Energy Internet System Control and Optimization: A Stochastic Risk-Sensitive Control Approach

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Abstract— **This paper introduces a new control approach for energy Internet (EI) system management. The considered EI system includes multiple AC microgrids (MGs) interconnected via energy routers (ERs). Two control targets are considered to be satisfied. First, due to the stochastic power output change of loads, photovoltaic panels (PVs) and wind turbine generators (WTGs), the resulting AC bus frequency deviation is aimed to be regulated. Second, a constraint for the size of control input is restricted, such that the situation of over-control is avoided. We formulate such EI system management issue into a stochastic risk-sensitive control problem and solve it analytically. It is highlighted that we are focusing on developing engineering applications supported by the existing theoretical results. Indeed, this is the first time that EI system management issue is formulated as a risk-sensitive control problem. We emphasize that the obtained optimal controller is linear with system state, which is easy to be implemented in real-world applications. Simulations show the feasibility and effectiveness of the proposed method.**

Keywords- energy Internet; energy router; microgrid; risk-sensitive control; stochastic systems

NOMENCLATURE

BES	Battery energy storage.
ER	Energy router.
EI	Energy Internet.
FC	Fuel cell.
MT	Micro-turbine.
MG	Microgrid.
ODE	Ordinary differential equation.
PV	Photovoltaic panel.
RES	Renewable energy source.
SDE	Stochastic differential equation.
WTG	Wind turbine generator.
T_{MT}	MT time constant.
T_{FC}	FC time constant.
T_{BES}	BES time constant.
ΔP_L	Load power change.
ΔP_{PV}	PV output power change.
ΔP_{WTG}	WTG output power change.
ΔP_{MT}	MT output power change.
ΔP_{FC}	FC output power change.
ΔP_{BES}	BES input/output power change.
ΔP_{ER}	ER input/output power change.
D	Damping coefficient.
M	Inertia constant.
i	Index of microgrids.

I. INTRODUCTION

The study of EI has been popular during the last few years [1]. The current EI infrastructure is designed based on the existence of a new type of electrical power routing device, named as ER [2], [3]. The EI can be regarded as a class of integrated system comprising multiple MGs interconnected by ERs [4]. With ERs, electricity can be transmitted via ERs likewise information exchange via routers. An EI scenario can function with connection to the utility grid, or, it shall be able to function in the off-grid mode. Assuming that multiple interconnected AC MGs exist in the EI scenario, it is pointed out that for the off-grid mode, the related system control problems are more challenging than that under the grid connected mode [5].

In the future, data acquisition and control can be achieved within micro-second level which is more precise than the current level. Within future EI scenarios, energy and information are fused, and power can be transmitted bi-directionally [4]. In the scope of EI, there exist a number of interesting topics worth considering, including power electronics, information and communication, power and energy management, system stability control, etc.; see, e.g., [5]-[9].

In this paper, we mainly focus on an EI scenario which is disconnected with the main power grid, and the comprised MGs' AC bus frequency deviations are expected to be regulated. The power deviation in each MG may come from different sources. For example, stochastic power output of PV and WTG due to rapid weather condition change [10], random power of local load devices due to various electricity usage customs [11], or the requirement of power transmission due to low state of change of local BESs [12].

The system stability issues with respect to MGs has attracted much attention and has been investigated in a number of previous works; see, e.g., [5], [13]-[16]. In [5], the technique of particle swam optimization has been used to achieve the frequency regulation target in frequency domain. In [14], the dynamics of an islanded MG has been modelled as a class of nonlinear SDE, and the H_∞ control approach has been applied to obtain sufficient solutions for the DC bus voltage alleviation issue. For frequency stabilization issues, a comparison of H_∞ control and μ-synthesis approach has been analyzed in [15]. In [16], the mixed H_2/H_∞ control approach has been applied to achieve both frequency stability and battery lifetime extension. It is notable that these aforementioned literatures have certain drawbacks. The MG system in [5] and [15] is studied in frequency domain only, which fails to consider the existing

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system stochasticity. The H_∞ control approach appears to be effective in [14], but it is quite possible that the situation of over-control would happen. In [16], only ODEs are applied to describe MG power dynamics in a deterministic system.

It is notable that system control issues in the field of EI would be more complicated than that in MGs or conventional power systems [4]. Motivated by the shortcomings in some existing works, e.g., [5], [13]-[16], in this paper, we focus on designing a class of controllers in EI, such that AC bus frequency deviations in all MGs are regulated well. Besides, the situation of over-control is considered to be avoided.

More specifically, our investigated EI scenario includes a number of AC MGs accessed via ERs, and the connection with the utility grid is not considered. We assume that the main power supply for MGs mainly come from RES, e.g., solar power and wind power. In each MG, some adjustable power generation devices, i.e., MTs and FCs, are utilized as complementary power supply sources. The controllers are set in ERs, MTs and FCs only. Although BESs are assumed to be existed in the considered ER, they are assumed to be uncontrollable. Then, we model the dynamics in the considered EI as a class of ODEs and SDEs. Our desired control targets are formulated as a cost functional. In this sense, the task of designing controllers is transformed into a mathematical control issue. In particular, to enhance the control effect, the so-called risk-sensitive control problem formulation is utilized in designing the criterion, which has not been considered in EI applications.

The importance and contribution of this paper can be outlined as follows:

1) This paper focuses on applying stochastic control theory into industrial applications. The solution to the considered optimization problem is linear with system state, which is convenient to be implemented in real-world applications.

2) This is the very first time that risk-sensitive control approach has been applied into an EI scenario. For the considered problem, instead of using normal linear-quadratic (LQ) control approach which has been extensively studied in EI, the risk-sensitive control method can achieve better control effect.

3) For the considered EI scenario and the obtained control law, power supply-demand balance within the whole scenario can be achieved. Besides, the targets of frequency regulation and avoiding over-control have been achieved simultaneously.

4) The adequacy and feasibility of the proposed method have been verified by numerical examples. In simulations, three different scenarios corresponding to different control targets are studied and analyzed.

II. SYSTEM MODELLING

A. EI Scenario

A typical EI system is formed by multiple MGs interconnected by ERs, whose topology is given in Fig. 1. It is notable that such EI scenario has no access with the utility grid, and an autonomous power supply-demand balance can be achieved via proper energy control and routing strategies. Without loss of generality, it is assumed that PVs, WTGs, MTs, FCs, BESs and loads are installed in each MG in the considered EI system.

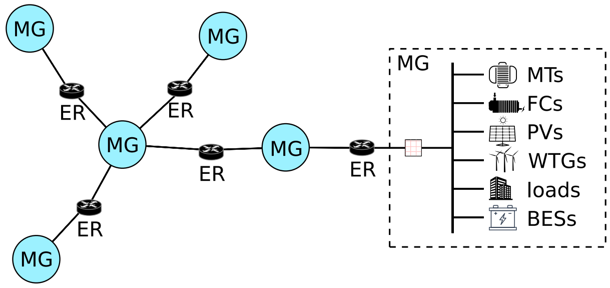

Figure 1. The topology of the considered EI.

B. MG System Modelling

For the i-th local MG in Fig. 1, each device's power dynamical equation can be written as ODEs and SDEs, as is shown in (1),

$$\begin{cases} \mathrm{d}\Delta P_{L_i} = -r_{L_i}\Delta P_{L_i}dt + s_{L_i}\mathrm{d}w_{L_i}(t), \\ \mathrm{d}\Delta P_{PV_i} = -r_{PV_i}\Delta P_{PV_i}dt + s_{PV_i}\mathrm{d}w_{PV_i}(t), \\ \mathrm{d}\Delta P_{WTG_i} = -r_{WTG_i}\Delta P_{WTG_i}\mathrm{d}t + s_{WTG_i}\mathrm{d}w_{WTG_i}(t), \\ \Delta\dot{P}_{MT_i} = -\dfrac{1}{T_{MT_i}}\Delta P_{MT_i} + \dfrac{1}{T_{MT_i}}u_{MT_i}, \\ \Delta\dot{P}_{FC_i} = -\dfrac{1}{T_{FC_i}}\Delta P_{FC_i} + \dfrac{1}{T_{FC_i}}u_{FC_i}, \\ \Delta\dot{P}_{BES_i} = -\dfrac{1}{T_{BES_i}}\Delta P_{BES_i} + \dfrac{1}{T_{BES_i}}\Delta f_i, \\ \Delta\dot{f}_i = -\dfrac{2D_i}{M_i}\Delta f_i + \dfrac{2}{M_i}\Delta P_i, \end{cases} \tag{1}$$

where $w_{L_i}(t)$, $w_{PV_i}(t)$ and $w_{WTG_i}(t)$ are scalar Wiener processes that are used to describe the short-term power deviation in PVs, WTGs and loads; u_{MT_i} and u_{FC_i} are controllers for MTs and FCs in the i-th MG, respectively. The parameters in (1) can be obtained via parameter estimation methods [17], [18]. The similar modelling approach for MG dynamics have been used in many works; see, e.g., [11], [12], [14]-[16].

Similarly, for the ER between the i-th and j-th MGs, the dynamics of power flow transmitted via $ER_{i,j}$ is approximated by (2)

$$\Delta\dot{P}_{ER_{i,j}} = -\frac{1}{T_{ER_{i,j}}}\Delta P_{ER_{i,j}} + \frac{1}{T_{ER_{i,j}}}u_{ER_{i,j}}. \tag{2}$$

where $u_{ER_{i,j}}$ is the controller for the ER set between the i-th and j-th MGs. Since $\Delta P_{ER_{i,j}}$ and $\Delta P_{ER_{j,i}}$ refer to power of the same ER, in this paper, only $\Delta P_{ER_{i,j}}, (i > j)$ is considered. To obtain $\Delta P_{ER_{j,i}}$, we can simply change the positive or negative sign of $\Delta P_{ER_{i,j}}$.

Additionally, the term ΔP_i in (1) represents the imbalance between power consumption and generation, and

$$\begin{aligned} &\Delta P_i \\ &= -\Delta P_{L_i} + \Delta P_{PV_i} + \Delta P_{WTG_i} + \Delta\dot{P}_{MT_i} + \Delta\dot{P}_{FC_i} + \Delta\dot{P}_{BES_i} \\ &- \Delta\dot{P}_{ER_{i,j}}. \end{aligned}$$

III. PROBLEM FORMULATION AND SOLUTION

In this section, the EI system management problem is formulated as a stochastic risk-sensitive control issue.

A. Mathematical Control System

The system states considered in (1) and (2) includes the power changes of PVs, WTGs, MTs, FCs, BESs and loads in the i-th MG as well as the power change of the ER connecting the i-th and j-th MGs. For notation simplicity, let us denote these states at time t as vector $x(t)$, i.e., (time t omitted)

$$x = \left[\Delta P_{L_i}, \Delta P_{PV_i}, \Delta P_{WTG_i}, \Delta P_{MT_i}, \Delta P_{FC_i}, \Delta P_{BES_i}, \Delta f_i, \Delta P_{ER_{i,j}}\right]'.$$

Also, the controllers for MTs, FCs and ERs in (1) and (2) are represented with a vector denoted as $u(t)$ (time t omitted)

$$u = [u_{MT_i}, \quad u_{FC_i}, \quad u_{ER_{i,j}}]'.$$

Based on the modelling for the considered EI system introduced in Section II, we are able to rewrite (1)-(2) as a linear SDE which is given as follows.

$$\begin{cases} \mathrm{d}x(t) = [A(t)x(t) + B(t)u(t)]\mathrm{d}t + C\mathrm{d}w(t), \\ x(t) = x_0, \end{cases} \tag{3}$$

where $w(t)$ is a multidimensional Wiener process; x_0 is the initial value of the system state $x(t)$. The coefficient matrices $A(t)$, $B(t)$, and C could be easily obtained based on (1) and (2), and they are not explicitly given in this paper due to their large dimensions.

In this sense, the dynamical EI system has been modelled as a class of SDE. Next, the system management criteria shall be formulated as a mathematical cost function.

B. Risk-Sensitive Control Problem Formulation

In this paper, for all MGs in EI, two main issues are considered. The first is to ensure that each MG's AC bus frequency is stabilized. The second is to avoid the situation of over-control. Assuming that there are totally N MGs and M ERs in the considered EI system, the overall cost functional for the considered EI system management issue is formulated as follows.

$$J(u(\cdot)) = \mathbb{E}\left\{\exp\left[\sum_{i=1}^{N} \Delta f_i(T)^2 + \int_0^T \left[\sum_{i=1}^{N} q\Delta f_i(t)^2 + ru(t)'u(t)\right] dt\right]\right\}, \tag{4}$$

where scalars q and r are weighting coefficients.

The cost function in (4) can be reduced to a more general form, which is shown in (5).

$$J(u(\cdot)) = \mathbb{E}\left\{\exp\left[x(T)'Sx(T) + \int_0^T [x(t)'Qx(t) + u(t)'Ru(t)]dt\right]\right\}, \tag{5}$$

where the parameter matrices S, Q and R could be directly obtained from (4). The detailed explanation of such formulation is introduced as follows.

In cost function (5), for the frequency stabilization issue, the terminal frequency deviation and the running costs are expected to be minimized. In this sense, a terminal condition is considered in formulating the cost functional of the optimization problem, which refers to the term $x(T)'Sx(T)$. To make sure that all MGs' AC bus frequency could be regulated well during time $[0, T]$, minimizing the term $\int_0^T [x(t)'Qx(t)]dt$ is taken into consideration.

On the other hand, a strong controller is possible to achieve frequency stability, but an over-strong controller might bring extra operation cost. The situation of over-control might reduce the service life of controllable electric devices [5]. Besides, due to the bottom-up energy management principle introduced in [12], the power transmitted via ERs is not expected to be relatively large. Thereby, it is necessary to set some constraints with respect to the size of control input signals. In this sense, minimizing the term $\int_0^T [u(t)'Ru(t)]dt$ has been set in the cost functional.

It is notable that in the setting of risk-sensitive control problem, objective function can be enlarged exponentially, which is different from the LQ control criterion. In this paper, the targets of regulating frequency deviation and constraining the size of control input are emphasized, which is the reason for setting the risk-sensitive type cost function.

More specifically, small deviations of frequency would result in large value of cost function (4). In this sense, the impact from the stochastic character of power of PVs, WTGs and loads on frequency stability could be amplified. The obtained optimal controller would take the magnitude of the stochastic terms, i.e., C, in to consideration, such that the frequency deviations could be alleviated more efficiently.

C. Solution to Risk-Sensitive Control Problem

In this sense, the EI system management issue has been transformed into an optimization problem as follows,

$$\begin{cases} \min\limits_{u(\cdot)} \ J(u(\cdot)), \\ s.t. \quad (3). \end{cases} \tag{6}$$

This is known as the stochastic risk-sensitive control problem and has been extensively studied in e.g., [19], [20]. Before we present the main result, an assumption is introduced.

Assumption 1. $R > 0$ *is satisfied, and the following Riccati equation has a unique global solution. (time* t *omitted)*

$$\dot{P} + Q + PA + A'P - P(BR^{-1}B' - \gamma CC')P = 0.$$

The solution to problem (5) is provided in Theorem 1.

Theorem 1. [20] *Let Assumption 1 hold. Then, there exists a unique solution to optimization problem (6), and the desired optimal controller is*

$$u(t)^* = -R^{-1}B'P(t)x(t).$$

IV. SIMULATIONS

In this section, the effectiveness of the risk-sensitive control method employed in this paper is evaluated with several case studies. In simulation, an EI system consisting of four MGs is investigated, with its structure shown in Fig. 2.

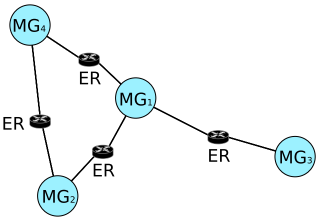

Figure 2. The EI topology for simulation.

Typical system parameters for MG dynamical systems in (1) and (2) are given in Table I. During the simulation, the parameters for the considered four MGs are obtained from the product of typical values and scaling factors generated from the uniform distribution on [0.8,1.3].

TABLE I. SYSTEM PAEAMETERS

Parameter	Value	Parameter	Value	Parameter	Value
r_{PV}	17.9	r_{WTG}	15.8	r_L	28.6
s_{PV}	0.3	s_{PV}	0.4	s_L	0.26
T_{MT}	0.02	T_{FC}	0.03	T_{BES}	0.01
T_{ER}	0.10	M	0.018	D_3	2.1

A. *Case I*

In this case, the effectiveness of the risk-sensitive control approach for the EI system is evaluated. The coefficients in (4) is set to be $q = 1.0$ and $r = 0.001$. The power deviations of PVs, WTGs and loads in a MG are shown in Fig. 3 in which stochastic nature of their output power is properly represented by SDEs.

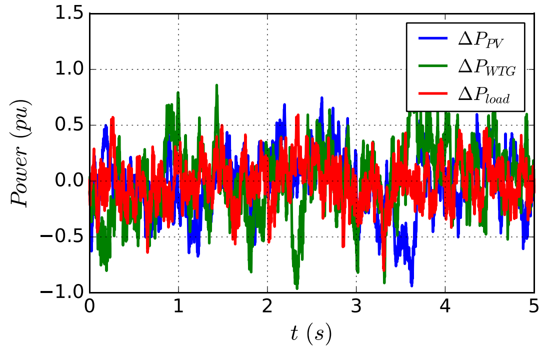

Figure 3. Typical power deviations of PVs, WTGs and loads.

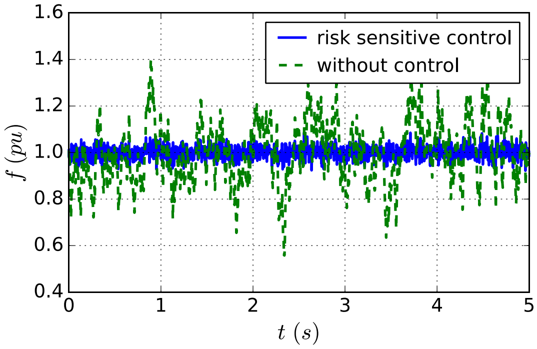

Figure 4. Frequency deviations in MG_1.

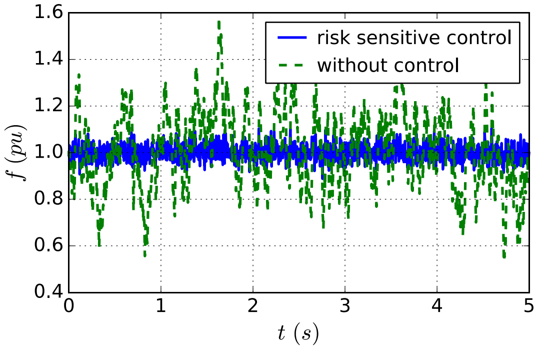

Figure 5. Frequency deviations in MG_2.

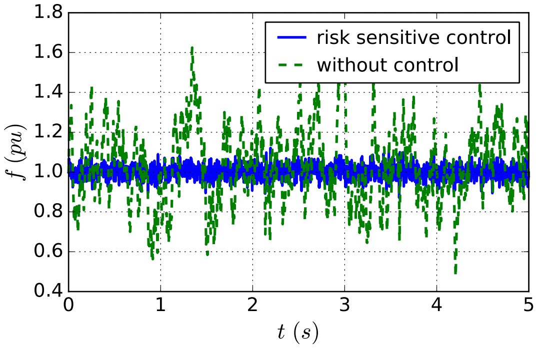

Figure 6. Frequency deviations in MG_3.

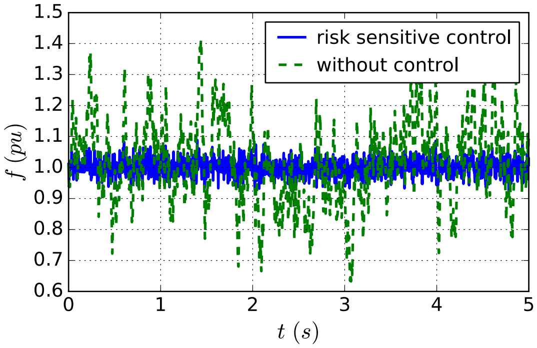

Figure 7. Frequency deviations in MG_4.

For the frequency regulation issue, the frequency deviations in the considered four MGs under risk-sensitive control method is compared with that when no controller is applied. The corresponding results are shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7, respectively. It is clear that the risk-sensitive control approach has excellent frequency regulation performance. The frequency deviations in all four MGs are restricted within a small range.

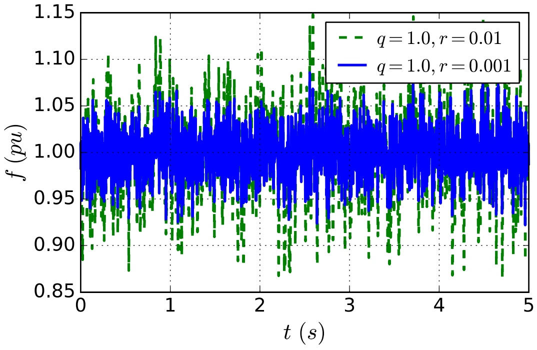

Figure 8. Frequency deviations in MG_1.

B. *Case II*

In this case, the impact of the coefficient r in (4) on the control effect is studied. Two pairs of coefficients $q = 1.0, r = 0.001$ and $q = 1.0, r = 0.01$ are used for comparison. Firstly, the frequency regulation performance is compared. The deviations of AC bus frequency in four MGs are illustrated in Fig 8, Fig, 9, Fig. 10 and Fig. 11, respectively. We can find that both of the tested controllers are able to regulate the frequency deviation into a reasonable range. However, with a smaller r, i.e., $r = 0.001$, the magnitude of control signals would be considered less in the cost functional, which would potentially improve the frequency regulation performance.

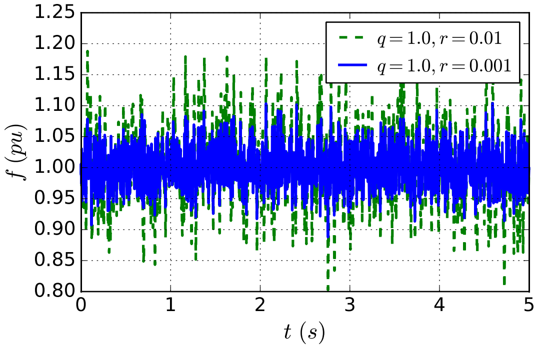

Figure 9. Frequency deviations in MG_2.

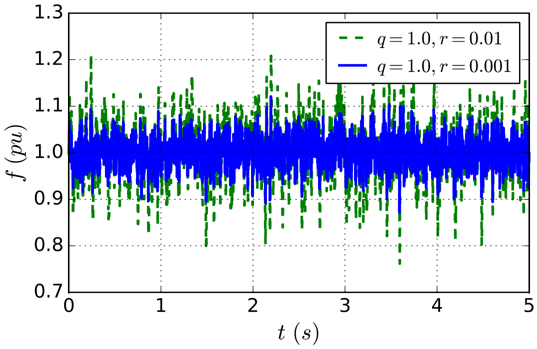

Figure 10. Frequency deviations in MG_3.

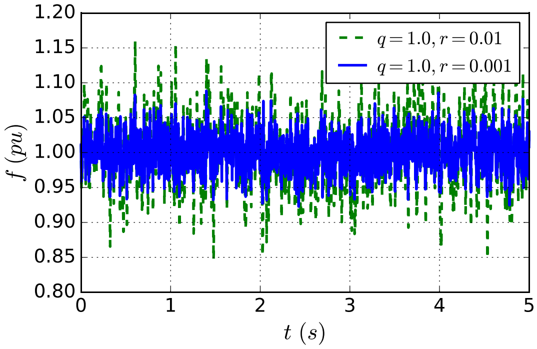

Figure 11. Frequency deviations in MG_4.

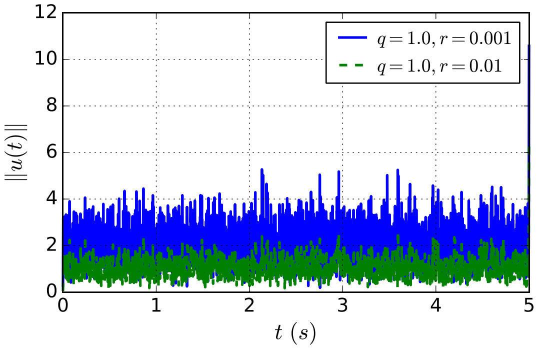

Figure 12. Norm of control signals with different parameters.

Additionally, the 2-norm of the obtained controllers with different parameters are plotted in Fig. 12. We can find that, with larger valued r, the magnitude of the controllers is effectively constrained.

C. *Case III*

Similar as Case II, in this case, the effectiveness of the controller parameter q is investigated. With $q = 1.0, r = 0.001$ and $q = 10.0, r = 0.001$, two risk-sensitive controllers are obtained based on Theorem 1. The frequency deviations in four MGs under these two controllers are shown in Fig 13, Fig, 14, Fig. 15 and Fig. 16, respectively.

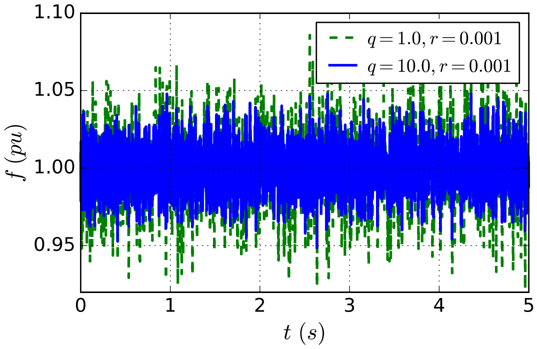

Figure 13. Frequency deviations in MG_1.

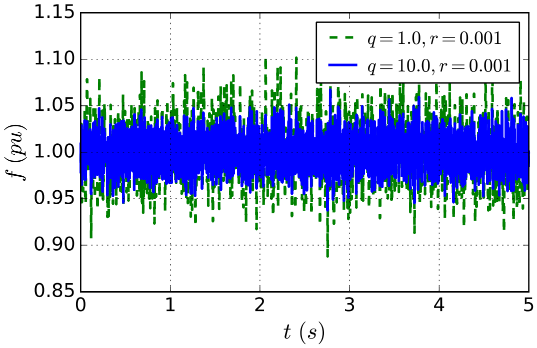

Figure 14. Frequency deviations in MG_2.

We can find that, a larger q would emphasize the impact from AC bus frequency deviations on cost functional, which would lead to stronger risk-sensitive controller. In this sense, the frequency deviations could be better regulated.

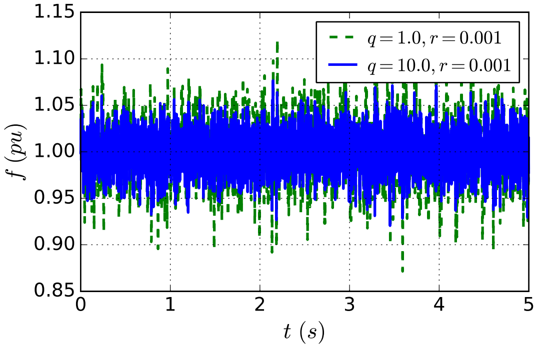

Figure 15. Frequency deviations in MG_3.

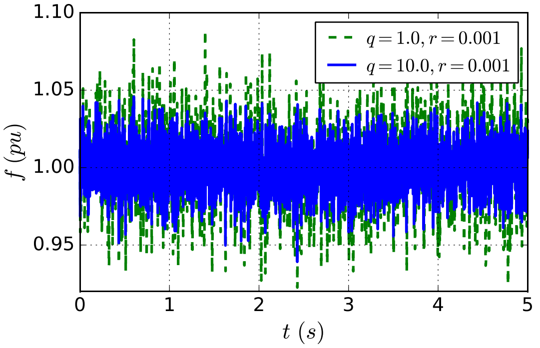

Figure 16. Frequency deviations in MG_4.

The norms of the controllers with different parameters in Fig. 17 suggests the similar conclusion as well.

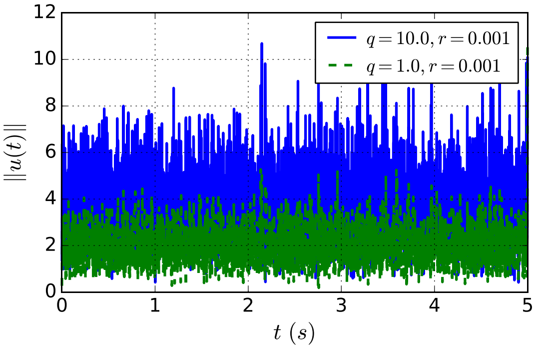

Figure 17. Norm of control signals with different parameters.

V. CONCLUSION

In this paper, the risk-sensitive control approach has been utilized in the system management issue in the field of EI. A linear state-feedback controller is obtained, such that an optimal control effect can be achieved. The theoretical results are verified via numerical simulations.

It is notable that one shortcoming of this work is that in order to obtain linear differential equations as power dynamics of the EI, some approximation has to be performed, which makes the obtained results not accurate. In the future, techniques based on neural networks shall be implemented. Instead, we shall be able to solve the optimization problem with real-world data from PVs, WTGs and loads directly, without establishing explicit mathematical formulas for EI dynamics.

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