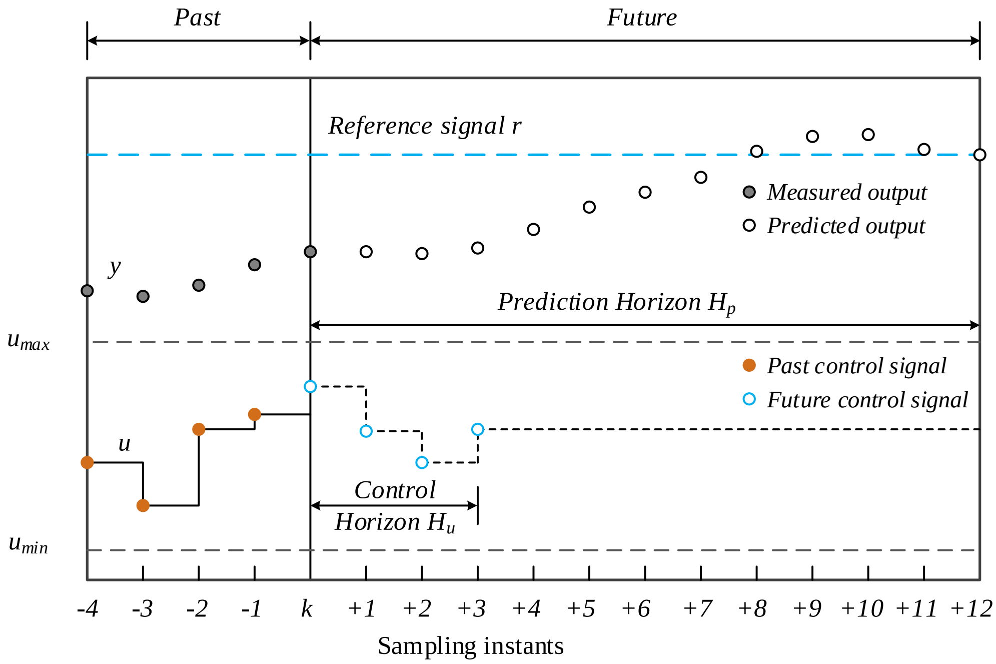

Figure 3. Operation Strategy of MPC

The MPC operates in two phases to calculate the control signals, which consists of state estimation phase and optimization phase [16]. By measuring the current state variables, the future trend of state variables is estimated by using the prediction model, as given by (7).

$$x(k+1) = Ax(k) + Bu(k)$$
$$y(k) = Cx(k) \tag{7}$$

where A, B, and C are the system matrices, as mentioned in (4), (5), and (6).

The second phase of the controller is to minimize the cost function (8) to obtain the control action at time k. The first term of the cost function is the penalizing deviation of the control variable that is the frequency in this paper. The second term of the cost function is used to minimize the variations in the control signals that is the control action of ESS. The third term represents the priority for the control signals of FESS and BESS.

$$J(k) = \sum_{i=0}^{H_p} \|y(k+i|k) - r(k+i|k)\|_Q^2 + \sum_{i=0}^{H_u-1} \sum_{j=1}^{n} \left\|w_j^{\Delta u} \Delta u_j(k+i|k)\right\|_R^2 + \sum_{i=0}^{H_u-1} \sum_{j=1}^{n} \left\|w_j u_j(k+i|k) - u_{jtarget}(k+1)\right\|^2 \tag{8}$$

subject to: $u_j^{max} \leq u_j \leq u_j^{min}$; $y_{max} \leq y \leq y_{min}$

where: $y(k+i|k)$ is the predicted output at time k; $\Delta u(k+i|k) = u(k+i) - u(k+i-1)$ is the predicted control increment; u_j^{max} and u_j^{min} are the maximum and minimum control increment, respectively; $r(k+i|k)$ is the reference at time k; n is the number of control variable (in this study, n is equal to 2 that corresponds to the control signal of FESS and BESS); $w_j^{\Delta u}$ and w_j are the weight factors; H_p and H_u are the prediction and control horizons, respectively; Q and R are the weighting matrices, which are considered to be unchanged for the prediction horizon H_p.

The cost function (8) can be minimized by a quadratic programming (QP) to find the optimal values [18]. When the solution of the cost function (8) is obtained, the sequence output of the controller after optimization is determined. Only the first value in the optimal trajectory, $\Delta u(k/k)$, is used to compute $u(k)$ as in (9) whereas the rest of samples $\Delta u(k+i/k)$ are discarded. At the next sampling interval, the entire procedure is repeated to solve the new optimization problem based on the measured output signal at time $k+1$.

$$u(k) = u(k-1) + \Delta u(k/k) \tag{9}$$

In this study, we consider the sampling time of MPC is equal to 0.01 s; the prediction horizon H_p is equal to 10; the control horizon equals to 2; Q equals to 0 and R equals to 0.1. The selection of the weight factors w_j is equally important for coordination control of FESS and BESS. The smaller value of w_j represents the less important behavior of the corresponding variable to the overall performance index. In this study, the control performance of FESS is quite important to the transient response of overall system due to its rapid response characteristic. Therefore, the weight factors w_j of FESS and BESS are chosen equal to 0.005 and 0, respectively. The weight factors $w_j^{\Delta u}$ are chosen equal to 1 for both of BESS and FESS.

3. Simulation Results

Several scenarios such as load change and wind fluctuation are carried out to evaluate the effectiveness of the proposed control strategy. The robustness of MPC method against the system uncertainties is also presented in this section. A comparison of MPC and PI for frequency regulation in MG system is presented. For effective comparison, the PI parameters are tuned automatically according to [23].

Firstly, the frequency response of MG system to the load change is shown in Figure 3. The load is increased with amount of 0.02 pu at 0.5 s, which results in the reduction of system frequency. The MG frequency is gradually recovered to the nominal value because the FESS and BESS generate powers to compensate for the load disturbance. It can be seen that the frequency response of MG system with MPC strategy is faster than that with PI regulator. For MG system with MPC method, frequency is recovered to the nominal value at about 0.8 s while frequency in MG system with PI regulator is restored to the rated value at about 1.8 s. In addition, the overshoot of frequency under MPC is double lower than that under PI control.

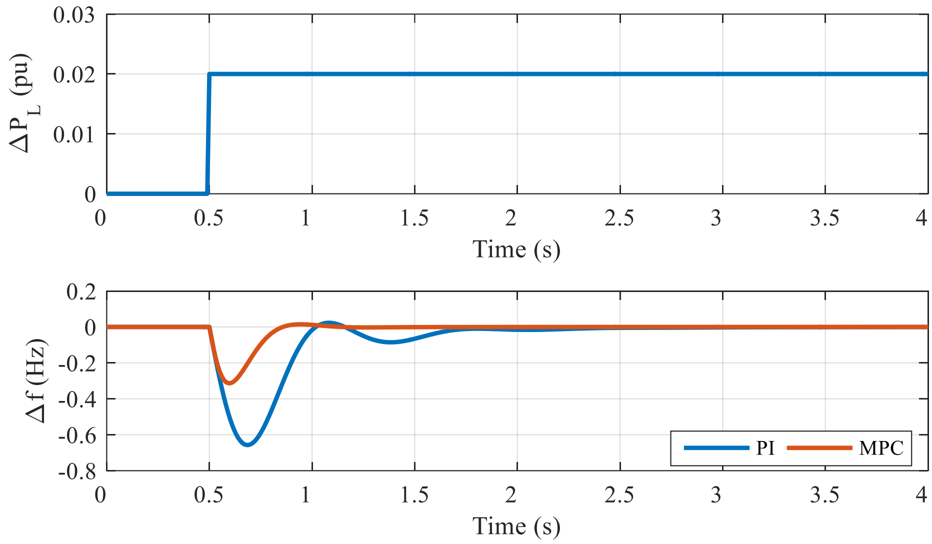

Figure 3. Frequency Response when Load Changes

FESS and BESS increase their power output to meet the fast change in load. Figure 4 shows the power response of FESS and BESS to the load change in MG system with either MPC or PI control. There are significant differences between MG system with MPC and PI. For the MG system with PI regulator, FESS always supplies bigger power than BESS. It is quite inadequate for the FESS because the main characteristic of FESS low energy density, which is suitable for short-term operation. By comparison, for MG system with MPC strategy, the FESS increases its power output rapidly to meet the load change. Then, the FESS decreases its output power gradually whereas the BESS increases its power gradually. It is suitable for MG operation because the main characteristic of BESS is high energy density, which can supply power for long-term operation. It can be seen that by using MPC strategy the coordinated control of FESS and BESS can be achieved easily. The frequency response to the multiple load changes and active power of FESS and BESS are shown in Figures 5 and 6. The frequency deviation in MG system with MPC is smaller than that in MG system with PI regulation. In addition, the coordination between FESS and BESS in MG system with MPC is achieved effectively, in which the response of FESS is faster than that of BESS.

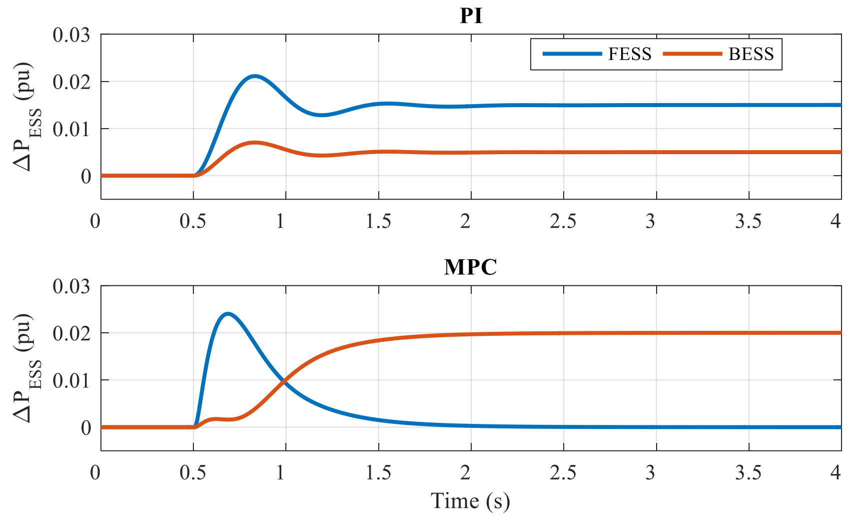

Figure 4. Active Power of FESS and BESS when Load Changes

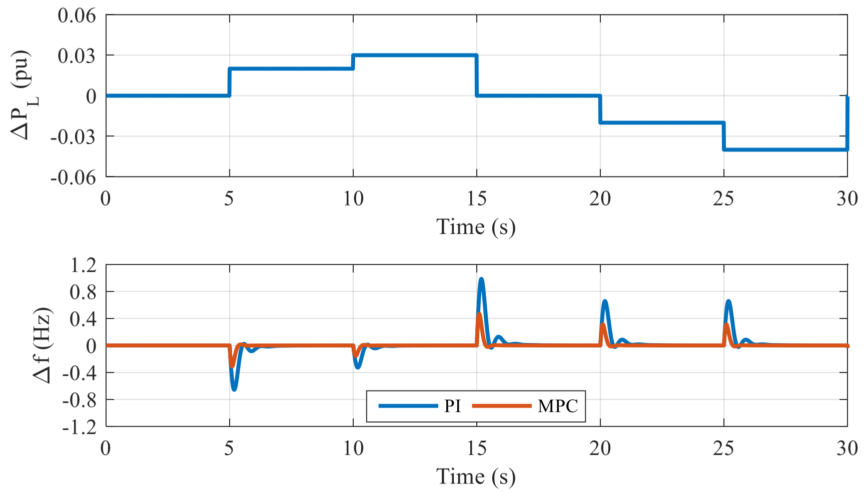

Figure 5. MG Frequency when Multiple Loads Change

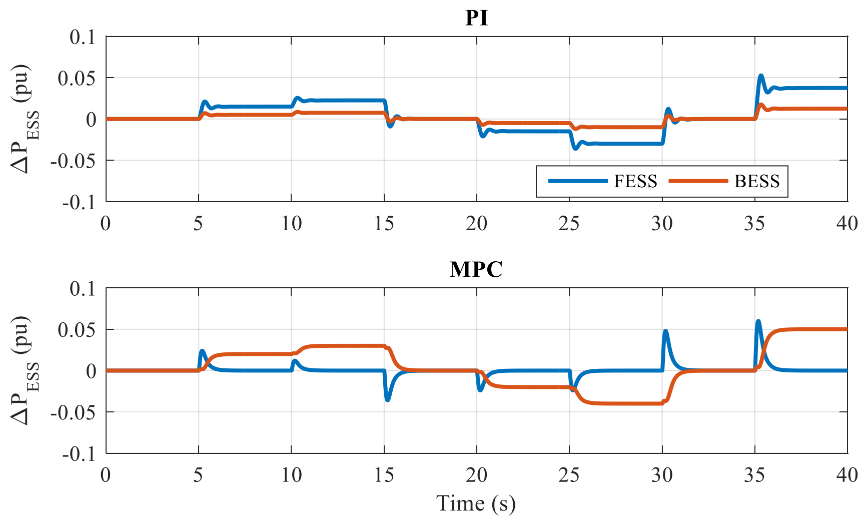

Figure 6. Active Power of FESS and BESS when Multiple Loads Change

In the islanded MG system, fluctuation in wind generation causes the frequency deviation from the nominal value. The controller should be designed properly to minimize the frequency deviation. The frequency responses of MG system with either MPC or PI regulator when wind generation fluctuates are shown in Figure 7. The wind power increases gradually and fluctuates slightly with the average value of 0.3 pu. It can be seen that the frequency deviation of MG system with MPC strategy is much smaller than that of MG system with PI regulator. The maximum frequency deviation of MG system with PI regulator is 0.6 Hz while it is 0.2 Hz in case of MG system with MPC strategy. The active powers of FESS and BESS when wind power fluctuates are shown in Figure 8. The difference between MG system with MPC and PI regulator is the power output of FESS system. While the output power of FESS in MG system with PI regulator always higher than that of BESS, the FESS output power in MG system with MPC is kept much smaller than BESS power. Since the wind power changes gradually, the BESS is suitable for the main power supply to compensate for the fluctuation in wind power due to the slow response characteristic of BESS.

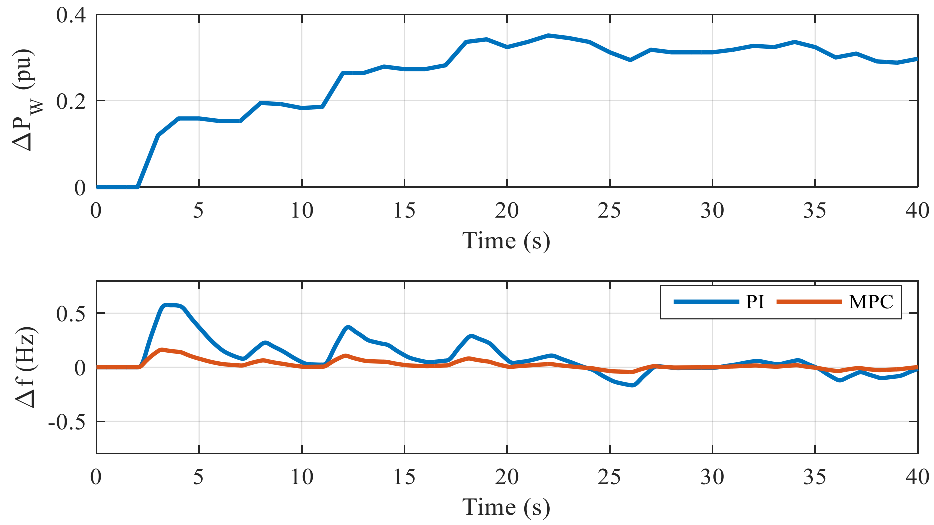

Figure 7. MG Frequency with Fluctuation in Wind Power

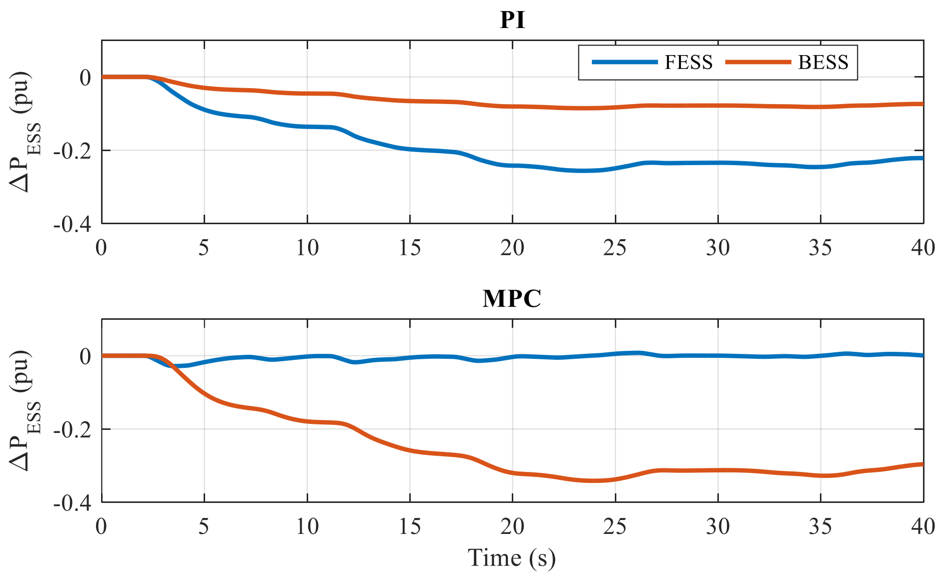

Figure 8. Active Power of FESS and BESS when Wind Power Fluctuates

The multiple disturbances such as wind fluctuation and load change might occur in the islanded MG system. Figure 9 shows the frequency response of MG system in the condition of load change at every 5 s and wind fluctuation. The frequency deviation of MG system with MPC strategy is much smaller than that of MG system with PI regulator. The maximum frequency deviation of MG system with PI regulator is 1.1 Hz whereas it is 0.5 Hz in case of MG system with MPC strategy. The FESS and BESS output powers in the condition of multiple disturbances are shown in Figure 10. The FESS with rapid response and low energy density characteristics can supply a large power in fraction of second whereas the BESS with slow response and high energy density characteristics can provide low power in a few hours. In case of MG system with PI regulator, since the main power supply for the disturbance is in the FESS, the number of charge and discharge the FESS might be increased significantly. By using MPC-based frequency control in the islanded MG system, the FESS is coordinated effectively with BESS to regulate MG system frequency. The FESS responds firstly to the disturbances then decreasing its power gradually. The BESS increases its power output gradually to compensate for the disturbances.

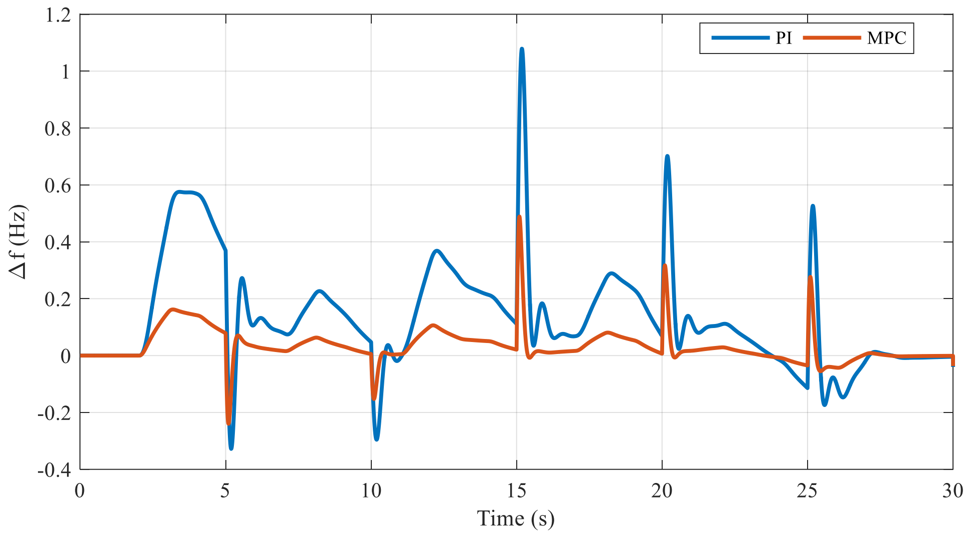

Figure 9. MG Frequency with Load Change and Wind Fluctuation

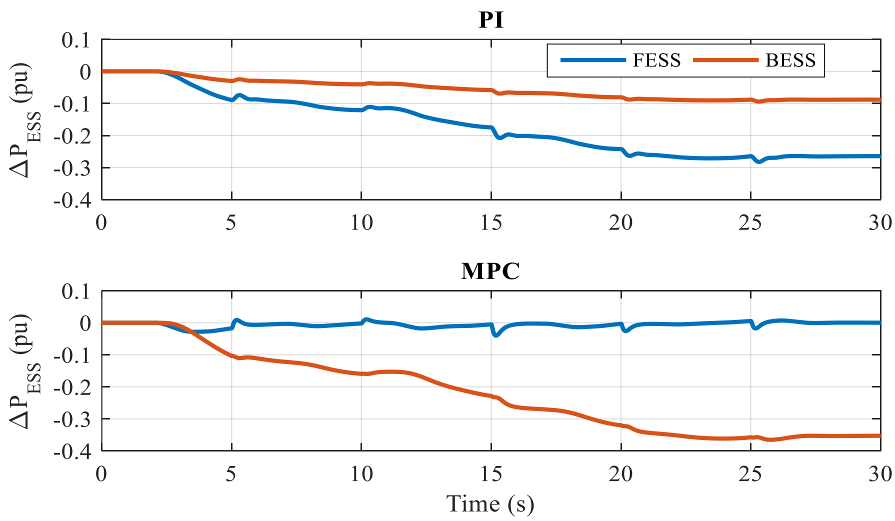

Figure 10. FESS and BESS Powers with Load Change and Wind Fluctuation

Finally, the robustness of the controller against the system parameter changes is tested in this section. The system parameters are changed significantly according to Table 2. The frequency response of MG system in this condition is shown in Figure 11. It can be seen that the frequency of both MG system with either MPC or PI regulator is still stable although the system parameters change significantly. The effect of system uncertainties on the PI control performance is the increase of oscillation frequency and magnitude of frequency deviation. Meanwhile, in case of MG system with MPC strategy, the system uncertainties have only effect on the increase of magnitude frequency deviation. However, the frequency deviation of MG system with MPC strategy is still smaller than that of MG system with PI regulator.

Table 2. Variation of System Parameters

Parameters	Variation Range	Parameters	Variation Range
D	-20%	T_W	-50%
$2H$	-50%	T_B	+40%
T_g	-20%	T_F	+30%
T_t	+30%	K_B	+40%
R	-30%	K_F	+30%

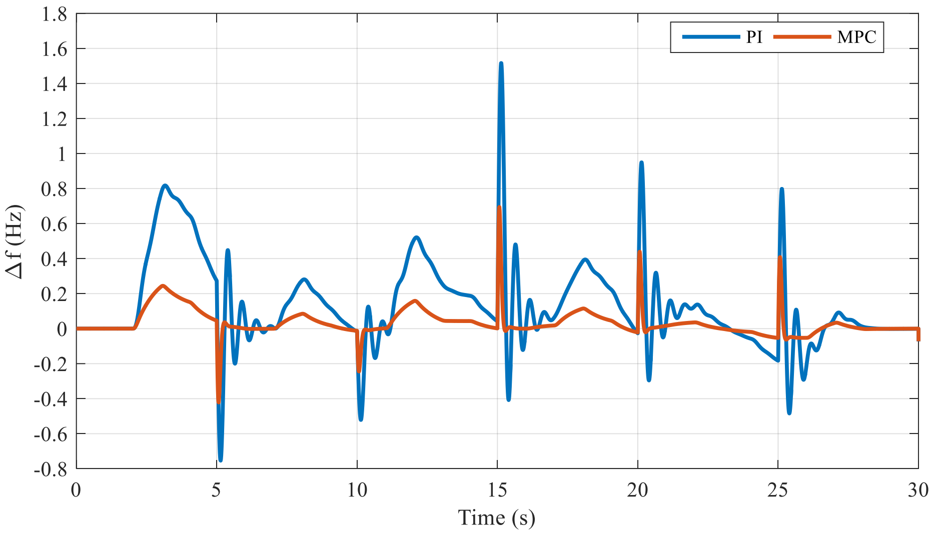

Figure 11. MG Frequency Considering System Uncertainties

4. Conclusions

This study has proposed the coordination frequency control of FESS and BESS for the islanded MG system based on a centralized MPC. The control performance of MPC is compared to PI regulator to evaluate the effectiveness of MPC strategy for coordination control of FESS and BESS. Simulation results showed that the frequency response of MG system with MPC strategy is much faster than that with PI regulator. The frequency deviation with MPC strategy is much smaller than the PI regulator. Since the characteristics of FESS and BESS are different, the coordinated control of FESS and BESS can be obtained easily by using MPC strategy. The FESS with rapid response ability could firstly respond to the disturbance in the islanded MG system then decreasing its power output gradually. Meanwhile, the BESS could gradually respond to the disturbance due to its characteristic of slow response.

Acknowledgments

This work was supported by Incheon National University Research Grant in 2015.

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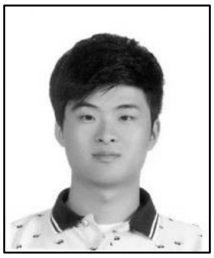

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