

# A Class of Optimal and Robust Controller Design for Islanded Microgrid

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**Abstract**—This paper proposes a class of optimal and robust controller for the islanded AC microgrid (MG) system which is composed of wind turbine generator (WTG), photovoltaic generator (PV), fuel cell (FC), micro turbine (MT), battery energy storage (BES) and loads. The proposed controller has two main functions: rationally utilizing MT, FC and BES, and regulating the AC bus frequency deviation. For such islanded MG, we formulate the control system via a group of ordinary differential equations (ODEs), where we consider the power of wind and solar radiation as system disturbance inputs. The control input is designed in MT and FC. The AC bus frequency deviation is denoted as the system controlled output. The problem of rationally utilizing MT, FC and BES is formulated as an optimal control ( $H_2$  control) problem, whereas the frequency regulation issue is formulated as an  $H_\infty$  control problem. Our aim is to find a controller such that both  $H_2$  and  $H_\infty$  performances are achieved, which can be viewed as solving a mixed  $H_2/H_\infty$  control problem. We solve it analytically via the Nash game approach. Finally, based on real-world data, numerical results are illustrated, and simulations show that our target is achieved.

*Keywords*—optimal control; robust control; mixed  $H_2/H_\infty$  control; frequency control; microgrid; Nash equilibrium

## I. INTRODUCTION

Presently, human beings around the world are facing challenges for example global warming, energy crisis, environmental pollution, etc. In the past decades, the distributed energy resources (DERs) such as wind power, solar power and hydro power have attracted much attention and significant advances on DERs have been made; see, e.g., [1]. These DERs are popular since they are renewable, clean and inexpensive [2]. For remote places that are not connected to the utility grid, the distributed generators (DGs) such as wind turbine generators (WTGs) and photovoltaic panels (PVs) are utilized to provide electricity to local loads; see, e.g., [3]–[5].

The small and isolated power system in [3]–[5] for instance is called microgrid (MG) system [6]. According to the category of the MG bus line, the MG can be classified into two types: AC MG and DC MG. A common MG is composed of the DG units, loads and energy storage devices. Normally, for a MG there are two modes of functioning. When the MG is interconnected with the main power grid, we call it as the grid-connected mode, whereas when the MG is functioning on its own, we name it as the islanded mode, or the off-grid mode [7].

Apart from the advantages, the power generation by DERs have defects as well, e.g., intermittence, nonlinearity, stochasticity, uncertainties, uncontrollability, etc. Especially when the MG is functioning on an off-grid mode, the DERs will bring challenges to the MG's autonomous operation. For example, a small unbalance between power generation and consumption would cause the MG bus frequency and voltage to fluctuate, which might lead to the collapse of the whole MG system [8], [9].

Such power deviation between power generation and consumption can be absorbed by the energy storage (ES) system [10], [11], which normally refers to battery energy storage device (BES) and flywheel energy storage device (FES). On the other hand, the energy storage is relatively expensive [12], and sustaining large-scale power input/output would bring damage to ES. In order to save the operation cost of the MG, extending the lifetime of ES has become a common target [10]–[12].

For the voltage and frequency regulation problems in MG, robust control schemes can be used as effective tools to achieve system robust stability and robust performance [13], [14]. In [15], a decentralized robust control scheme is studied for a multi-DER islanded MG, in which the robust controller is designed for each distributed power generation unit. The robust  $H_\infty$  control problem for power sharing in both grid-connected and islanded MG is investigated in [16]. For the other works using robust  $H_\infty$  approaches on the MGs, reader can consult [17] and [18].

When the role of BES is considered in MG, recent work [19] proposes a novel robust load frequency control strategy for the islanded MG. In [20], it is reported that by controlling the power of BES when charging and discharging, the MG system frequency can be regulated. A novel hybrid operation strategy for frequency regulation is proposed for the wind energy conversion system with BES in [21]. For other works that consider both the MG frequency regulation and BES, reader can refer to [22]–[26], and the references therein.

In this paper, we consider an islanded AC MG which is assumed to be composed of WTG, PV, MT, FC, BES and load only. The dynamic MG system is transformed into a control system formed by a group of ordinary differential equations (ODEs). Our purpose is to design a novel controller in MT and FC, such that the AC bus frequency deviation is stabilized, and MT, FC and BES are rationally utilized. We formulate the frequency regulation problem into a  $H_\infty$  control problem. Meanwhile, we formulate the MT, FC and BES rational utilization issue into a  $H_2$  control

problem. Mathematically, our aim is to design a controller such that both  $H_\infty$  and  $H_2$  performances are achieved, which is denoted as the mixed  $H_2/H_\infty$  control problem. We highlight this is the very first time that the problems of both frequency regulation and the rational utilization of MT, FC and BES in an islanded MG are simultaneously considered. Such problems are formulated into a mixed  $H_2/H_\infty$  control problem which is solved analytically via Nash game approach. It is notable that our new problem formulation is different from the existing works, see, e.g., [19]–[26]. Finally, the numerical results show the usefulness and effectiveness of our proposed mixed  $H_2/H_\infty$  controller.

The rest of the paper is organized as follows. In Section II we describe the system modelling and formulate the optimal and robust control problem mathematically. Section III gives the analytical solution to our  $H_2/H_\infty$  control problem. Section IV provides some numerical simulations. Finally, we conclude this paper in Section V.

## II. SYSTEM MODELLING AND PROBLEM FORMULATION

In this paper, we consider an islanded MG based on AC bus. The considered MG includes WTG, PV, MT, FC, BES and load. A simplified configuration is shown in Fig. 1.

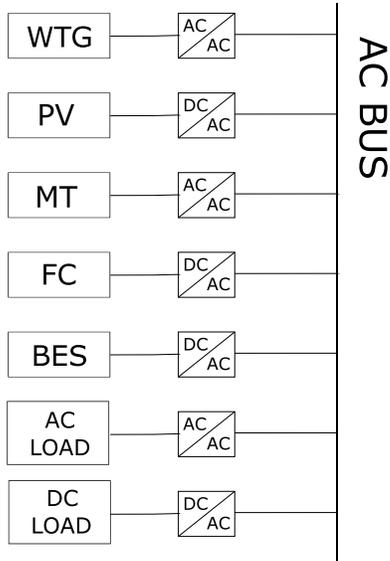


Figure 1. System configuration.

The total power generation in MG comprises the power generation from WTG, PV, FC, MT, including/excluding power input/output from BES. The total power generation shall be equal to the total power consumption from load. If we denote scalars  $P_{WTG}$ ,  $P_{PV}$ ,  $P_{FC}$ ,  $P_{MT}$ ,  $P_{BES}$ ,  $P_L$  as power output of WTG, PV, FC, MT, BES and load, respectively, then the MG power balance relationship can be expressed by the following equation,

$$P_{WTG} + P_{PV} + P_{FC} + P_{MT} \pm P_{BES} = P_L. \quad (1)$$

Let us denote scalars  $\Delta P_{WTG}$ ,  $\Delta P_{PV}$ ,  $\Delta P_{FC}$ ,  $\Delta P_{MT}$ ,  $\Delta P_{BES}$ ,  $\Delta P_L$  as power output change of WTG, PV, FC, MT, BES and load, respectively. Then we have

$$\Delta P_{WTG} + \Delta P_{PV} + \Delta P_{FC} + \Delta P_{MT} + \Delta P_{BES} + \Delta P_L = 0. \quad (2)$$

For the simplified dynamical power models for distributed generators and energy storage devices, reader can consult [18], [27]–[29]. In this paper, only low order dynamical models are considered, which is suitable for our target stated in the previous section. We use the linearized state-space model to describe the dynamics of the MG. Consider the following ODEs,

$$\begin{cases} \Delta \dot{P}_{WTG}(t) = -\frac{1}{T_{WTG}} \Delta P_{WTG}(t) + \frac{1}{T_{WTG}} \Delta P_w, \\ \Delta \dot{P}_{PV}(t) = -\frac{1}{T_{PV}} \Delta P_{PV}(t) + \frac{1}{T_{PV}} \Delta P_\phi, \\ \Delta \dot{P}_{MT}(t) = -\frac{1}{T_{MT}} \Delta P_{MT}(t) + \frac{1}{T_{MT}} u, \\ \Delta \dot{P}_{FC}(t) = -\frac{1}{T_{FC}} \Delta P_{FC}(t) + \frac{1}{T_{FC}} u, \\ \Delta \dot{P}_{BES}(t) = -\frac{1}{T_{BES}} \Delta P_{BES}(t) + \frac{1}{T_{BES}} \Delta f, \\ \Delta \dot{f} = -\frac{2D}{M} \Delta f + \frac{2}{M} \Delta P_L. \end{cases} \quad (3)$$

Here,  $\Delta P_w$  and  $\Delta P_\phi$  stand for the power change of wind, solar radiation, respectively. Considering (2), we rewrite (3) into the following mathematical state space control system (time  $t$  is omitted)

$$\dot{x} = Ax + Bu + Cv, \quad (4)$$

and

$$z = D_2 x, \quad (5)$$

in which the system coefficients are given as follows

$$A = \begin{bmatrix} -\frac{1}{T_{WTG}} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{PV}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{MT}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{FC}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{BES}} & \frac{1}{T_{BES}} \\ -\frac{2}{M} & -\frac{2}{M} & -\frac{2}{M} & -\frac{2}{M} & -\frac{2}{M} & -\frac{2D}{M} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 1 \\ \frac{1}{T_{MT}} \\ 1 \\ \frac{1}{T_{FC}} \\ 0 \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} \frac{1}{T_{WTG}} & 0 \\ 0 & \frac{1}{T_{PV}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$D_2 = [0 \ 0 \ 0 \ 0 \ 0 \ 1].$$

In our considered system (4) – (5), system state is vector  $x(t) = [\Delta P_{WTG} \ \Delta P_{PV} \ \Delta P_{MT} \ \Delta P_{FC} \ \Delta P_{BES} \ \Delta f]'$ , scalar  $u(t)$  is the control input, vector  $v(t) = [\Delta P_w \ \Delta P_\phi]'$  is the system disturbance input, scalar  $z(t) = \Delta f$  is the system controlled output. We define the scalar  $y(t)$  to be equal to  $\Delta P_{BES}$ , then we have  $y = D_1 x$ , where  $D_1 = [0 \ 0 \ 0 \ 0 \ 1 \ 0]$ .

Now we have transformed the physical islanded MG dynamics into mathematical control systems (4) – (5).

Our aim is to design a controller such that BES, MT and FC are utilized rationally, and meanwhile the AC bus frequency is regulated properly. Next, we formulate the above purpose into two cost functionals, mathematically.

First, we define a criterion to consider the rationality of the utilization of BES, MT and FC as follows, (time  $t$  is omitted)

$$J_1 = \int_0^T (ay'y + bu'u)dt. \quad (6)$$

In (6),  $a$  and  $b$  stand for the given weight parameters, which depend on the specific standard of the real scenario. Intuitively, the term  $ay'y$  enlarges the power output change of BES, and we use the term  $bu'u$  to describe the potential cost that the controller in (4) brings to the MG system. It is notable that such settings in (6) consider one interesting possible scenario that although a controller minimizes the power output change of BES effectively (which is one approach to extending the service life of BES), such controller might be costly. This is quite possible in reality. For example, a powerful controller in MT and FC might make the power output change of MT and FC very large and it would possibly bring damage to the MT and FC accompany with a long-term use. Thus, we have to consider both issues: the protection of BES and rationality of the controller in MT and FC. Regarding (6), we are looking for a controller such that  $J_1$  is minimized, which can be regarded as an optimal control problem, also known as the  $H_2$  control problem. We highlight that such formulation in (6) is new in comparison with the existed works, e.g., [10]–[12].

Second, we formulate the AC bus frequency regulation problem into the other criterion. Similar to [29], we apply the  $H_\infty$  control theory to the considered MG system, and we define the  $H_\infty$  performance of the AC bus frequency as follows

$$\|z(t)\| < \gamma \|v(t)\|, \quad (7)$$

where we define the norm

$$\|z(t)\| = \left( E \left\{ \int_0^\infty |z(t)|^2 dt \right\} \right)^{1/2}.$$

In (7), the given scalar  $\gamma$  is the so-called disturbance attenuation. For the detailed definition of  $H_\infty$  control, readers can consult [30].

To evaluate the  $H_\infty$  performance of the system, we define the corresponding cost function in (8),

$$J_2 = \int_0^T (\gamma^2 \|v(t)\|^2 - \|z(t)\|^2) dt. \quad (8)$$

Now that both  $H_2$  and  $H_\infty$  performances have been defined in (6) and (8), respectively, we consider the optimal and robust control performance synthetically. A straightforward problem is that a controller might lead to an excellent  $H_2$  performance, together with a disappointing  $H_\infty$  performance. Alternatively, a satisfactory  $H_\infty$  performance is achieved, but the  $H_2$  control problem is remained unsolved.

In order to achieve the balance between the  $H_2$  and  $H_\infty$  performance, we apply the concept of Nash equilibrium [31] into our model, and formulate our optimal and robust control problem into a game theoretic mixed  $H_2/H_\infty$  control problem. In this sense, we define the mixed  $H_2/H_\infty$  control problem as follows.

**Definition 1:** (See, e.g., [31]) For given disturbance attenuation level  $\gamma > 0$ ,  $0 < T < \infty$ , the finite horizon mixed  $H_2/H_\infty$  control problem is to find a state feedback controller  $u^*$  such that  $\int_0^T z'z dt < \gamma^2 \int_0^T v'v dt$ , and when the worst case disturbance  $v^*$ , if existing, is implemented to system (4),  $u^*$  minimizes  $\int_0^T (ay'y + bu'u) dt$ . If we define  $J_1(u, v) = \int_0^T (ay'y + bu'u) dt$ , and  $J_2(u, v) = \int_0^T (\gamma^2 \|v(t)\|^2 - \|z(t)\|^2) dt$ , then our mixed  $H_2/H_\infty$  control problem is equal to finding the Nash equilibrium  $(u^*, v^*)$  defined as  $J_2(u^*, v^*) \leq J_2(u^*, v)$  and  $J_1(u^*, v^*) \leq J_1(u, v^*)$ .

### III. SOLVING THE OPTIMAL AND ROBUST CONTROL PROBLEM

According to the results in [31], we solve our optimal and robust control problem, and the main result is presented as Theorem 1.

**Theorem 1:** (See, e.g., [31]) For system (4), supposing that the coupled differential equations

$$\begin{cases} -\dot{P}_1 = A'P_1 + P_1A + D_1'D_1 - \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}' \begin{bmatrix} BR^{-1}B' & CQ^{-1}C' \\ CQ^{-1}C' & 0 \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}, \\ -\dot{P}_2 = A'P_2 + P_2A - D_2'D_2 - \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}' \begin{bmatrix} 0 & BR^{-1}B' \\ BR^{-1}B' & CQ^{-1}C' \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}, \end{cases}$$

have a pair of solution  $(P_1, P_2)$  meeting the terminal condition  $P_1(T) = 0, P_2(T) = 0$ , then the solution to our mixed  $H_2/H_\infty$  control problem is  $u^* = -R^{-1}B'P_1x$  and  $v^* = -Q^{-1}C'P_2x$ .

The proof is similar to the one in [31]. Here we omit the details.

To compare our obtained  $H_2/H_\infty$  controller with the normal  $H_2$  controller and  $H_\infty$  controller, we present the following two special cases.

**Corollary 1:** (See, e.g., [32]) For system (4), assuming that  $v = 0$ , if the Riccati equation  $-\dot{P} = A'P + PA + D_1'D_1 - PBR^{-1}B'P$  has a solution  $P$  meeting the terminal condition  $P(T) = 0$ , then the optimal controller  $u^* = -R^{-1}B'Px$  minimizes the cost functional  $J_1$  in (6).

**Corollary 2:** (See, e.g., [30]) For system (4), Given a scalar  $\gamma > 0$ , then this system is robustly stochastically stabilizable with disturbance attenuation  $\gamma$  if there exist matrices  $X > 0$  and  $Y$  such that the following linear matrix inequality LMI holds,

$$\begin{bmatrix} \Phi & C & XD_2' \\ C' & -\gamma^2 I & 0 \\ D_2X & 0 & -I \end{bmatrix} \leq 0,$$

where  $\Phi = XA' + AX + Y'B' + BY$ , then the  $H_\infty$  controller is  $u(t) = Kx(t)$ ,  $K = YX^{-1}$ .

If we only consider the  $H_2$  performance, then the desired controller is given in Corollary 1. If we only consider the  $H_\infty$  performance, then the desired controller is given in Corollary 2.

#### IV. NUMERICAL SIMULATION

In this section, we give some numerical examples. Based on the real-world data, the parameters of system (4), (6) and (8) are shown in Table I.

TABLE I. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
$T_{WTG}$	1.5	$M$	0.2
$T_{PV}$	1.8	$a$	1
$T_{MT}$	2	$b$	0.8
$T_{FC}$	1.5	$\gamma_1$	0.02
$T_{BES}$	0.1		
$D$	0.012		

Using Theorem 1, Corollary 1 and Corollary 2, we work out the controllers for the mixed  $H_2/H_\infty$  control problem,  $H_2$  control problem, and  $H_\infty$  control problem via Python and MATLAB, respectively.

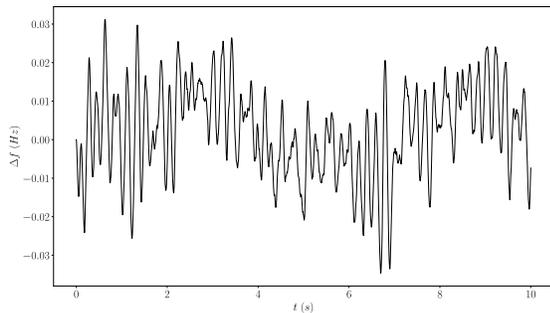


Figure 2.  $\Delta f$  under  $H_2$  control.

We plot the graphs of  $\Delta f$  under three situations: under  $H_2$  control, under  $H_\infty$  control, and under mixed  $H_2/H_\infty$  control in Fig. 2, Fig. 3 and Fig. 4, respectively.

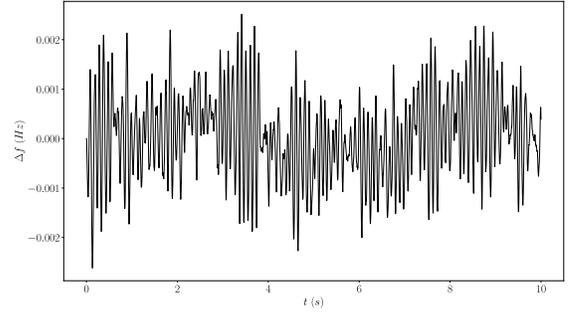


Figure 3.  $\Delta f$  under  $H_\infty$  control.

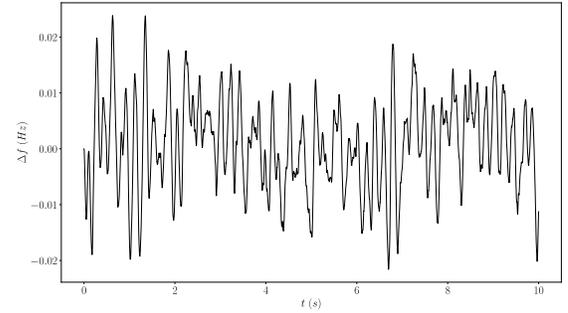


Figure 4.  $\Delta f$  under mixed  $H_2/H_\infty$  control.

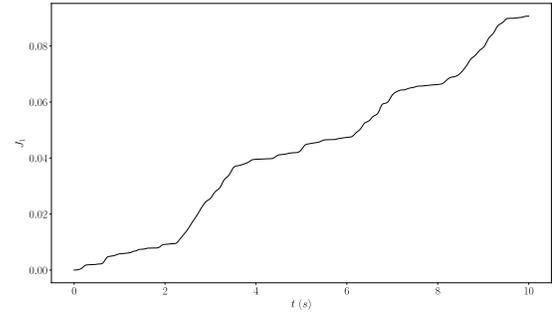


Figure 5. The  $H_2$  performance under  $H_2$  control.

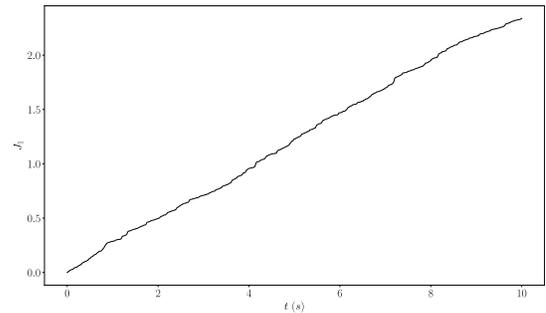


Figure 6. The  $H_2$  performance under  $H_\infty$  control.

In addition, we plot the graphs of  $H_2$  performances under three situations: under  $H_2$  control, under  $H_\infty$  control, and under mixed  $H_2/H_\infty$  control in Fig. 5, Fig. 6 and Fig. 7, respectively.

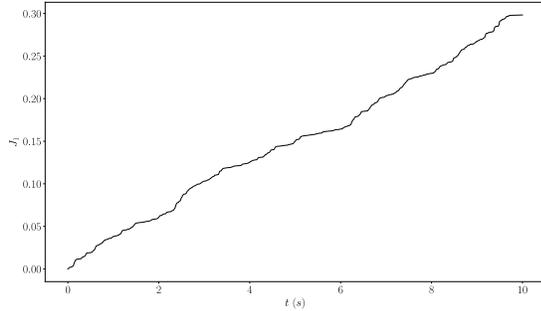


Figure 7. The  $H_2$  performance under  $H_2/H_\infty$  control.

The MG dynamics under mixed  $H_2/H_\infty$  control is shown in Fig. 8.

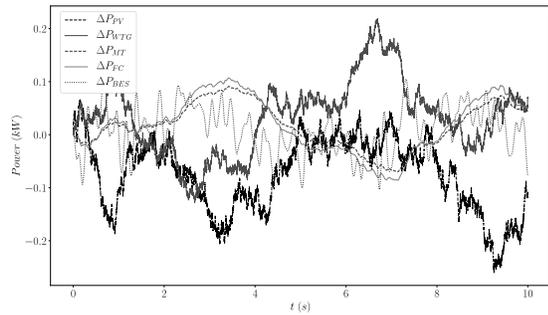


Figure 8. MG dynamics under mixed  $H_2/H_\infty$  control.

According to Fig. 2 and Fig. 4, it is obvious that the frequency deviation is better regulated via the  $H_2/H_\infty$  controller than the  $H_2$  controller. From Fig. 3 and Fig. 4, we see that although the frequency is better regulated by the  $H_\infty$  controller, the  $H_2$  performance under  $H_\infty$  controller is worse than the one under the  $H_2/H_\infty$  controller, which can be seen via Fig. 6 and Fig. 7.

Similarly, if we compare Fig. 6 with Fig. 7, we see that the  $H_2$  performance under the  $H_2/H_\infty$  controller is better than the one under the  $H_\infty$  controller. From Fig. 5 and Fig. 7, one can see although the  $H_2$  performance is better controlled by the  $H_2$  controller, the frequency deviation under the  $H_2$  controller is worse than the one under the  $H_2/H_\infty$  controller, which can be seen from Fig. 2 and Fig. 4.

The above simulation results show the successfulness and effectiveness of the proposed  $H_2/H_\infty$  controller.

## V. CONCLUSION

This paper considers a typical islanded AC MG system, including WTG, PV, MT, FC, BES and load. We use ODEs to model the dynamics of the power output change of WTG, PV, MT, FC, BES and AC bus frequency. The rational utilization of BES, MT and FC is considered as the  $H_2$

performance; whereas the frequency regulation issue is formulated as the  $H_\infty$  performance. We formulate a mixed  $H_2/H_\infty$  control for the islanded MG and we solve it via the Nash game approach. Analytical results are obtained, and numerical simulations show the feasibility of the proposed method.

## ACKNOWLEDGMENT

This work was supported in part by National Natural Science Foundation of China (grant No. 61472200) and Beijing Municipal Science & Technology Commission (grant No. Z161100000416004).

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