Energy Sharing and Frequency Regulation in Energy Internet via Mixed H_2/H_∞ Control with Markovian Jump

Haochen Hua, Yuchao Qin, Zicheng He, Liuying Li and Junwei Cao

***Abstract*—In this paper, the problem of mixed optimization for energy sharing and frequency regulation in a typical energy Internet (EI) scenario where energy routers (ERs) interconnected AC microgrids (MGs) is investigated. Continuous-time Markov chains are introduced to describe the switching paths in the power dynamics of MGs. Such that the modelling of considered EI system could be closer to the real-world engineering practice. Advanced parameter estimation techniques are integrated into the proposed method to achieve better modelling accuracy and controlling performance. Based on the parameters of MG power dynamics, the mixed H_2/H_∞ controllers are obtained via stochastic control theory. The feasibility and efficacy of the proposed approach are evaluated in numerical examples.**

***Index Terms*—Energy Internet, Microgrids, H_2/H_∞ control, Markov jump.**

NOMENCLATURE

BES	Battery energy storage.
DER	Distributed energy resource.
EI	Energy Internet.
ER	Energy router.
FC	Fuel cell.
MG	Microgrid.
MT	Micro-turbine.
ODE	Ordinary differential equation.
PV	Photovoltaic panel.
RES	Renewable energy source.
SDE	Stochastic differential equation.
WT	Wind turbine generator.
P_{PV}	Output power of PV.
P_{WT}	Output power of WT.
P_{MT}	Output power of MT.
P_{FC}	Output power of FC.
P_{BES}	Charging/Discharging power of BES.
f	Frequency deviation.
D	Damping coefficient.
M	Inertia constant.

I. INTRODUCTION

Haochen Hua is with the College of Energy and Electrical Engineering, Hohai University, Nanjing, 211100, P. R. China.

Yuchao Qin and Junwei Cao are with Beijing National Research Center for Information Science and Technology, Tsinghua University, Beijing, 100084, P. R. China.

Zicheng He is with Institute of Information Technology, Fudan University, Shanghai, 200433, P. R. China.

Liuying Li is with International Automotive Research Centre, WMG, University of Warwick, Coventry, CV4 7AL, UK.

Corresponding Author: Junwei Cao, e-mail: jcao@tsinghua.edu.cn

OVER the past decades, human beings have faced great challenges such as environmental pollution, global warming, especially the energy crisis. Consequently, much attention has been paid on the RESs such as wind power, solar power and hydropower [1]. In order to integrate DERs into the utility grids, the operational architecture called MG is utilized. Typically, a MG consists of not only the DERs mentioned above, but also conventional power generation devices, energy storage devices and local loads. A variety of RESs in the MG system may cause intermittence, nonlinearity and uncertainty in power deviations. These features could make the energy management of MG very challenging [2], [3].

With the development of information and communication technologies, EI is proposed to deal with such issues [4]. Within the demonstrating projects of EI, multiple MGs are interconnected through ERs to share information and energy cooperatively [5]. These MGs usually work in the grid-connected mode. In contrast, they should also function well in the islanded mode (also known as the off-grid mode) considering the expensive cost of energy delivery and potential outage of the main grids [6]. Aiming at realizing a reliable and efficient operation of the EI, a new class of energy control scheme is desired. The stabilization and optimization problems in smart power systems have already been extensively studied in the past.

Firstly, regarding the stability of power systems in the EI scenario, there have been tremendous amount of research outputs investigating the stabilization of MG systems from different perspectives. For distributed DC MGs, a system-level stability analysis method is proposed in [7]. Taking into account the uncertainty existing in the power deviations of RESs and loads, a class of robust energy scheduling approach is introduced for MG systems [8]. Similarly, in [9], with the application of advanced robust control techniques, a novel robust voltage stabilization strategy is proposed for DC MG such that the time delay and modelling errors can be properly addressed. To regulate the frequency deviation induced by DERs, the H_∞ and μ-synthesis control methods have been applied to ensure the robustness of an islanded MG [10]. Taking modelling uncertainties into account, the system stabilizing issue of MG incorporating WTs has been studied in [11]. In [12], the two-level control strategy involving centralized controllers and multiple droop controllers enables MGs to function in both grid-connected and islanded modes. Updating the stability criterion of EI, authors in [13] design an impulsive feedback control method for consuming the fault energy, thus stabilizing the EI system. To maintain the stability of the energy sharing functionality in the EI system, in [14], the robust H_∞ control method is proposed for ERs such that the short-term energy storage utilization can be appropriately achieved. For further results regarding robust control in the field of MGs, readers can consult [15]–[18], and the references therein.

Besides, research on the optimal energy control and management in the field of EI has been popular in recent years. In [19], a criterion is formulated to assess the rationality of utilizing the connected DERs. The desired controller is obtained by solving the coupled differential Riccati equations. Notably that multiple-layer optimization can be applied as an effective tool to solve the optimal control problems of power systems with various RESs [20]. By installing controllers in MTs and ERs, the bottom-up energy management principle for EI is achieved accompanied by the lifetime extension of BESs [21]. Recently, the significant growth of demand-side resources in EI has motivated the research of optimal energy flow control in the case of the high operating expense [22]–[24].

There is also a great amount of research on optimization problems in the multi-microgrid setting. Take into account the time-of-use electricity price mechanism, a particle swarm optimization based optimal scheduling method is proposed in [25] for the coordinated power dispatching in multi-microgrid systems. For the energy management problem in multi-microgrid, a sequential operation based optimal control method is utilized in [26] to improve the system efficiency. In [27], [28], the model predictive control techniques are adopted for coordinated management tasks in multi-microgrid scenarios. To achieve the utilization of RESs effectively, the coordinated power dispatching and energy sharing problem in networked MG systems are discussed in [25], [29], [30]. Also, with the advances in deep learning, the application of reinforcement learning methods in the optimization problems in power systems has attracted much attention [31]–[34].

The mixed H_2/H_∞ control problems considering both criteria of optimization and robustness are raised naturally by deeply exploring the robust and optimal control issues in EI. Such mixed H_2/H_∞ control problems have been well investigated in both frequency domain and time domain [35]–[41]. Nevertheless, these aforementioned works still have deficiencies. The control approaches proposed in [36] and [37] lack of consideration for the nonlinearity and stochasticity of MG system. DERs such as PVs and WTs are not explicitly considered in [39]. It may lead to results inaccuracy and could be less applicable. In [40], linear feedback controllers are obtained without considering system constraints. To facilitate the maturity and application of EI, solutions to the mixed H_2/H_∞ control problems considering system complexity should be the foreground.

In this paper, we propose a class of mixed H_2/H_∞ controller for short-term operation cost management and frequency regulation of AC MGs in EI. The considered application scenario of EI is assumed to function without access to the main power grid. First, the dynamical EI system is formulated as SDEs with Markovian switching (also known as Markov jump) in system parameters. Then, the problem of short-term operation cost optimization and system stabilization is formulated as a mixed H_2/H_∞ control problem mathematically. Eventually, the control issue is solved by stochastic optimization methods.

The importance and main technical contributions made in this work can be summarized as below:

- This work is investigated theoretically under the scope of a generalized off-grid EI topology in which each AC MG is allowed to be composed of PVs, WTs, FCs, MTs, BESs and loads. In particular, the power dynamics of all these components are considered from the control perspective. Markov jump SDEs and system disturbance inputs are adopted in the power modelling of renewable power generation devices (WTs and PVs) and loads. It is highlighted that with such a new model, the stochasticity and uncertainty of WTs, PVs and loads can be better represented.
- A class of mixed H_2/H_∞ controller is designed for the considered EI. The H_2 performance refers to the optimal short-term operation cost management, including three aspects: the cost of utilizing BESs, the extra cost involved by controllers, and short-term operation cost of ERs for the adjustment of power transmission among MGs. The H_∞ performance refers to each MG's AC bus frequency stabilization against external disturbance inputs. It is notable that there has been few work taking all of these criteria into consideration simultaneously.
- Based on typical system parameters, numerical simulations for four interconnected MGs demonstrate the feasibility of our proposed method. The performances of the proposed mixed H_2/H_∞ control method are compared with the results when there is no controller employed. The comparison shows that the controller proposed in this paper is effective.

The rest of the paper is organized as follows. Section II describes the modelling for system dynamics of the considered EI. Section III formulates the mixed H_2/H_∞ control problem and introduces the approach to solving it. Section IV provides some simulations. Finally, we conclude our paper in Section V.

II. Energy Internet Dynamical System Modelling

In this section, the short-term dynamical system of EI is formulated as continuous SDEs with Markovian switching in system parameters.

A. The EI Topology and MG Components

In this work, in order to show the effectiveness of the designed controller for common engineering scenarios, a generalized version of off-grid EI including m interconnected AC MGs is considered. Such EI topology is illustrated in Fig. 1.

In Fig. 1, m AC MGs are interconnected via multiple ERs. For illustrative purpose, each individual MG is assumed to be composed of WTs, PVs, FCs, MTs, BESs and loads. We focus on power dynamics of these devices.

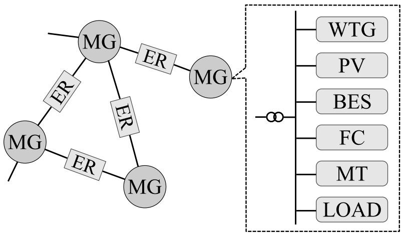


Fig. 1. A general EI topology.

B. Dynamical Power Modelling for MG Components and ERs

In this subsection, the dynamics of components within the entire EI are considered and formulated into mathematical control systems.

Most of the existing literatures adopt ODEs to model the dynamics of MG systems [10], [12]. In recent years, SDEs have been popular in power dynamical modelling; see, e.g., [21]. When Markovian switching is considered in the system parameters, readers can refer to [42], [43]. It is notable that there has been few work in power systems considering SDEs with Markov jumps. In this paper, continuous time SDEs driven by Brownian motion (also known as Weiner process) with Markovian switching in system parameters are applied for the modelling of MG power dynamics.

Throughout this paper, let $(\Omega, \mathcal{F}, \mathcal{P}, \mathcal{F}_t)$ be a given complete filtered probability space, where there exist m right continuous homogeneous Markov chain r_t^k, $t \geq 0$, $k = 1, 2, \ldots, m$ with state space $S = \{1, 2, \ldots, s\}, s \in \mathbb{N}^+$ and scalar Wiener processes $W_{PV}^1(t), W_{PV}^2(t), \ldots, W_{PV}^m(t)$, $W_{WT}^1(t), W_{WT}^2(t), \ldots, W_{WT}^m(t)$, $W_L^1(t), W_L^2(t), \ldots, W_L^m(t)$. It is assumed that all these Wiener processes and Markovian jumps are mutually independent. In this paper, it is assumed that the state transition of system parameters follows a continuous time Markov chain, which is introduced as follows. Firstly, let τ denotes the time during which a state stays unchanged, and τ follows the exponential distribution

$$p(\tau) = \begin{cases} \frac{1}{\lambda} \exp(-\tau/\lambda), & \tau \geq 0, \\ 0, & \text{otherwise.} \end{cases}$$

Then, when the state transition occurs, the transition probability is given by

$$P\{S = j | S = i\} = \begin{cases} \frac{1}{s-1}, & i \neq j, \\ 0, & i = j, \end{cases}$$

Assuming the time constants for PVs, WTs and loads vary with Markov jumps, for the k-th MG, the linearized power dynamical models for PVs, WTs and loads are presented in (1), (2), (3), respectively, (time t omitted)

$$dP_{PV}^k = -\frac{1}{T_{PV}^k(r_t^k)} P_{PV}^k dt + \sigma_{PV}^k(r_t^k) dW_{PV}, \tag{1}$$

$$dP_{WT}^k = -\frac{1}{T_{WT}^k(r_t^k)} P_{WT}^k dt + \sigma_{WT}^k(r_t^k) dW_{WT}, \tag{2}$$

$$dP_L^k = -\frac{1}{T_L^k(r_t^k)} P_L^k dt + \sigma_L^k(r_t^k) dW_L, \tag{3}$$

where $T_{PV}^k(r_t^k)$, $T_{WT}^k(r_t^k)$, $T_L^k(r_t^k)$, $\sigma_{PV}^k(r_t^k)$, $\sigma_{WT}^k(r_t^k)$ and $\sigma_L^k(r_t^k)$ are system time-invariant parameters following Markov jumps. For notation simplicity, time t for all the equations throughout this paper is omitted.

Based on real power data and corresponding climate condition; see, e.g., [44], the paths of Markov jumps can be obtained via parameter estimation approaches with the technique proposed in [45]. In the similar way, system parameters $T_{PV}^k(r_t^k)$, $T_{WT}^k(r_t^k)$, $T_L^k(r_t^k)$ and $\sigma_{PV}^k(r_t^k)$, $\sigma_{WT}^k(r_t^k)$, $\sigma_L^k(r_t^k)$ could be obtained.

In the considered EI system, controllers are set in MTs, FCs and ERs only. ODEs have been used to model power dynamics of MTs, FCs, BESs, ERs and oscillations of AC bus frequencies in many works; see, e.g., [10], [46]. In this paper, the ODE-based modelling approach is also adopted.

Let us denote u_{MT}, u_{FC}, u_{ER} as control inputs for MTs, FCs, ERs, respectively. For the k-th MG, the power dynamics of MTs, FCs, BESs, ERs are presented in (4), (5), (6) and (7), respectively, and the frequency deviation is expressed in (8).

$$\dot{P}_{MT}^k = \frac{1}{T_{MT}^k(r_t^k)} [-P_{MT}^k + b_{MT}^k(r_t^k) u_{MT}^k], \tag{4}$$

$$\dot{P}_{FC}^k = \frac{1}{T_{FC}^k(r_t^k)} [-P_{FC}^k + b_{FC}^k(r_t^k) u_{FC}^k], \tag{5}$$

$$\dot{P}_{BES}^k = \frac{1}{T_{BES}^k(r_t^k)} [-P_{BES}^k + \Delta f^k], \tag{6}$$

$$\dot{P}_{ER}^p = \frac{1}{T_{ER}^p(r_t^k)} [-P_{ER}^p + b_{ER}^p(r_t^k) u_{ER}^p] + v_{ER}^p, \tag{7}$$

$$\dot{f}^k = -\frac{2D^k(r_t^k)}{M^k(r_t^k)} \Delta f^k + \frac{2}{M^k(r_t^k)} \Delta P^k, \tag{8}$$

where $b_{MT}^k(r_t^k)$, $b_{FC}^k(r_t^k)$, $b_{ER}^p(r_t^k)$ are time-variant coefficients for the control inputs, which are determined by the mechanical characteristics of these devices. Due the the communication delay and the limited energy cache capability of ERs, the power adjustment of ERs might be disturbed against the control input. Thus, in (7), the term v_{ER}^p is used to represent the disturbances existing in the power transmission of ERs.

We denote ΔP^k in (8) as the total power deviation within the AC bus of the k-th MG. Considering the power balance in each MG, we have

$$\Delta P^k = P_{PV}^k + P_{WT}^k + P_{MT}^k + P_{FC}^k - P_L^k \pm P_{BES}^k + P_{ex}^k, \tag{9}$$

where P_{ex}^k is the total energy transmitted from other MGs to the k-th MG. Based on the topology of ER network in the considered EI system, we are able to assign different numbers as labels for the transmission lines in the ER network. By denoting P_{ER}^p as the power transmitted via the p-th transmission line, we are able to calculate P_{ex}^k based on the topology of the considered EI system. The dynamic model for P_{ER}^p is presented in (7).

Since power outputs by PVs, WTs and loads vary stochastically according to various factors, e.g., the change of weather in different time of a day, (1) – (3) are only valid for short-term power dynamics of the considered devices, e.g., 5 minutes. In this paper, it is assumed that the short-term dynamics of PVs, WTs and loads can be approximated by linear SDEs with jumping parameters and external disturbance inputs. We assume that there exist several typical parameter sets which could be estimated along with the Markov chains simultaneously. By utilizing the power forecast results obtained with advanced modelling methodologies for DERs and loads; see, e.g., [47], [48], we are able to establish our model for the EI system for a longer period.

C. Dynamical Power Modelling for EI

As long as the power dynamics of each component in EI are formulated in (1) – (8), let us rewrite the dynamical equation of the entire EI system in an explicit formula.

In this paper, it is assumed that, for any MG in the considered EI, there exist switching modes in its power dynamics. Thus, the parameters in (1) – (3) would change when mode alteration occurs. Based on the observation of real-world power data in [44] and the nature of continuous time Markov chain, in most cases, there exist few drastic parameter change in the considered MGs. In this sense, during the time when system parameters for the considered EI stay unchanged, we are able to apply control approaches for stochastic systems with constant parameters.

In this paper, a new control method for the considered EI system is proposed. Firstly, advanced parameter estimation and identification techniques, see, e.g., [42], [43], [45], could be employed to identify the system modes for MGs. Assuming that the identification results are already obtained, based on the results, the entire EI system can be described with a linear SDE with time-invariant parameters within a short period.

Suppose that during $t \in [0, T]$, no mode change occurs in the EI system, and all the parameters can be regarded as constants. Since the dynamics for MGs and ER network are modelled with linear differential equations shown in (1) – (8), they can be rewritten into an explicit form as follows,

$$dx = [A(r_t)x + B(r_t)u + Cv]dt + D(r_t)dW, \tag{10}$$

in which,

$$\begin{aligned} x = [&P^1_{PV}, P^1_{WT}, P^1_L, P^1_{MT}, P^1_{FC}, P^1_{BES}, f^1, \\ &\ldots, \\ &P^m_{PV}, P^m_{WT}, P^m_L, P^m_{MT}, P^m_{FC}, P^m_{BES}, f^m, \\ &P^1_{ER}, \ldots, P^n_{ER}]' \end{aligned}$$

is system state,

$$u = [u^1_{MT}, u^1_{FC}, \ldots, u^m_{MT}, u^m_{FC}, u^1_{ER}, \ldots, u^n_{ER}]'$$

is system control input,

$$v = [v^1_{ER}, \ldots, P^p_{ER}, \ldots, P^n_{ER}]'$$

is system disturbance input,

$$W = W^1_{PV} = W^1_{WT} = W^1_L = \ldots = W^m_{PV} = W^m_{WT} = W^m_L$$

is Weiner process. In (10), A, B, C and D are system parameters obtained from individual dynamic models of the EI system.

III. The Mixed H_2/H_∞ Control Approach

In this section, the problem of short-term operation cost optimization and system stabilization in EI is formulated as the mixed H_2/H_∞ control problem.

First, we formulate the problem of short-term operation cost optimization as a H_2 control problem. We define the main short-term operation cost of EI as the summation of the following three aspects: the cost of utilizing BESs, extra cost involved by controllers and power transmission cost via any pair of interconnected MGs. The cost function of H_2 performance is defined as follows,

$$\begin{aligned} J_1 = \mathbf{E}\Bigg[\int_0^T \Big[&\varepsilon_1 \sum_k (P^k_{BES})^2 + \varepsilon_2 \sum_p (P^p_{ER})^2 \\ &+ \varepsilon_3 \sum_k [(u^k_{MT})^2 + (u^k_{FC})^2]\, dt\Bigg], \end{aligned} \tag{11}$$

where constants $\varepsilon_1, \varepsilon_2$ and ε_3 are weighting coefficients, $\mathbf{E}$ stands for mathematical expectation. The detailed explanation for each explicit term in (11) is as follows.

Since long-term charging or discharging of BESs would lead to losses of battery's service life [49], a rational utilization of BESs is urged, in the sense that BESs shall be used only when necessary. One typical example of irrationally utilizing BESs is given as follows for illustrative purpose. For any MG in EI, if the amount of power generated by PVs and WTs is constantly large, and its interconnected MGs are not lack of power, the BESs in the considered MG are still discharging unnecessarily. We claim such energy management strategy to be irrational. In order that RESs in MGs can be utilized with priority, BESs shall be regarded as the supplementary power supplier. Meanwhile, any unnecessary large-scale power input/output via BESs shall be avoided. In (11), the term $\mathbf{E}[\int_0^T \varepsilon_1 \sum_k (P^k_{BES})^2 dt]$ stands for the cost of utilizing BESs. It is notable that such formulation has been used in many works; see e.g., [49], [50].

On the other hand, irrational utilization of ERs would also lead to additional costs [21]. Besides, according to the bottom-up principle in EI, power supply-demand balance should be achieved within local MGs with priority, and only if the local power balance cannot be maintained, energy routing within wide area network shall be implemented. For detailed explanation and discussion on the bottom-up principle in EI, readers can refer to [21], and the references therein. In (11), the term $\mathbf{E}[\int_0^T \varepsilon_2 \sum_p (P^p_{ER})^2 dt]$ stands for the cost of utilizing ERs. By minimizing the value of such term, the adjustment for energy exchange via ERs within the whole considered EI scenario is minimized, which is beneficial for the achievement of bottom-up energy management principle.

In real engineering scenarios, the additional costs introduced by the controllers themselves are inevitable. Generally, strong controllers set in MTs and FCs can achieve satisfactory control effects. But the possible situation of over-control might bring damage to these devices, which may result in high costs for equipment maintenance. Thus, the cost brought by controllers shall be restricted properly, which is reflected in setting the term $\mathbf{E}[\int_0^T \varepsilon_3 \sum_k [(u^k_{MT})^2 + (u^k_{FC})^2]dt]$ in (11).

As long as the value of J_1 is minimized, the optimal energy management strategy for EI is achieved, in the sense that the considered short-term operation cost is controlled to a minimum amount. In addition to the H_2 performance, the H_∞ performance of EI system is considered.

For the considered system in Fig. 1, electric power is assumed to be transmitted between MGs via DC transmission technology. Hence, the frequency deviation in the AC bus of each individual MG is independent [51]. It is notable that load fluctuation, wind power deviation and solar irradiation disturbance, damping coefficient and inertia constants can significantly influence the stability of frequencies in MGs. To alleviate such frequency fluctuations, the frequency regulation issue for the considered EI is formulated as a H_∞ control problem. Similar to the problem formulation introduced in [19], [52], the H_∞ performance of EI is defined as follows,

$$J_2 = \mathbf{E}\left[\int_0^T \left[-\sum_p (v_{ER}^p)^2 + \gamma^{-2}\sum_k (\Delta f^k)^2\right]dt\right]. \quad (12)$$

Next, by considering both H_2 and H_∞ criteria simultaneously, we formulate the mixed H_2/H_∞ control problem which is defined as follows.

We denote $\mathcal{U}$ as the set for all feasible controllers for system (10). Similarly, $\mathcal{V}$ is denoted as the set for all possible disturbance inputs of system (10). If there exist a pair of controller $u^*(x,t)$ and disturbance $v^*(x,t)$ for system (10), such that for any $u \in \mathcal{U}, v \in \mathcal{V}$,

$$J_1(u, v^*) \geq J_1(u^*, v^*), \quad (13)$$
$$J_2(u^*, v^*) \geq J_2(u^*, v), \quad (14)$$

holds, then (u^*, v^*) is called a H_2/H_∞ solution to the mixed H_2/H_∞ problem. The inequalities in (13) and (14) indicate that, when v^* is used as the disturbance input for (10), u^* is the best possible controller that shall be able to minimize the H_2 performance. On the other hand, when u^* is applied to (10), v^* is the worst case disturbance which will result in the maximum value of the H_∞ performance index J_2. In this sense, u^* would be the desired mixed H_2/H_∞ controller if there exists only one pair of such H_2/H_∞ solution.

Once parameters of MGs in the EI system are determined, we are able to rewrite the entire system with the form shown in (10). The H_2 and H_∞ performance J_1 and J_2 in (11) and (12) can be rewritten as the following forms,

$$J_1 = \mathbf{E}\left[\int_0^T \left[x'Mx + \varepsilon u'u\right]dt\right],$$
$$J_2 = \mathbf{E}\left[\int_0^T \left[\gamma^{-2}x'Fx - v'v\right]dt\right],$$

where x, u and v are of the same definitions as the ones introduced in (10), and M, F, ε can be obtained via matrix transforming techniques. The dynamical system (10) of the proposed mixed H_2/H_∞ control problem are inconsistent with the required form in classic mixed H_2/H_∞ control problem. However, it could be transformed to the compatible one without essential difficulty. We denote $\mathbf{1}$ as a vector with proper dimension, and all of its elements are assigned to be 1. By simply expanding the state variable x as $X = [x', \mathbf{1}']'$ and expanding the corresponding coefficient matrices with zero matrix $\mathbf{0}$ (with proper dimension),

$$\hat{A}(r_t) = \left(\begin{array}{c|c} A(r_t) & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{array}\right), \hat{B}(r_t) = \begin{pmatrix} B(r_t) \\ \mathbf{0} \end{pmatrix}, \hat{C} = \begin{pmatrix} C \\ \mathbf{0} \end{pmatrix},$$
$$\hat{D}(r_t) = \left(\begin{array}{c|c} \mathbf{0} & D(r_t) \\ \mathbf{0} & \mathbf{0} \end{array}\right), \hat{M} = \left(\begin{array}{c|c} M & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{array}\right), \hat{F} = \left(\begin{array}{c|c} F & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{array}\right),$$

we have

$$dX = [\hat{A}(r_t)X + \hat{B}(r_t)u + \hat{C}v]dt + \hat{D}(r_t)X dW. \quad (15)$$

As mentioned above, it is assumed that we have already obtained the parameter mode identification results via observation of the system. In this sense, at each time t, the state r_t of the Markov chain could be estimated. During the period that the system stays at one certain state r_t, the system parameters, i.e., $\hat{A}(r_t)$, $\hat{B}(r_t)$, $\hat{C}$ and $\hat{D}(r_t)$, are actually fixed. So, the mixed H_2/H_∞ controller $u(x, r_t)$ could be calculated with Theorem 1 provided in Appendix A.

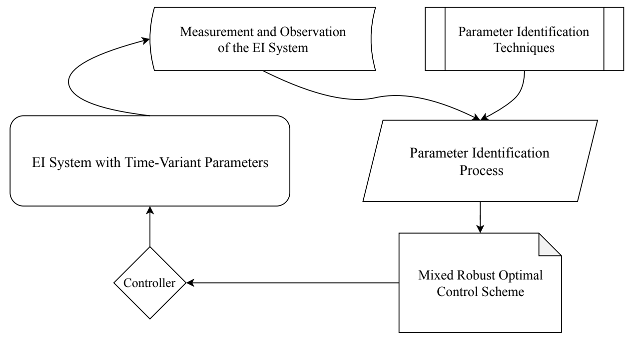


Fig. 2. Typical control scheme for the considered EI system.

Such procedure is depicted in Fig. 2. The identification results r_t of the system parameters are obtained based on the measurements from smart meters deployed in the EI system, and many different techniques could be applied in this task. Then, regarding the obtained system parameters, the mixed H_2/H_∞ controller $u(x, r_t)$ are calculated according to the mixed robust and optimal control scheme in Theorem 1. Finally, the controller is applied in the EI system. In this manner, the mixed H_2/H_∞ control for the Markovian jumping stochastic EI system is achieved.

Notice that dynamic system (10) would only be valid for a limited time period, for each short time segment, the corresponding desired controller can be obtained with the proposed method. By continuously performing the above calculations for all the short time segments, we are able to achieve a long-term optimal and robust performance for the entire EI system.

IV. Numerical Examples

In this section, we solve the mixed H_2/H_∞ control problem based on typical system parameters in real-world engineering scenarios. Based on the modelling for MG dynamics in Section II, it is clear that, for each MG, there exist a negative feedback law in BES power dynamics. Thus, the frequencies of the considered AC MGs would fluctuate within small ranges. Intuitively, without violent disturbance inputs or strong stochastic deviations in power dynamics of PVs, WTs and loads, the EI system would maintain stable even with an H_2 controller for MTs, FCs and ERs. In order to show the effectiveness of the proposed method, the performances under the proposed mixed H_2/H_∞ controller are compared with the results when a claasic H_2 controller is employed. The simulations are implemented based on *Python*.

TABLE I
TYPICAL PARAMETER OF THE CONSIDERED EI SYSTEM

Parameter	Values(s)	Parameter	Values(s)
T_L	0.9	σ_L	0.3
T_{PV}	1.3	σ_{PV}	0.1
T_{WT}	1.2	σ_{WT}	0.2
T_{MT}	0.2	b_{MT}	1.0
T_{FC}	0.3	b_{FC}	1.0
T_{ER}	0.2	b_{ER}	1.0
T_{BES}	0.05	D	0.012
M	1.8		

For illustrative purpose, we consider an EI composed of four MGs interconnected via ERs, whose specific connection topology is shown in Fig. 1. Each MG consists of PVs, WTs, MTs, FCs, BESs and loads. We presume that the EI works at the balanced state, meaning that the power balance in the EI system is achieved, and the frequency oscillations are mainly related to the stochastic power fluctuation of RESs and loads.

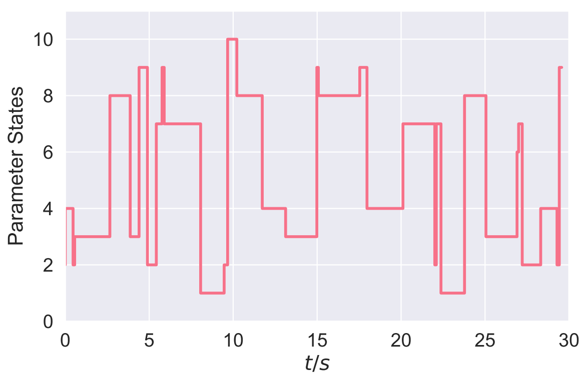


Fig. 3. State transition of system parameters.

Typical parameters of the considered EI system are shown in Table I. Without loss of generality, it is assumed that the parameter transition for all MGs in the considered EI follows the same Markov process. Besides, we assume that there are ten possible changing patterns, namely, r_t^k could take values in $\{1, 2, \ldots, 10\}$. For simulations, the parameters under different modes are randomly generated by combining typical values in Table I with random variables following uniform distribution.

It is assumed that the state of the Markov chain for system parameters could be obtained with certain parameter identification approaches at high precision. Thus, we are able to apply appropriate controller in the EI system at different periods. The trajectory of system mode transition corresponding to the numerical simulation setting is illustrated in Fig. 3.

The frequency deviation curves in different MGs with the proposed H_2/H_∞ controller are shown in Fig. 4. It is clear that

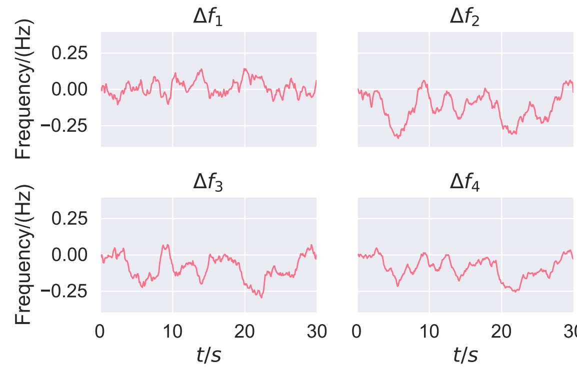


Fig. 4. Frequency deviations in EI system under H_2/H_∞ control.

the AC bus frequency deviations in each MG are effectively alleviated. The power dynamics of BESs, MTs and FCs under the proposed H_2/H_∞ control scheme are illustrated in Fig. 5, Fig. 6 and Fig. 7 respectively. It can be found that, under the proposed control scheme, parts of the drastic power deviations on the AC bus can be properly absorbed by MTs and FCs. Thus, fluctuations in the charge/discharge power of the BESs can be limited, which suggests that the BESs can be protected by adjusting the power outputs of MTs and FCs.

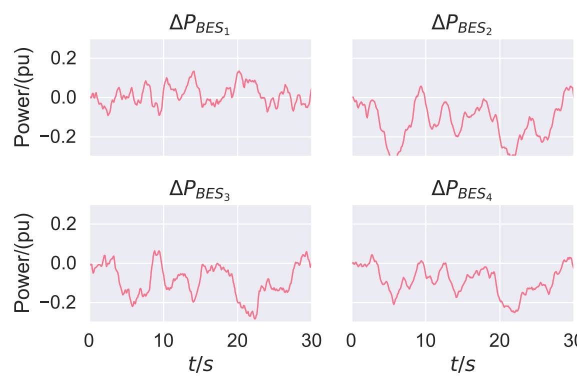


Fig. 5. Power of BESs under H_2/H_∞ control.

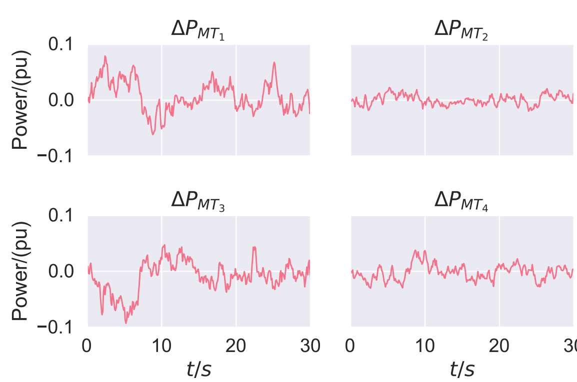


Fig. 6. Power of MTs under H_2/H_∞ control.

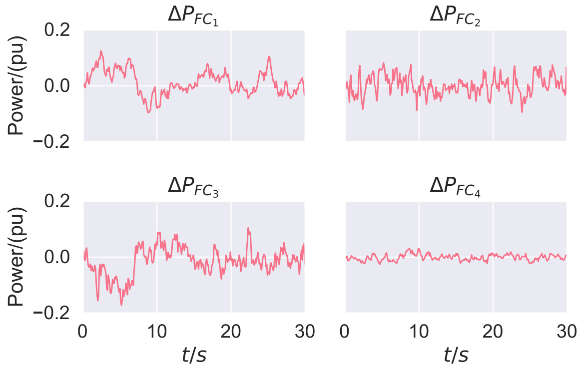


Fig. 7. Power of FCs under H_2/H_∞ control.

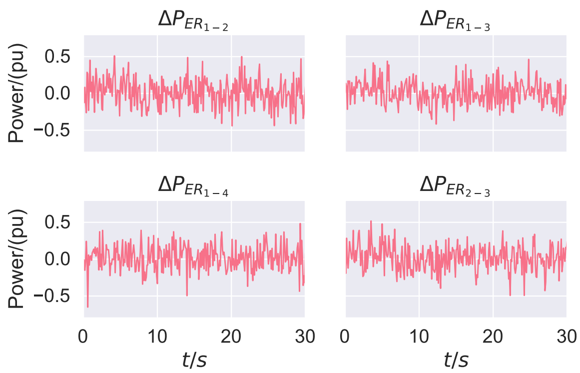


Fig. 8. Power of ERs under H_2/H_∞ control.

Similarly, the power deviations of ERs with disturbance inputs are depicted in Fig. 8, where $P_{ER_{i-j}}$ denotes the power transmitted from MG_i to MG_j. According to the curves in Fig. 4 and Fig. 8, one can infer that, the impacts from disturbances in ERs on power bus frequencies in MGs are successfully restricted. At the same time, the power exchange via ERs could help the rational utilization of the power generation devices and BESs. With the proposed H_2/H_∞ control scheme applied, the MGs could better utilize the advantages from the ER networks without significant detraction of frequency stability.

To show the advantage of the proposed H_2/H_∞ control method over the conventional H_2 control method in the frequency regulation problem, in Fig. 9, the frequency fluctuations in MG_1 under these two different control strategies are plotted. The notation $\Delta f_1^\star$ refers to the frequency deviation in MG_1 under the H_2/H_∞ control scheme $u^\star$ proposed in this paper. In the meantime, the frequency deviation in MG_1 under a classic H_2 controller $u^\clubsuit$ is illustrated as $\Delta f_1^\clubsuit$ in Fig. 9. Specifically, with the disturbance input v in (10) omitted, the corresponding H_2 controller is obtained via optimizing the weighted sum of objectives J_1 and J_2, i.e., $J_1 + \gamma^2 J_2$. It is obvious that the proposed H_2/H_∞ control method has better frequency regulation performance. As delineated in Fig. 9, the corresponding frequency deviations of $\Delta f_1^\star$ have been limited within a relatively smaller range compared with $\Delta f_1^\clubsuit$.

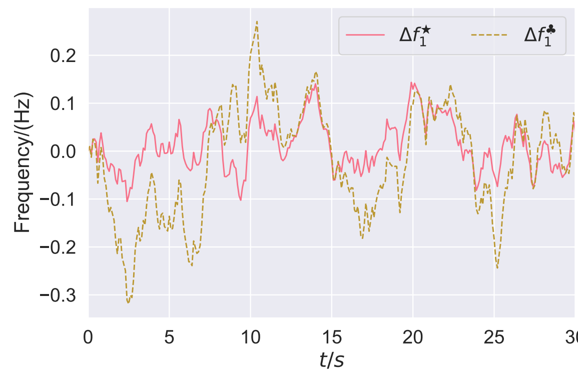


Fig. 9. Frequency regulation performance comparison.

In the meantime, the adjustments to the MT power outputs in MG_1 when the aforementioned two control methods are applied are illustrated in Fig 10. Clearly, though the proposed H_2/H_∞ controller $u^\star$ can achieve higher frequency stability for multi-microgrid systems, it would require more drastic and frequent adjustments in controllable generators like MTs, which will thus lead to higher operation costs to the considered energy internet system. In contrast, only moderate level of power adjustments for MTs are conducted by the classic H_2 controller $u^\clubsuit$ in Fig 10. This is related to the property of the H_2/H_∞ control scheme $u^\star$. By the definition in (13) and (14), $u^\star$ only ensures its optimality when the worst disturbance v^* is imposed on the system (10). In this sense, $u^\star$ may not guarantee its corresponding operation costs measurement J_1 to be the minimum in other cases.

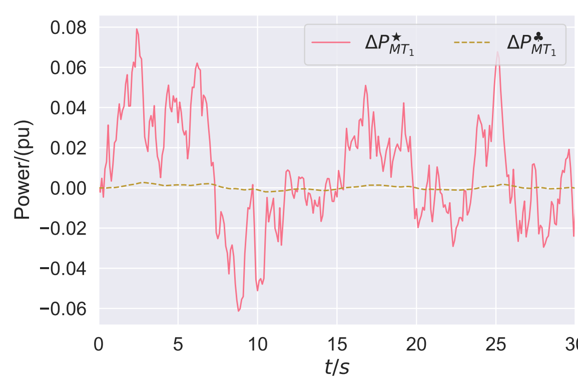


Fig. 10. Comparison of MT power curves under different control schemes.

In summary, by evaluating the controllers obtained from Theorem 1 with numerical simulations, the advantages and validity of our proposed method is demonstrated.

V. Conclusions

In this paper, the frequency regulation problem for a typical EI system is investigated. The dynamics of the considered multi-microgrid system are modeled with SDEs driven by

Brownian motions, and the complex patterns exist in power deviations are modelled as Markovian jump noises. In order to achieve the rational utilization of controllable devices like MTs and ERs as well as stabilizing the frequency fluctuations on AC buses, a novel H_2/H_∞ control scheme with Markovian jump is proposed. With the numerical example provided in this paper, the feasibility and efficacy of the proposed control scheme is evaluated. Based on the simulation results presented in this paper, both of the frequency regulation target and the short-term costs minimization target can be properly achieved, which demonstrates the effectiveness of the proposed method.

In this paper, for the Internet layer, we have developed a centralized control method. The proposed strategy should rely on a central controller, and once the control center is under cyber-attack, the security of the whole EI system is risky. Compared with the distributed control method, under which case each interconnected microgrid does not need to disclose full private information with others, more attention should be paid on cyber security when the centralized method is implemented in real engineering scenario. In addition, in the Internet layer, the computation time and cost is also worth consideration, especially when the scale of the control problem is relatively large. This is also a limitation or restriction of the proposed centralized control method. Nevertheless, the performance of decentralized control approaches suffers from problems like low precisions and slow convergence speed as well. Thereby, we should consider both centralized and distributed control methods simultaneously in our future research.

Appendix

A. The Mixed H_2/H_∞ Control Theorem

Theorem 1 ([52]): For the EI system (15), if the coupled differential Riccati equations in (16) has one solution (P_1, P_2, K_1, K_2) such that $P_1(T) = 0$, $P_2(T) = 0$, $P_1(0) \geq 0$, $P_2(0) \geq 0$, then the solution to the mixed H_2/H_∞ control problem is $u^* = K_2 x$ and $v^* = K_1 x$.

$$\begin{cases} -\dot{P}_1 &= -\hat{F} + \hat{D}' P_1 \hat{D} + \gamma^2 K_1' K_1 + 2P_1\hat{A} \\ &\quad +2P_1\hat{B}K_2 + 2P_1\hat{C}K_1, \\ -\dot{P}_2 &= \hat{M} + \hat{D}' P_2 \hat{D} + \varepsilon K_2' K_2 + 2P_2\hat{A} \\ &\quad +2P_2\hat{B}K_2 + 2P_2\hat{C}K_1, \\ K_1 &= -\gamma^{-2}\hat{C}' P_1', \\ K_2 &= -\varepsilon^{-1}\hat{B}' P_2'. \end{cases} \tag{16}$$

Acknowledgments

This work was funded in part by National Key Research and Development Program of China (Grant No. 2017YFE0132100) and the BNRist Program under (Grant No. BNR2019TD01009).

References

[1] A. Olabi, “Renewable energy and energy storage systems,” *Energy*, vol. 136, pp. 1–6, Oct. 2017.

[2] D. Thomas, O. Deblecker, and C. S. Ioakimidis, “Optimal design and techno-economic analysis of an autonomous small isolated microgrid aiming at high RES penetration,” *Energy*, vol. 116, pp. 364–379, Dec. 2016.

[3] J. W. Eising, T. V. Onna, and F. Alkemade, “Towards smart grids: Identifying the risks that arise from the integration of energy and transport supply chains,” *Appl. Energy*, vol. 123, pp. 448–455, Jun. 2014.

[4] J. Cao, H. Hua, and G. Ren, *Energy use and the Internet*. The SAGE Encyclopedia of the Internet; SAGE Publications: Thousand Oaks, CA, USA, 2018.

[5] R. Wang, J. Wu, Z. Qian, Z. Lin, and X. He, “A graph theory based energy routing algorithm in energy local area network,” *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3275–3285, Dec. 2017.

[6] X. Fang, Q. Yang, J. Wang, and W. Yan, “Coordinated dispatch in multiple cooperative autonomous islanded microgrids,” *Appl. Energy*, vol. 162, pp. 40–48, Jan. 2016.

[7] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, “DC microgrids—part i: A review of control strategies and stabilization techniques,” *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4876–4891, 2015.

[8] G. Liu, M. Starke, B. Xiao, and K. Tomsovic, “Robust optimisation-based microgrid scheduling with islanding constraints,” *IET Generation, Transmission & Distribution*, vol. 11, no. 7, pp. 1820–1828, 2017.

[9] H. Hua, J. Cao, G. Yang, and G. Ren, “Voltage control for uncertain stochastic nonlinear system with application to energy Internet: Non-fragile robust H_∞ approach,” *Journal of Mathematical Analysis and Applications*, vol. 463, no. 1, pp. 93–110, 2018.

[10] H. Bevrani, M. R. Feizi, and S. Ataee, “Robust frequency control in an islanded microgrid: H_∞ and μ-synthesis approaches,” *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 706–717, Mar. 2016.

[11] Y. Han, P. M. Young, A. Jain, and D. Zimmerle, “Robust control for microgrid frequency deviation reduction with attached storage system,” *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 557–565, Mar. 2015.

[12] M. J. Hossain, H. R. Pota, M. A. Mahmud, and M. Aldeen, “Robust control for power sharing in microgrids with low-inertia wind and PV generators,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1067–1077, Jul. 2015.

[13] Q. Sun, Y. Zhang, H. He, D. Ma, and H. Zhang, “A novel energy function-based stability evaluation and nonlinear control approach for energy internet,” *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1195–1210, May 2017.

[14] Y. Qin, H. Hua, and J. Cao, “Short-term energy cache regulation for energy router: A robust h-infinity approach,” in *2019 IEEE International Conference on Energy Internet (ICEI)*. IEEE, 2019, pp. 161–166.

[15] Y. Zhang, N. Gatsis, and G. B. Giannakis, “Robust energy management for microgrids with high-penetration renewables,” *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 944–953, Oct. 2013.

[16] A. H. Etemadi, E. J. Davison, and R. Iravani, “A generalized decentralized robust control of islanded microgrids,” *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 3102–3113, Nov. 2014.

[17] D. I. Makrygiorgou and A. T. Alexandridis, “Distributed stabilizing modular control for stand-alone microgrids,” *Appl. Energy*, vol. 210, pp. 925–935, Jan. 2018.

[18] J. Cao, W. Zhang, Z. Xiao, and H. Hua, “Reactive power optimization for transient voltage stability in energy internet via deep reinforcement learning approach,” *Energies*, vol. 12, no. 8, p. 1556, 2019.

[19] H. Hua, Y. Qin, J. Cao, W. Wang, Q. Zhou, Y. Jin, Z. Zhao, and J. Jin, “Stochastic optimal and robust control scheme for islanded AC microgrid,” in *Proc. IEEE Int. Conf. on Probabilistic Methods Applied to Power Systems*. Boise, Idaho, USA: IEEE, Jun. 2018, pp. 1–6.

[20] J. Han, S. Khushalani-Solanki, J. Solanki, and J. Liang, “Adaptive critic design-based dynamic stochastic optimal control design for a microgrid with multiple renewable resources,” *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2694–2703, Nov. 2015.

[21] H. Hua, Y. Qin, C. Hao, and J. Cao, “Stochastic optimal control for energy Internet: A bottom-up energy management approach,” *IEEE Trans. Ind. Informat.*, 2018.

[22] X. Yang, Y. Zhang, B. Zhao, F. Huang, Y. Chen, and S. Ren, “Optimal energy flow control strategy for a residential energy local network combined with demand-side management and real-time pricing,” *Energy and Buildings*, vol. 150, pp. 177–188, Sep. 2017.

[23] H. Dagdougui, A. Ouammi, and R. Sacile, “Optimal control of a network of power microgrids using the Pontryagin’s minimum principle,” *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 5, pp. 1942–1948, Sep. 2014.

[24] P. Tenti and T. Caldognetto, “Optimal control of local area energy networks (E-LAN),” *Sustain. Energy, Grids and Networks*, vol. 14, pp. 12–24, Jan. 2018.

[25] N. Nikmehr and S. N. Ravadanegh, “Optimal power dispatch of multi-microgrids at future smart distribution grids,” *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1648–1657, 2015.

[26] N.-O. Song, J.-H. Lee, H.-M. Kim, Y. H. Im, and J. Y. Lee, “Optimal energy management of multi-microgrids with sequentially coordinated operations,” *Energies*, vol. 8, no. 8, pp. 8371–8390, 2015.

[27] P. Kou, D. Liang, and L. Gao, “Distributed EMPC of multiple microgrids for coordinated stochastic energy management,” *Applied energy*, vol. 185, pp. 939–952, 2017.

[28] A. N. Venkat, I. A. Hiskens, J. B. Rawlings, and S. J. Wright, “Distributed mpc strategies with application to power system automatic generation control,” *IEEE Trans. Control Syst. Technol.*, vol. 16, no. 6, pp. 1192–1206, 2008.

[29] Z. Wang, B. Chen, J. Wang, M. M. Begovic, and C. Chen, “Coordinated energy management of networked microgrids in distribution systems,” *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 45–53, 2014.

[30] T. Lv and Q. Ai, “Interactive energy management of networked microgrids-based active distribution system considering large-scale integration of renewable energy resources,” *Appl. Energ.*, vol. 163, pp. 408–422, 2016.

[31] J. Duan, Z. Yi, D. Shi, C. Lin, X. Lu, and Z. Wang, “Reinforcement-learning-based optimal control of hybrid energy storage systems in hybrid AC–DC microgrids,” *IEEE Trans. Ind. Informat.*, vol. 15, no. 9, pp. 5355–5364, 2019.

[32] E. Mocanu, D. C. Mocanu, P. H. Nguyen, A. Liotta, M. E. Webber, M. Gibescu, and J. G. Slootweg, “On-line building energy optimization using deep reinforcement learning,” *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3698–3708, 2018.

[33] R. Yousefian and S. Kamalasadan, “Energy function inspired value priority based global wide-area control of power grid,” *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 552–563, 2016.

[34] H. Hua, Y. Qin, C. Hao, and J. Cao, “Optimal energy management strategies for energy internet via deep reinforcement learning approach,” *Applied energy*, vol. 239, pp. 598–609, 2019.

[35] H. Hua, C. Hao, Y. Qin, and J. Cao, “A class of control strategies for energy internet considering system robustness and operation cost optimization,” *Energies*, vol. 11, no. 6, p. 1593, 2018.

[36] S. Vachirasricirikul and I. Ngamroo, “Robust LFC in a smart grid with wind power penetration by coordinated V2G control and frequency controller,” *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 371–380, Jan. 2014.

[37] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, “A decentralized robust mixed H_2/H_∞ voltage control scheme to improve small/large-signal stability and FRT capability of islanded multi-DER microgrid considering load disturbances,” *IEEE Syst. J.*, vol. 12, no. 3, pp. 2610–2621, Sep. 2018.

[38] C. Li, Y. Xu, X. Yu, C. Ryan, and T. Huang, “Risk-averse energy trading in multienergy microgrids: a two-stage stochastic game approach,” *IEEE Trans. Ind. Informat.*, vol. 13, no. 5, pp. 2620–2630, Oct. 2017.

[39] M. Rasheduzzaman, T. Paul, and J. W. Kimball, “Markov jump linear system analysis of microgrid stability,” in *Proc. of the American Control Conf.* Portland, Oregon, USA: IEEE, Jun. 2014, pp. 5062–5066.

[40] L. Sedghi and A. Fakharian, “Robust voltage regulation in islanded microgrids: A LMI based mixed H_2/H_∞ control approach,” in *Proc. 24th Mediterranean Conf. on Control and Automation*. Athens, Greece: IEEE, Jun. 2016, pp. 431–436.

[41] H. Hua, Y. Qin, J. Geng, C. Hao, and J. Cao, “Robust mixed H_2/H_∞ controller design for energy routers in energy internet,” *Energies*, vol. 12, no. 3, p. 340, 2019.

[42] R. Sayed, Y. Hegazy, and M. Mostafa, “Modeling of photovoltaic based power stations for reliability studies using Markov chains,” in *Proc. Int. Conf. on Renewable Energy Research and Applications*. Madrid, Spain: IEEE, Oct. 2013, pp. 667–673.

[43] M. Miozzo, D. Zordan, P. Dini, and M. Rossi, “SolarStat: Modeling photovoltaic sources through stochastic Markov processes,” in *Proc. IEEE Int. Energy Conf.* Dubrovnik, Croatia: IEEE, May 2014, pp. 688–695.

[44] Data Port. Accessed 2018-06-01. [Online]. Available: "https://dataport.cloud/"

[45] J. L. Mathieu, S. Koch, and D. S. Callaway, “State estimation and control of electric loads to manage real-time energy imbalance,” *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 430–440, Feb. 2013.

[46] Y. Qin, H. Hua, and J. Cao, “Stochastic optimal control scheme for battery lifetime extension in islanded microgrid via a novel modeling approach,” *IEEE Trans. Smart Grid*, 2018.

[47] H.-T. Yang, C.-M. Huang, Y.-C. Huang, Y.-S. Pai *et al.*, “A weather-based hybrid method for 1-day ahead hourly forecasting of PV power output,” *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 917–926, Jul. 2014.

[48] O. Abedinia, N. Amjady, and H. Zareipour, “A new feature selection technique for load and price forecast of electrical power systems,” *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 62–74, Jan. 2017.

[49] Q. Wei, D. Liu, Y. Liu, and R. Song, “Optimal constrained self-learning battery sequential management in microgrid via adaptive dynamic programming,” *IEEE/CAA J. Autom. Sinica*, vol. 4, no. 2, pp. 168–176, Apr. 2017.

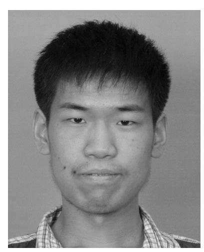
[50] D. Tran and A. M. Khambadkone, “Energy management for lifetime extension of energy storage system in micro-grid applications,” *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1289–1296, Sep. 2013.

[51] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, “AC-microgrids versus DC-microgrids with distributed energy resources: A review,” *Renewable and Sustain. Energy Rev.*, vol. 24, pp. 387–405, Aug. 2013.

[52] B. Chen and W. Zhang, “Stochastic H_2/H_∞ control with state-dependent noise,” *IEEE Trans. Autom. Control*, vol. 200, no. 4, pp. 45–57, Feb. 2014.

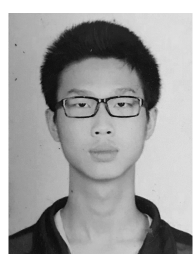
Haochen Hua was born in Jiangsu, P. R. China in 1988. He received the B.Sc. degree in mathematics with finance in 2011, and the Ph.D. degree in mathematical sciences in 2016, both from the University of Liverpool, Liverpool, UK. From 2016 to 2020, he was a Postdoctoral Fellow in the Research Institute of Information Technology, Tsinghua University, Beijing, P. R. China.

Since 2020, he has been a Professor in the College of Energy and Electrical Engineering, Hohai University, Nanjing, P. R. China. His current research interests include optimal and robust control theory and its applications in power systems, smart grids, and the energy internet.



Yuchao Qin was born in Henan, P. R. China in 1994. He received the B.Sc. degree in automation in 2017 from Tsinghua University, Beijing, P. R. China.

He is currently a postgraduate student in the Research Institute of Information Technology, Tsinghua University, Beijing, P. R. China. His current research interests include control and optimization, machine learning and their applications in power system.

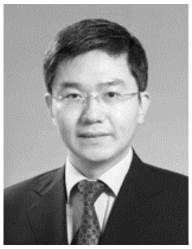


Zicheng He was born in JiangXi, P. R. China in 1997. He will receive the B.Sc. degree in microelectronics in 2019 from Fudan University, Shanghai, P. R. China.

He is currently an undergraduate student in the Institute of Information Technology, Fudan University, Beijing, P. R. China. His current research interests include control and optimization of power systems and the application of deep learning.

Liuying Li received her Ph.D. and bachelor degrees in electrical engineering and electronics in 2017 and 2012, respectively, both from the University of Liverpool, Liverpool, UK.

She has been a research fellow in the Warwick Manufacturing Group, University of Warwick, Coventry, UK, since 2018, where she has been involved in state estimation and control in advanced battery management systems. Her current research interests include modelling, estimation, parameterization, optimization, and control systems.



Junwei Cao received his Ph.D. in computer science from the University of Warwick, Coventry, UK, in 2001. He received his bachelor and master degrees in control theories and engineering in 1998 and 1996, respectively, both from Tsinghua University, Beijing, China. He is currently Professor and Vice Dean of Research Institute of Information Technology, Tsinghua University, Beijing, China. He is also Director of Open Platform and Technology Division, Tsinghua National Laboratory for Information Science and Technology.

Prior to joining Tsinghua University in 2006, he was a Research Scientist at MIT LIGO Laboratory and NEC Laboratories Europe for about 5 years. He has published over 200 papers and cited by international scholars for over 18,000 times. He has authored or edited 8 books. His research is focused on distributed computing technologies and energy/power applications.

Prof. Cao is a Senior Member of the IEEE Computer Society and a Member of the ACM and CCF.