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Robust Mixed H_2/H_∞ Controller Design for Energy Routers in Energy Internet

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Abstract: In this paper, a class of mixed H_2/H_∞ controller is designed for an energy router (ER) within the scenario of an energy Internet (EI). The considered ER is assumed to have access with photovoltaic panels, wind turbine generators, micro-turbines, fuel cells, diesel engine generators, battery energy storage devices, flywheel energy storage devices, loads, and other ERs. Two types of control targets are considered. First, due to the access of large-scale renewable energy sources, the DC bus voltage deviation within the ER system shall be regulated. Second, an optimal energy management strategy shall be achieved, such that the autonomous power supply-demand balance within each ER is achieved with priority and the rational utilization of controllable power generation devices and energy storage devices are realized. When these objectives are considered simultaneously, the control issues with respect to ER is formulated as a mixed robust H_2/H_∞ control problem with analytical solutions provided. Several numerical examples are given, and the feasibility and effectiveness of the proposed method are demonstrated.

Keywords: energy Internet; energy router; mixed H_2/H_∞ control; microgrid; parameter uncertainty

1. Introduction

1.1. Motivation

In recent years, with the deterioration of the global environmental issues and the development of renewable energy technology, researchers are increasingly inclined to use renewable energy, e.g., wind power, solar power, hydro power, etc. However, power generated by renewable energy sources (RESs) is flexible and unpredictable, resulting in great obstacles to access to traditional power systems. Being regarded as a new version of the smart grid, energy Internet (EI) integrates the most advanced energy technology and communication technology, providing a basic platform for energy control and transmission [1,2].

Power network nodes, composed of distributed energy acquisition devices, distributed energy storage devices, and various types of loads, can be interconnected within EI scenarios. Besides, energy peer-to-peer exchange and bi-directional energy flow can be realized simultaneously in EI [3]. As a new energy architecture, EI can be compatible with conventional power grids and can make full use of distributed RESs [4]. It also provides a common energy exchange and sharing platform for energy consumers [5]. It is suggested that EI can help to integrate the energy industry chain and form the mechanism of supply-demand interaction and trade [6]. Short-term load forecasting can be achieved in real time to achieve demand response management [7].

Compared with other forms of power systems, EI has many key technical characteristics. A large number of distributed renewable power generation devices are interconnected in EI. Within the scope of high permeability of RESs, there is a great difference between energy control and management of EI and those of traditional power grids [8]. Notably, distributed RESs shall be the main body of future EI and they have disadvantages such as uncertain and intermittent power output [9]. Meanwhile, the changes of real-time electricity price and operation mode are also random [10]. In this sense, stochastic characteristics appear in EI systems and the related control, optimization, and scheduling are becoming challenging [11]. More importantly, EI operates in a highly informative environment. The implementation of distributed power generation, energy storage, and demand side response lead to huge data, including meteorological information, electricity usage custom and energy storage status [12]. With the popularization and application of advanced measurement technology, the number of intelligent terminals with measurement function in EI would increase greatly, and the amount of the generated data would also increase dramatically [13]. Finally, EI is a deeply coupled system of material, energy and information [14]. As a super-large-scale complex network with interdependence of society, information, and physics, EI has broader openness and greater system complexity than traditional power grids, showing complex dynamical characteristics [15].

In order to realize the interconnection and scheduling of energy networks and to upgrade the energy production and distribution, a new type of electrical device, called energy router (ER), has been proposed and designed [16]. Similar to the role of routers in the Internet, ERs can be viewed as energy forwarding and caching nodes in EI. More importantly, ERs can also effectively control the power quality and optimize the energy transmission cost by collecting and processing energy information.

1.2. Literature Review

The concept of ER was first proposed by American researchers. In 2008, a project called the future renewable electric energy delivery and management (FREEDM) system [17] studied a new grid structure based on renewable energy generation and distributed energy storage devices. Following the core of network technology in the field of information, FREEDM researchers put forward the concept of ER and implemented its prototype design [18]. In the same year, a Swiss research team developed the so-called energy hub [19]. The hubs are derived from the concept of hubs in computer science, also known as energy control centers. In 2013, Japanese researchers put forward the concept of power router which is able to dispatch and manage the power of a certain area.

Power conversion is an indispensable function of ER that connects various forms of RESs. The terminals in the energy network are connected, such that the controllability of energy transmission is greatly enhanced. For power energy, an ER structure composed of communication platform, controller, and solid-state transformer is proposed in [20]. The functions of ER in the current energy environment are summarized in [21], while the structure composed of system controller, network adaptive model, DC bus and sockets, and circuit breakers with multiple interface standards is also introduced. A hierarchical ER design is proposed in [22], where information support layer provides information support for the energy control layer, and it is able to integrate with the protection and other basic components to form the unique security function of ER. Furthermore, functional layer can realize energy control, optimization management, safety protection, maintenance, etc. Moreover, there are extensive studies on ER architecture, most of which are based on solid-state transformers and other power electronic conversion devices [23–27].

The research related with energy routing has been popular. A class of energy routing algorithm based on graph theory within local area energy network has been studied in [28]. In reference [29], stochastic optimal controllers are designed in ERs and micro-turbines (MT), such that the bottom-up energy management principle in EI is achieved. In reference [30], energy routing for delay-tolerant loads and mobile energy buffers has been investigated. Based on economic dispatching requirement, the corresponding energy routing strategy is reported in [31]. For low-voltage distribution power grids, an open energy routing network has been investigated in [32]. For an islanded microgrid (MG), non-fragile H_∞ controllers are designed for ERs and other controllable power generation devices, such that the DC bus voltage deviation is regulated [33]. For other related research outputs on ERs, readers can refer to [34–36], and the references therein. It is notable that in the field of EI, there has been few work focusing on both problems of frequency/voltage regulation and optimal operation cost management for ERs from the control perspective. In addition, when power dynamics of various electrical devices are considered, most of the works focus on control issues within a short time scale only, which is restrictive [33].

1.3. Contribution

In this paper, we consider the problems of voltage regulation and optimal operation cost management simultaneously for the ER system that is designed based on the DC bus topology. The considered ER system is assumed to have access to renewable power generation devices (i.e., photovoltaics (PVs) and wind turbine generators (WTs)), controllable power generation devices (i.e., MTs, diesel engine generators (DEGs), and fuel cells (FCs)), energy storage devices (i.e., battery energy storages (BES) and flywheel energy storages (FES)), as well as other ERs. The similar connection topology has been used in many works; see, [33,36]. The power dynamics of ER system are modelled as ordinary differential equations (ODEs) and parameter uncertainty is taken into consideration, due to unavoidable modelling errors. For the considered ER system, we formulate the voltage alleviation issue as a robust H_∞ control problem (the definition of H_∞ control is introduced in Appendix A), whereas the energy management optimization issue is formulated as an optimal control (also known as H_2 control) problem. Our purpose is to design a controller for the ER system such that both H_∞ and H_2 performances are satisfied simultaneously. Next, a mixed H_2/H_∞ control problem is formulated and solved analytically. From the control perspective, two theorems are presented as the main results. Simulations based on different scenarios are performed to show the feasibility and effectiveness of the proposed method. It is notable that restriction of this article is that our research is focused on new ER system based on future EI infrastructure, in the sense that there exists no current grid regulation or grid code regarding EI scenario.

The main contribution of this paper can be outlined as follows.

This is the first time that a mixed robust H_2/H_∞ controller is designed for ER system within an EI scenario, considering norm bounded parameter uncertainties. In this sense, the following targets are achieved simultaneously. (1) The DC bus voltage deviation of the studied ER system is regulated. (2) The considered ER system is robust against parameter uncertainty. (3) The autonomous power supply-demand balance within each ER is achieved with priority. (4) The rational utilization of controllable power generation devices and energy storage devices is achieved. (5) We are able to adjust the weighting factors in the objective functions, which leads to a more flexible solution for the operation of the ER system. (6) Although the considered ER system is expressed with short-term power dynamics, a long-term operation target can be achieved technically. (7) Based on real-world data, different scenarios are considered for simulations and the advantage of our proposed approach over the conventional ones is demonstrated.

The rest of the paper is organized as follows: Section 2 introduces the ER system modelling. Problem formulation is given in Section 3. We solve the H_2/H_∞ control problem in Section 4. In Section 5, numerical examples are illustrated. Finally, Section 6 concludes the paper.

2. System Modelling

In this paper, a general type of ER is considered within an EI scenario. The physical structure of the considered ER system is presented in Figure 1.

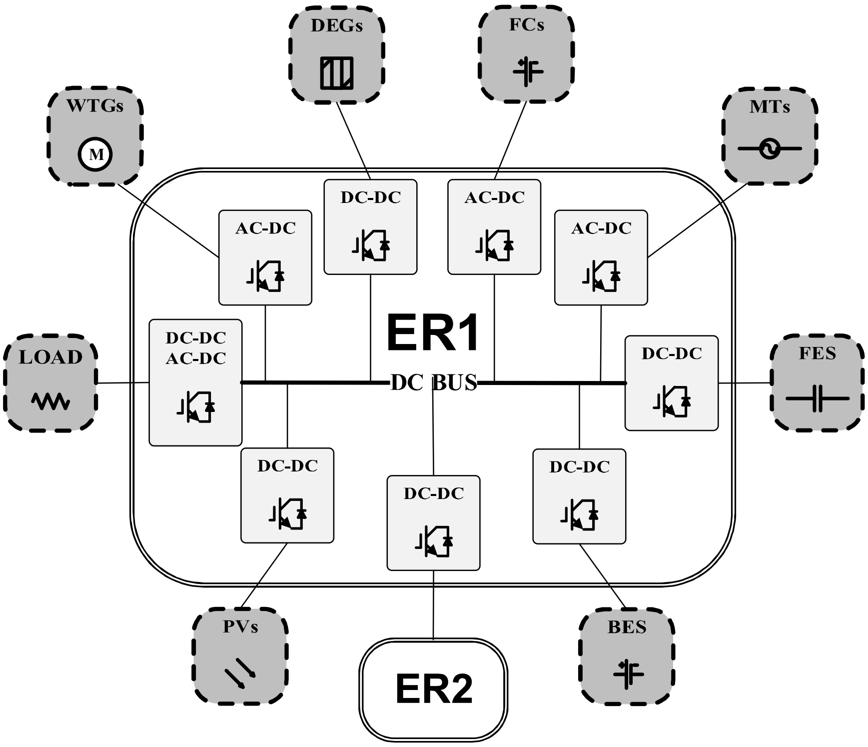

Figure 1. The studied energy router (ER) system.

Let us denote the considered ER system as ER_1 which has access to loads, PVs, WTs, MTs, DEGs, FCs, BESs, FESs and another ER system (denoted as energy router 2 (ER_2)). For energy router 1 (ER_1), we assume that power input mainly relies on power generation by massive PVs and WTs, whereas distributed controllable devices MTs, DEGs and FCs are considered to be complementary power generation devices. Influenced by changeable weather conditions, such as solar radiation and wind speed, the varying power outputs of PVs, WTs and loads may cause excessive ER's DC bus voltage deviation. In order to compensate power deviations and to absorb surplus electric power, BESs and FESs are equipped and connected to ER_1.

The balance of power supply and demand within the considered ER system is expressed as (time t omitted):

$$\Delta P_{AER} = \Delta P_{PV} + \Delta P_{WT} + \Delta P_{MT} + \Delta P_{FC} + \Delta P_{DEG} - \Delta P_{BES} - \Delta P_{FES} - \Delta P_L, \tag{1}$$

in which ΔP_{AER} represents the surplus power which is transmitted from ER_1 to ER_2.

Linearized state-space model has been widely used in the application of the robust MG control issues. Within a relatively small-scale time period, power dynamics of RESs, energy storage devices, distributed controllable power generation devices and loads can be expressed as ODEs. Such linearized state-space model is mostly used for the controller designing. (For illustrations, readers can refer to [33,37,38]).

The power utilization of load devices and power generated by PVs and WTs are heavily affected by time-varying environmental conditions, such as customer behaviors at demand side, solar radiation, and wind speed. Besides, the parameter measurement errors of the considered ER system are inevitable. Thus, parameter uncertainties are considered for the dynamical model of ER_1.

Then, the power dynamics of the considered ER system in Figure 1 can be presented with ODEs as follows.

$$\begin{cases} \Delta\dot{P}_{PV} = -\left(\frac{1}{T_{PV}} + \Delta o_{PV}\right)\Delta P_{PV} + \frac{1}{T_{PV}} v_{PV}, \\ \Delta\dot{P}_{WT} = -\left(\frac{1}{T_{WT}} + \Delta o_{WT}\right)\Delta P_{WT} + \frac{1}{T_{WT}} v_{WT}, \\ \Delta\dot{P}_{L} = -\left(\frac{1}{T_{L}} + \Delta o_{L}\right)\Delta P_{L} + \frac{1}{T_{L}} v_{L}, \\ \Delta\dot{P}_{MT} = -\frac{1}{T_{MT}}\Delta P_{MT} + \frac{1}{T_{MT}}(b_{MT} + \Delta b_{MT})u_{MT}, \\ \Delta\dot{P}_{FC} = -\frac{1}{T_{FC}}\Delta P_{FC} + \frac{1}{T_{FC}}(b_{FC} + \Delta b_{FC})u_{FC}, \\ \Delta\dot{P}_{DEG} = -\frac{1}{T_{DEG}}\Delta P_{DEG} + \frac{1}{T_{DEG}}(b_{DEG} + \Delta b_{DEG})u_{DEG}, \\ \Delta\dot{P}_{BES} = -\frac{1}{T_{BES}}\Delta P_{BES} + \frac{1}{T_{BES}}(r_{BES} + \Delta r_{BES})\Delta V, \\ \Delta\dot{P}_{FES} = -\frac{1}{T_{FES}}\Delta P_{FES} + \frac{1}{T_{FES}}(r_{FES} + \Delta r_{FES})\Delta V, \\ \Delta\dot{V} = -\frac{1}{p}\Delta V + \frac{1}{q}\Delta P_{AER}, \end{cases} \tag{2}$$

where p, q are system coefficients in the linearized voltage deviation equation.

Let us denote vector $x = \begin{bmatrix} \Delta P_{PV} & \Delta P_{WT} & \Delta P_{L} & \Delta P_{MT} & \Delta P_{FC} & \Delta P_{DEG} & \Delta P_{BES} & \Delta P_{FES} & \Delta V \end{bmatrix}'$, vector $u = \begin{bmatrix} u_{MT} & u_{FC} & u_{DEG} \end{bmatrix}'$ and vector $v = \begin{bmatrix} v_{PV} & v_{WT} & v_{L} \end{bmatrix}'$.

Then, the power dynamics in (2) can be rewritten in the following elaborated expression (time t omitted),

$$\dot{x} = (A + \Delta A)x + (B + \Delta B)u + Cv. \tag{3}$$

In the state-space control system (3), $x(t)$ is system state, $u(t)$ is system control input, $v(t)$ is system disturbance input. The coefficient matrices A, B, $C, \Delta A$ and ΔB in system (3) are presented in Appendix B. The parameter uncertainties ΔA and ΔB in (3) are of the form given in (4).

$$[\Delta A(t) \Delta B(t)] = HF(t)[E_1 \; E_2], \tag{4}$$

where $F(\cdot)$ is an unknown time-varying matrix, satisfying

$$F(t)'F(t) \leq I, \tag{5}$$

where I is the identity matrix, and H, E_1 and E_2 are real constant matrices whose values are obtained from engineering practice. The uncertainties formulated in (4) and (5) are widely used [33,39].

3. Problem Formulation

In this section, we formulate the hybrid problem of maintaining ER's DC bus voltage stability and realizing an optimal energy dispatching strategy of ER into a robust mixed H_2/H_∞ control problem.

3.1. Robust H_∞ Control Problem Formulation

In the field of power systems, robust control theory has been applied to voltage alleviation problems [33] and frequency regulation issues [37,38]. For the considered DC-type ER, to alleviate its bus voltage deviation, proper control input signals have to be designed for MTs, FCs, and DEGs. In this section, a robust H_∞ control problem is formulated to achieve the desired DC bus voltage stability.

To maintain the voltage stability, both system internal parameter uncertainty and system external disturbance inputs shall be considered. First, the definition of robustly stable is given.

Definition 1. For all system parameter uncertainties ΔA and ΔB, if $|x(t)|^2 < \varepsilon$ is achieved for $\varepsilon > 0$, then ER system (3) with $u = 0$ and $v = 0$ is said to be robustly stable.

Second, for the considered ER system, in order to guarantee the DC bus voltage stability against external disturbance input, we apply the definition of the time domain H_∞ performance [39] to describe the desired anti-interference performance against changeable output power of PVs, WTs and loads. The DC bus voltage deviation ΔV in (2) is viewed as the controlled output of the ER system, which is denoted as z_1. Then, we have $z_1 = D_1 x$, where matrix $D_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$.

The definition of H_∞ performance is presented as follows.

Definition 2. [39] Given a scalar $\gamma > 0$, the H_∞ performance of the ER system is defined as $||z_1(t)|| < \gamma||v(t)||$, where norm $|| \cdot ||$ is defined as $||z_1(t)|| \triangleq (\int_0^\infty |z_1(t)|^2 dt)^{\frac{1}{2}}$. The scalar γ is known as disturbance attenuation. The H_∞ cost functional $J_\infty(u, v)$ can be formulated as

$$J_\infty(u, v) \triangleq \int_0^T \left({z_1}' z_1 - \gamma^2 v' v \right) dt. \tag{6}$$

As long as an ER dynamical system satisfies both Definition 1 and Definition 2, we claim that the robust H_∞ performance is achieved. Apart from the robust H_∞ performance, the operation cost optimization issue for the ER shall be considered, which is known as H_2 performance from the control perspective and is presented in the next subsection.

3.2. H_2 Control Problem Formulation

Based on the operational principle of EI, the target of autonomous power supply-demand balance of each ER is expected to be achieved with priority [2,29]. Thus, the event of power imbalance within any ER would lead to complicated energy dispatching issues within the whole ER network, which brings extra time and operational cost. Generally, the operational costs of the considered ER system could be affected by many factors, such as the adjustments of controllable distributed generators and the power exchange among different ERs.

In order to realize a flexible power management solution for the considered ER system, the corresponding system observation is designed as a vector, denoted as z_2, and we define $z_2 = \begin{bmatrix} \alpha_1 \Delta P_{AER} & \alpha_2 \Delta P_{MT} & \alpha_3 \Delta P_{FC} & \alpha_4 \Delta P_{DEG} & \alpha_5 \Delta P_{BES} & \alpha_6 \Delta P_{FES} \end{bmatrix}'$, where the coefficients $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$ and α_6 are used to adjust the weights of the concerned factors, which would influence operational costs of the ER system. The discussion for the influences brought by these factors are given below.

Firstly, it is remarkable that, if two interconnected ERs are far away from each other, the energy transmission cost may be relatively high. Besides, it is costly if power is frequently transmitted between multiple connection nodes within ER network [1,29]. Typically, in this note, since we are focusing on one specified ER system, i.e., ER_1, it is important to restrict power transmitted between ER_1 and ER_2.

Furthermore, distributed generators and energy storage devices in the ER system can also affect the operational costs. The collaborative functioning of MTs, FCs, DEGs, BESs and FESs is the premise of the desired energy management approach. Nevertheless, extra operation and maintenance costs would be raised from the irrational utilization of these devices. Thereby, when designing control strategies, additional costs from power outputting adjustment for MTs, FCs, and DEGs, and charging/discharging of BESs and FESs should also be taken into consideration.

From (1)–(3), we can easily find that there exist a matrix D_2, such that $z_2 = D_2 x$ where D_2 is given in Appendix B. With the observation z_2, the H_2 cost function is formulated as follows.

Definition 3. Considering all the parameter uncertainties, the H_2 cost functional $J_2(u, v)$ is formulated as an upper bound of the H_2 performance of the studied system (3) when the worst case disturbance input is implemented, defined by:

$$J_2(u, v) = \sup_{F(t)} \int_0^T z_2'(t) z_2(t) dt. \tag{7}$$

3.3. Mixed H_2/H_∞ Control Problem Formulation

So far, both of the objective functions for the robust H_∞ control and H_2 control are formulated. Thus, we are able to rewrite the considered ER system as follows,

$$\begin{cases} \dot{x} = (A + \Delta A)x + (B + \Delta B)u + Cv, \\ z_1 = D_1 x, \\ z_2 = D_2 x. \end{cases} \tag{8}$$

The definition of the mixed H_2/H_∞ control for the considered ER system is presented as follows.

Definition 4. The target of the mixed H_2/H_∞ control problem is to find a controller $u(t) = Kx(t)$, such that two statements below can be realized.

(i) The controlled system is stable for all parameter uncertainties, and the H_∞ performance $||z_1(t)|| < \gamma ||v(t)||$ is satisfied;
(ii) $J_2(u, v)$ defined by (7) is minimized for H_2 performance.

4. Solutions to the Mixed H_2/H_∞ Control Problem

Based on the results introduced in [39,40], two mathematical theorems are utilized to obtain the desired controller for the considered ER system. In this manner, the proposed mixed H_2/H_∞ control problem can be solved by searching solutions for the LMIs introduced in Theorem 1 and Theorem 2.

Theorem 1. (See, e.g., [39]) For a given constant $\gamma > 0$ and system (8), there exists a controller $u(t) = Kx(t)$, such that both system robust stability and H_∞ performance $||z_1(t)|| < \gamma ||v(t)||$ are satisfied, if there exist two scalars $\alpha > 0$, $\beta > 0$, a symmetric positive definite matrix X and a matrix V, such that the following LMI holds,

$$\Gamma = \begin{bmatrix} W & W_1' & X'D_1' & X'D_2' \\ W_1 & -\alpha I & 0 & 0 \\ D_1 X & 0 & -\beta I & 0 \\ D_2 X & 0 & 0 & -I \end{bmatrix} < 0, \tag{9}$$

where $W = X'A' + V'B' + AX + BV + \alpha HH' + \beta\gamma^{-2}CC'$, and $W_1 = E_1 X + E_2 V$.

Moreover, if (9) has a feasible solution (α, β, X, V), then the state feedback controller can be chosen as

$$u(t) = VX^{-1}x(t). \tag{10}$$

Meanwhile, an upper bound of the H_2 performance $J_2(u, v)$, which is obtained by substituting the controller (10) into (8), can be calculated by $J_2(u, v) = tr\left(C'X^{-1}C\right)$, where $tr(\cdot)$ denotes the trace function.

Theorem 2. [40] Consider a robustly stable system, if there exist two symmetric positive definite matrices X, N, a matrix V, and two scalars $\alpha > 0$, $\beta > 0$, such that the problem

$$\begin{aligned} \min_{\alpha,\beta,X,V,N} \quad & z = tr(N), \\ s.t. \quad & \Gamma < 0, \begin{bmatrix} -N & C' \\ C & -X \end{bmatrix} < 0, \end{aligned} \tag{11}$$

has a pair of solution (α, β, X, V, N), then $u(t) = VX^{-1}x(t)$ is the H_2/H_∞ controller.

The details of proofs for both theorems are omitted.

In this paper, due to the stochastic nature of the distributed energy resources and the uncertainties in environmental factors, the power dynamics for PVs, WTs, and loads described in (2) would only be valid for a short time period. In this sense, to achieve the long-term operation target of the considered ER system, the entire time horizon should be divided into a series of smaller time intervals, such that the linearized modelling (8) can be utilized to obtain a proper mixed H_2/H_∞ controller for each individual time interval.

Although there are certain limitations for linear models, in short time periods they are generally popular, since approximated solutions can be obtained with less computational complexity. Additionally, we are able to adjust the weighting factors in the H_2 performance based on the system states, which leads to a more flexible solution for the operation of the ER system. More specifically, the detailed procedures of the proposed mixed H_2/H_∞ control approach are illustrated in Figure 2.

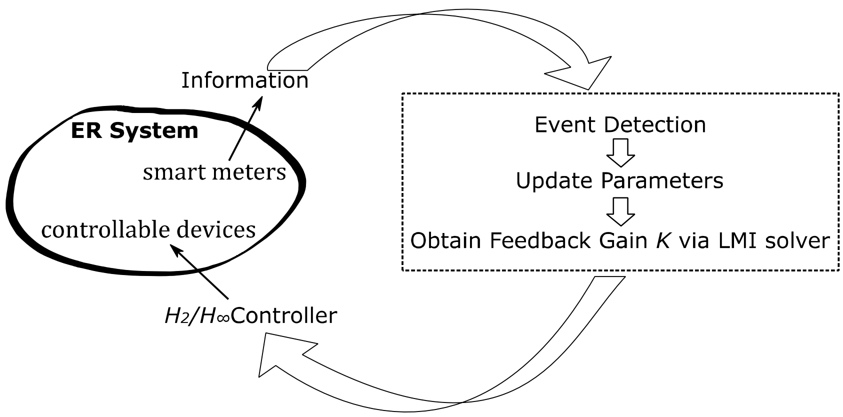

Figure 2. The detailed procedures of the proposed mixed H_2/H_∞ control approach.

From Figure 2, we can find that in iteration, parameters in D_2 are designed based on the information obtained from smart meters in previous interval, such that different events occur in the ER system can be properly tackled. Then, with system (8) and the H_2/H_∞ control method, the controller can be obtained via convex optimization techniques. Thereby, the calculated controller is applied to the ER system for current time interval until the next iteration. By repeating such iteration, the long-term operation for the ER system can be achieved.

5. Simulation Results and Analysis

In this section, three case studies under different senarios are provided to show the efficacy and feasibility of the propsoed mixed H_2/H_∞ control appraoch. The parameters for the considered ER system are generated based on parameter estimation methods from real-world engineering practice, given in Table 1.

In this paper, the LMI in Theorem 1 and the convex optimization problem in (11) are solved with the CVX toolbox of MATLAB R2018b. In this manner, the feedback gain K for the mixed

H_2/H_∞ controller is obtained. According to (7), by minimizing the H_2 performance J_2, the cumulative deviations of z_2 would be restricted. In this sense, in order to meet the demands under different scenarios, the weighting factors in D_2 are adjusted, such that different objectives could be achieved. For the simulation, Python packages, i.e., Numpy, Scipy, etc., are utilized to calculate the trajectory of the considered system. The effectiveness of the proposed approach is demonstrated via the results in the following scenarios.

Table 1. System parameters.

Parameter	Value	Parameter	Value
T_{PV} (s)	1.2	b_{MT}	1.2
T_{WTG} (s)	1.7	b_{FC}	1.3
T_L (s)	0.8	b_{DEG}	1.4
T_{MT} (s)	0.05	r_{BES}	0.1
T_{FC} (s)	0.06	r_{FES}	0.1
T_{DEG} (s)	0.07	p	0.01
T_{BES} (s)	0.9	q	0.49
T_{FES} (s)	0.8		

5.1. Scenario I

The voltage regulation performance of the proposed controller is evaluated in this scenario. The parameters in D_2 are set to be $\alpha_1 = 1.0$, $\alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = \alpha_6 = 0$. The simulation results are shown in Figure 3.

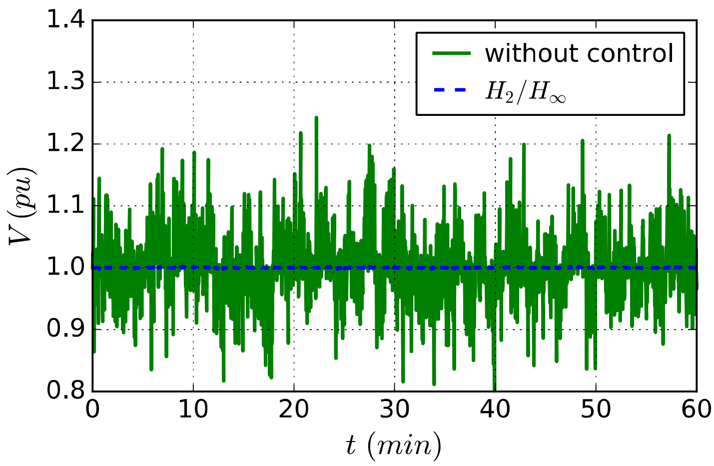

Figure 3. Dynamics of the DC bus voltage deviation.

We can observe that in Figure 3, when the proposed mixed H_2/H_∞ controller is applied to the ER system, dynamics of the DC bus voltage deviation are successfully restricted within a small range. Apparently, the voltage regulation performance under the mixed H_2/H_∞ control approach is better than that without control (control output $u = 0$). It is clear that the proposed control approach has satisfactory performance for the voltage stabilization target.

5.2. Scenario II

In this scenario, we focus on the rational utilization of FCs. As introduced above, the output power of FCs can be adjusted to match the power deviations of PVs, WTs and loads, such that the voltage regulation for the ER system could be achieved. However, unnecessary frequent power adjustment would lead to extra fuel consumption. Supposing that during the considered time period, a temporary fuel shortage of FCs is encountered. Thus, unnecessary frequent power adjustment in FCs is expected to be avoided. In order to maintain the normal operation of the ER system, the control for FC output power ought to be restricted. To achieve this target, the weighting factor α_3 for FCs in z_2 should be increased. More specifically, the parameters in D_2 are set to be $\alpha_1 = 1.0, \alpha_3 = 3.0, \alpha_2 = \alpha_4 = \alpha_5 = \alpha_6 = 0$. Additionally, in order to show the advantage of the proposed mixed H_2/H_∞ control approach over the H_∞ controller in Theorem 1, their performances are compared in the simulation results provided in Figures 4 and 5.

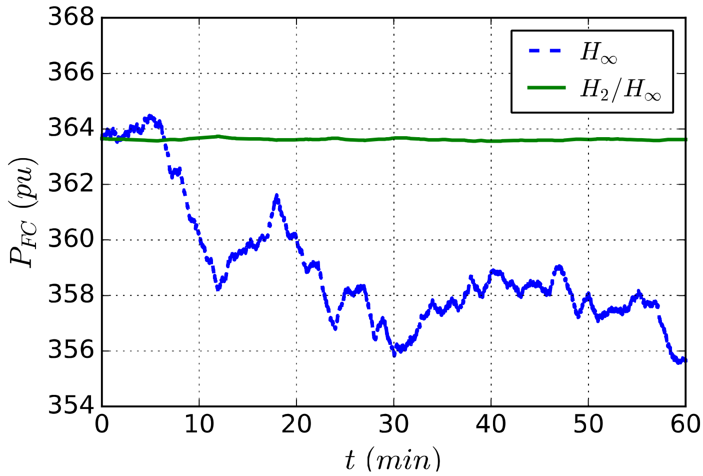

Figure 4. Power output curves of fuel cells (FC) under mixed H_2/H_∞ control and H_∞ control methods.

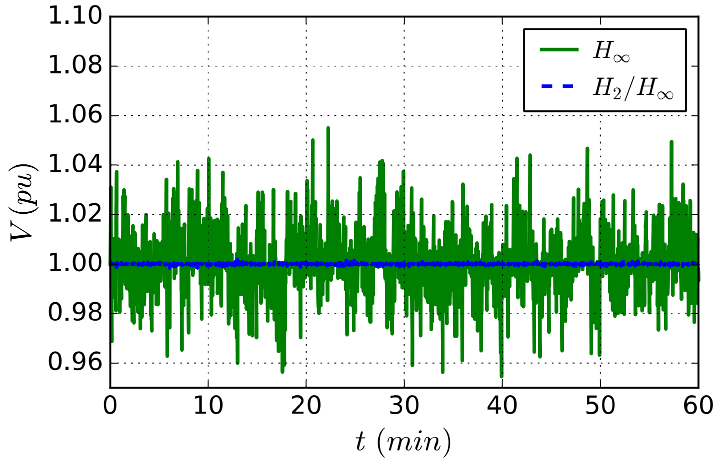

Figure 5. Voltage deviation curves under mixed H_2/H_∞ controller and H_∞ controller.

It is easy to find that, under the mixed H_2/H_∞ control, the fluctuations of the power dynamics for FCs in Figure 4 are smaller than that under H_∞ control significantly. Additionally, the voltage deviation curves in Figure 5 indicate that the controller obtained from the proposed H_2/H_∞ method has better voltage regulation performance than that of the H_∞ approach in Theorem 1. Thus, in this scenario, the proposed mixed H_2/H_∞ control approach is evaluated to be more flexible and satisfactory.

5.3. Scenario III

To further demonstrate the flexibility of the proposed method, a different scenario for the ER system is considered within a longer time period. Here, we take the assumption that within the considered three hours, part of the generators in MTs, DEGs, and FCs have experienced certain failure, which leads to a decrease in the adjustment range of total power outputs of MTs, FCs and DEGs. In order to ensure the normal operation of the ER system, the objectives for controller designing should also be adjusted accordingly. For the considered time period, the parameters for D_2 are set to be $\alpha_1 = 1.0, \ \ \alpha_2 = \alpha_3 = \alpha_4 = 1.0, \alpha_5 = \alpha_6 = 0$.

To evaluate the efficacy of the proposed control approach, during the simulation, the results with H_∞ controller are used for comparison. The power dynamics of MTs, FCs and DEGs in the considered three hours are illustrated in Figures 6–8, respectively.

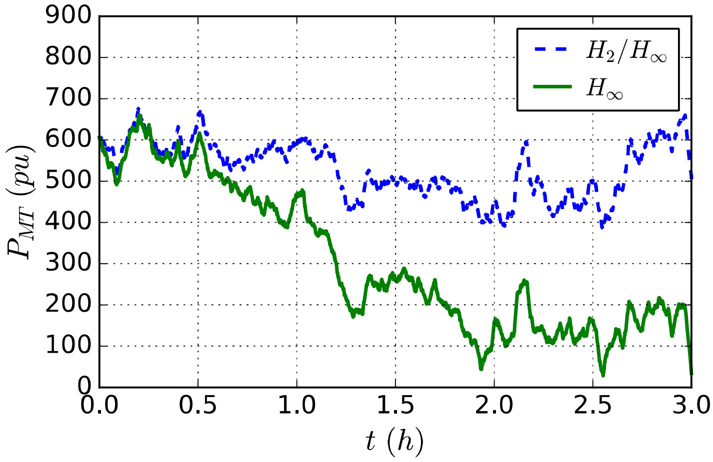

Figure 6. Power dynamics of micro-turbines (MT) under mixed H_2/H_∞ control and H_∞ control schemes.

We can find that in Figure 6, the magnitude of output power deviation of MTs under the proposed mixed H_2/H_∞ control scheme is smaller than that with the H_∞ controller. In this sense, the impacts of failures occur in MTs are properly considered in the proposed approach. On the other hand, the H_∞ controller might lead to system failure since such impacts are not fully considered.

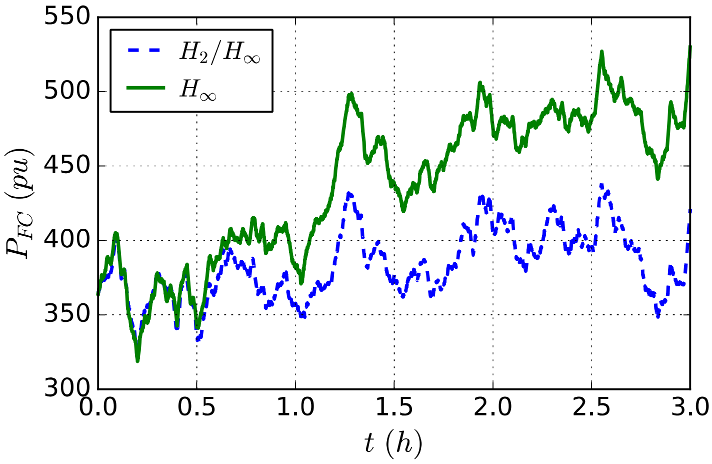

Figure 7. Power dynamics of FCs under mixed H_2/H_∞ control and H_∞ control schemes.

Similar conclusions can be drawn for the control effect for FCs and DEGs. With Figures 7 and 8, it is clear that the adjustments for power output of FCs and DEGs in the studied time period are successfully restricted according to system situations, i.e., failures occur in some of these devices. Additionally, from the dynamics of voltage deviation shown in Figure 9, we can find that the proposed mixed H_2/H_∞ controller is able to take different system conditions into consideration as well as ensuring almost the same voltage regulation performances as the H_∞ control scheme introduced in Theorem 1.

Through the comparative analysis of the considered scenarios above, the mixed H_2/H_∞ approach proposed in this paper is shown to be satisfactory. Additionally, by taking different constraints of the ER system into consideration, the proposed approach is able to achieve a more flexible management of the concerned devices, which leads to a steady and efficient operation of the ER system.

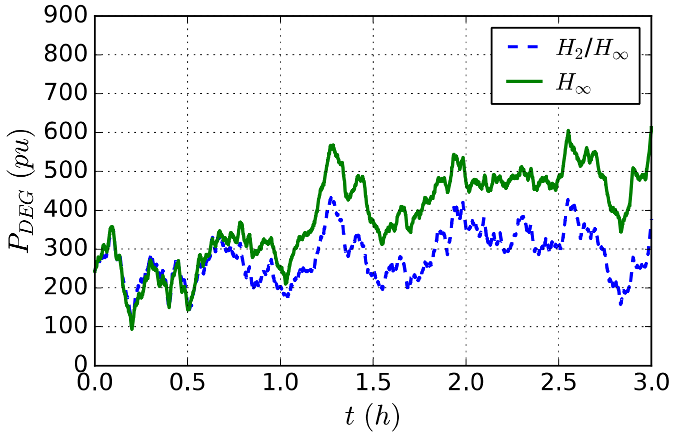

Figure 8. Power dynamics of diesel engine generators (DEG) under mixed H_2/H_∞ control and H_∞ control schemes.

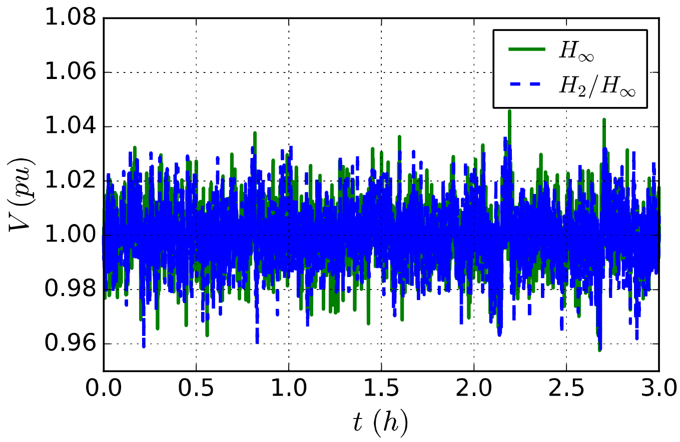

Figure 9. Voltage deviation curves under mixed H_2/H_∞ controller and H_∞ controller.

6. Conclusions

A typical ER system within an EI scenario has been investigated in this paper. To ensure the robust stability of the DC bus voltage and the rational energy managemnet strategy, ODEs are used to describe power dynamics of the considered ER system, and a mixed robust H_2/H_∞ control problem is formulated and solved.

It is notable that voltage stabilization of the ER's DC bus can be naturally obtained with a capacitor directly connected to the DC bus, which is regarded as possible future complementary work. Directly connecting the capacitor to the DC bus is a major improvement for the short-term transient stability of the ER system. Here, one of the interesting problems is that how long it takes for the DC bus stability to be achieved when supercapacitors are connected to DC bus. If an immediate system stabilization is desired to be achieved, instead of simply waiting for the natrural stabilization, how to design a class of control strategy is remain an open problem.

Currently, apart from joining some academic and engineering projects in the field EI, we are participating in drafting relevant national standards in China. For this paper, referencing to current grid regulations or grid code is beyond the scope. Indeed, for our future work, these issues shall be addressed.

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Nomenclature

BES	Battery energy storage
DEG	Diesel engine generator
EI	Energy Internet
ER	Energy router
FC	Fuel cell
FES	Flywheel energy storage
LMI	Linear matrix inequality
MG	Microgrid
MT	Micro-turbine
ODE	Ordinary differential equation
PV	Photovoltaic
RES	Renewable energy source
WT	Wind turbine generator
ER_1	Energy router 1
ER_2	Energy router 2
b_{MT}	System parameter of MTs
b_{FC}	System parameter of FCs
b_{DEG}	System parameter of DEGs
Δb_{MT}	Uncertainties of factor b_{MT}
Δb_{FC}	Uncertainties of factor b_{FC}
Δb_{DEG}	Uncertainties of factor b_{DEG}
Δo_{PV}	Uncertainties of the reciprocal of time constants of PVs
Δo_{WT}	Uncertainties of the reciprocal of time constants of WTs
Δo_L	Uncertainties of the reciprocal of time constants of loads
ΔP_{AER}	Power transmission from ER_1 to ER_2
ΔP_{BES}	BES output power change
ΔP_{DEG}	DEG output power change
ΔP_{FC}	FC output power change
ΔP_L	Load output power change
ΔP_{MT}	MT output power change
ΔP_{PV}	PV output power change
ΔP_{FES}	FES output power change
ΔP_{WT}	WT output power change
r_{BES}	System parameter of BESs
r_{FES}	System parameter of FESs
Δr_{BES}	Uncertainties of factor r_{BES}
Δr_{FES}	Uncertainties of factor r_{FES}
T_{PV}	Time constants of PVs
T_{WT}	Time constants of WTs
T_L	Time constants of loads
T_{MT}	Time constants of MTs
T_{DEG}	Time constants of DEGs
T_{FC}	Time constants of FCs
T_{BES}	Time constants of BESs
T_{FES}	Time constants of FESs
u_{MT}	Control input signal of MTs
u_{FC}	Control input signal of FCs
u_{DEG}	Control input signal of DEGs
ΔV	DC bus voltage deviation
v_{PV}	Change of solar irradiation
v_{WT}	Power of wind
v_L	Load power disturbances

Appendix A

According to [41], the basics of H_∞ is briefly given here. In control theory, H_∞ (i.e., H-infinity) methods are used to synthesize controllers, such that system stabilization with guaranteed performance is achieved. When H_∞ method is applied, such system stabilization problem can be formulated as a mathematical optimization problem and one is required to find the controller which solves this control problem. For the term H_∞, the letter H stands for Hardy space, and the symbol ∞ stands for infinity norm. The classic H_∞ control therory is investigated in frequency domain and the moderen H_∞ control therory is studied in time domain. In this paper, a time domain approach is applied to solve the formulated problem. The detailed definition for our specified H_∞ control problem is given in Definition 2.

Appendix B

The coefficient matrices $A,\ B,\ C, \Delta A$ and ΔB in system (3) are presented with (A1)–(A4).

$$A = \begin{bmatrix} -\frac{1}{T_{PV}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{WT}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_L} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{MT}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{FC}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{DEG}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{BES}} & 0 & \frac{r_{BES}}{T_{BES}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{FES}} & \frac{r_{FES}}{T_{FES}} \\ \frac{1}{p} & \frac{1}{p} & -\frac{1}{p} & \frac{1}{p} & \frac{1}{p} & \frac{1}{p} & -\frac{1}{p} & -\frac{1}{p} & -\frac{1}{p} \end{bmatrix}, \tag{A1}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{b_{MT}}{T_{MT}} & 0 & 0 \\ 0 & \frac{b_{FC}}{T_{FC}} & 0 \\ 0 & 0 & \frac{b_{DEG}}{T_{DEG}} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, C = \begin{bmatrix} \frac{1}{T_{PV}} & 0 & 0 \\ 0 & \frac{1}{T_{WT}} & 0 \\ 0 & 0 & \frac{1}{T_L} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \tag{A2}$$

$$\Delta A = \begin{bmatrix} -\Delta O_{PV} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\Delta O_{WT} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\Delta O_L & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\Delta r_{BES}}{T_{BES}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\Delta r_{FES}}{T_{FES}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{A3}$$

$$\Delta B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{\Delta b_{MT}}{T_{MT}} & 0 & 0 \\ 0 & \frac{\Delta b_{FC}}{T_{FC}} & 0 \\ 0 & 0 & \frac{\Delta b_{DEG}}{T_{BEG}} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{A4}$$

The coefficient matrix D_2 is presented with (A5)

$$D_2 = \begin{bmatrix} \alpha_1 & \alpha_1 & -\alpha_1 & \alpha_1 & \alpha_1 & \alpha_1 & -\alpha_1 & -\alpha_1 & 0 \\ 0 & 0 & 0 & \alpha_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \alpha_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \alpha_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \alpha_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \alpha_6 & 0 \end{bmatrix}. \tag{A5}$$

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