Stochastic Optimal Control Scheme for Operation Cost Management in Energy Internet

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***Abstract*—By integrating power flows and information bi-directly, energy Internet (EI) is regarded as an internet style solution for energy issues, and it has been considered as a promising architecture for the future energy systems. In this paper, we consider the optimal operation cost management problem for a generalized EI topology which is composed of multiple interconnected AC microgrids (MGs) and energy routers (ERs). We assume that all the MGs are composed of wind turbine generators (WTGs), photovoltaic (PV) units, fuel cells (FCs), micro turbines (MTs), battery energy storage (BES) devices, and loads. Multiple topologies of EI are discussed and a generalized one is studied for mathematical system modelling. A group of ordinary differential equations (ODEs) and stochastic differential equations (SDEs) are utilized to describe the dynamics of each component within the whole EI. The controllers are set in MTs, FCs and ERs. We consider the operation cost of EI as a combination of four parts: the cost of BES devices, the power transmission loss between the interconnected MGs, the risk from AC bus frequency deviation and the additional cost involved by the controllers. Then the cost optimization problem is formulated as a stochastic control problem which is solved numerically. The effectiveness of the obtained optimal controllers is illustrated through numerical simulations.**

Index Terms*—energy internet; differential equations; microgrids; optimal control; stochastic systems

I. INTRODUCTION

Due to the gradual increase of difficulty in locating and distilling fossil fuels, it is forecasted that the cost of energy shall increase significantly in the next couple of decades [1], [2]. The increasing cost and demand of energy, ecological issues, and economic influences are urging an essential transformation and upgrading for the global energy infrastructure in which distributed renewable energy sources are introduced to the existing grid [3], [4].

To solve the aforementioned challenges, recently, the new concept of an energy internet (EI) is proposed as the 2.0 version of smart grids [5]-[7]. Within the scenario of EI, microgrids (MGs) are designed to be interconnected via energy routers (ERs) which are also known as energy exchange devices, or energy hubs [8]-[10]. Inspired by the core of Internet, EI integrates flows of information and energy bi-directionally [6]. Within the scenario of EI, power balance of each individual MG is expected to be achieved autonomously with first priority, and if the local MG's power balance is hard to be achieved, then the wide area network (WAN) power routing strategy shall be implemented, such that the whole EI achieves power balance [6], [11].

In the field of smart grid and conventional power system, the problem of operation cost management has been widely investigated; see, e.g., [12]-[17], and the references therein. For example, the optimal energy management issue in MGs is formulated and solved as a multi-objective stochastic optimization problem in [12]. Nonlinear droop relations are utilized to achieve an optimal operation of islanded MGs via particle swarm optimization approach in [13]. One kind of stochastic continuous time model for MG energy management is studied in [14]. A cooperative optimal control strategy for the MG under both grid-connected and islanded modes is investigated in [15]. In [16], researchers consider the economic dispatch of distributed power generation as an optimal control problem in DC MGs. In [17], the optimal energy management problem is considered with the guarantee of AC bus frequency regulation in an islanded MG. Within the scenario of EI, the energy management issue and its related optimal control problems have not been fully investigated, particularly when ERs and large numbers of distributed renewable energy resources (e.g., solar power, wind power, etc.) are introduced into EI.

In this paper, we study a generalized scenario of EI which is composed of multiple AC MGs interconnected by ERs. Each MG includes: wind turbine generators (WTGs), photovoltaic (PV) units, fuel cells (FCs), micro turbines (MTs), battery energy storage (BES) devices, and loads. We focus on developing a series of controllers within FCs, MTs and ERs, such that the operation cost for the whole EI is minimized. We model the dynamics of the generalized EI into a group of ordinary differential equations (ODEs) and stochastic differential equations (SDEs). The cost is mainly formulated with respect to four parts: 1) the cost of BES devices, 2) the transmission loss between the interconnected MGs, 3) the risk from frequency deviation in AC bus of each MG, 4) the additional cost involved by the controllers. Then, the physical energy management issue in EI is successfully transformed into a stochastic optimal control problem which can be solved via the completion of square method [18]. The contribution of this article can be summarized as follows.

- This is the very *first* time that the operation cost (including the cost of BES devices, the transmission loss, the risk from AC bus frequency deviation and the

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additional cost involved by the controllers) optimization problem within the scenario of EI is considered.

- The EI dynamics are formulated based on multiple typical EI topologies, and we study a general mathematical system for all the EI dynamics.
- A deep learning approximation approach for stochastic control problems is applied to obtain a sub-optimal solution.

The rest of the paper is organized as follows: Section II introduces the EI system modelling. Problem formulation and solutions are introduced in Section III. In Section IV, numerical examples are illustrated. Finally, Section V concludes the paper.

II. SYSTEM MODELING OF ENERGY INTERNET

In this section, we introduce some typical topologies of EI consisting of AC MGs and ERs. Both ODEs and SDEs are utilized to describe the dynamics of each component in EI.

A. Series-Shaped Topology

In this subsection, we focus on a series-shaped EI topology in which n AC MGs (marked as MG_1, MG_2, …, MG_n) connected end-to end [11], as shown in Fig.1. For illustrative purposes, we assume that in the i-th MG, i.e., MG_i, there exists one local load device, one PV unit, one WTG, one MT, one FC and one BES device (denoted as L_i, PV_i, WTG_i, MT_i, FC_i and BES_i, respectively) interconnected via one AC bus. DC-AC converters and AC-DC converters are designed in the MG_i, ensuring that electricity is transformed into DC form before it is transmitted via the interconnected MGs. In this sense, AC bus frequency deviation in each MG is independent. Throughout this paper, any ER that connects MG_i and MG_{i+1} is denoted as $ER_{i,i+1}$, and it integrates controllers and converters. The notation $\mathrm{ER}_{i,j}$ indicates that power flows from MG_i to MG_j.

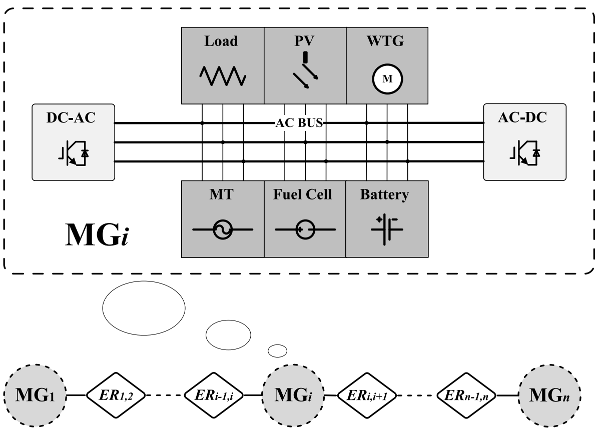

Figure 1. Series-Shaped Structure of EI.

In MG_i, we assume that BES_i is equipped with internal controllers and responds to the AC bus frequency deviation (denoted as Δf_i). Besides, we denote the power change of L_i, PV_i, WTG_i, MT_i, FC_i and BES_i, as ΔP_{L_i}, ΔP_{PV_i}, ΔP_{WTG_i}, ΔP_{MT_i}, ΔP_{FC_i} and ΔP_{BES_i}, respectively. The power change transmitted from MG_i to MG_{i+1} (also known as power change of $\mathrm{ER}_{i,i+1}$) is denoted as $\Delta P_{ER_{i,i+1}}$. In consideration of the stochastic nature of power dynamics of PV units, WTGs and loads, we use Brownian motions $w_{PV_i}(t)$, $w_{WTG_i}(t)$ and $w_{L_i}(t)$ to describe their randomness, respectively. We denoted the control inputs of MT_i, FC_i and $\mathrm{ER}_{i,i+1}$ as $u_{MT_i}(t)$, $u_{FC_i}(t)$ and $u_{ER_{i,i+1}}(t)$, respectively. By referring to previous literatures, e.g., [17], [19], [20], we obtain the power dynamics of all the components in EI with a group of ODEs and SDEs, as shown in (1) and (2) (time t omitted).

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

$$\begin{cases} \Delta\dot{P}_{ER_{i,i+1}} = -\frac{1}{T_{ER_{i,i+1}}}\Delta P_{ER_{i,i+1}} + \frac{1}{T_{ER_{i,i+1}}}b_{ER_{i,i+1}}u_{ER_{i,i+1}} \\ \Delta P_{ER_{n,n+1}} = 0, \qquad i = 1,2\ldots n, \end{cases} \quad (2)$$

where T_{L_i}, T_{PV_i}, T_{WTG_i}, T_{MT_i}, T_{FC_i}, T_{BES_i} and $T_{ER_{i,i+1}}$ stand for time constants of their corresponding corner marks. Scalars M_i and D_i stand for the inertia constants and the damping coefficients of frequency deviation Δf_i, respectively. System coefficients r_{L_i}, r_{WTG_i}, r_{PV_i}, r_{BES_i}, b_{FC_i}, b_{MT_i}, $b_{ER_{i,i+1}}$ depend on real engineering scenarios, and their values can be measured by parameter estimation methods. Let us denote the power change of AC bus in MG_i as ΔP_i. According to the desired power balance requirement for each MG_i, we have (time t omitted)

$$\Delta P_i = \Delta P_{PV_i} + \Delta P_{WTG_i} + \Delta P_{BES_i} + \Delta P_{MT_i} + \Delta P_{FC_i} + \Delta P_{ER_{i-1,i}} - \Delta P_{L_i} - \Delta P_{ER_{i,i+1}}. \quad (3)$$

B. A Genralized EI Topology

It is reported in [11] that the series-shaped EI structure may lead to high operation costs. Another common topology of EI is the so-called annular structure [11]. A simple annular connection topology is shown in Fig.2 where three MGs are interconnected as a ring via ERs.

Within the three-transmission line power, we assume that energy flows from MG_1 to MG_2, from MG_1 to MG_3, and from MG_2 to MG_3. In this case, we use differential equations (1) and

(4) to describe the dynamics of these three MGs and ERs in Fig. 2. In this model, we have $i, j \in \{1,2,3\}$.

$$\Delta\dot{P}_{ER_{i,j}} = -\frac{1}{T_{ER_{i,j}}}\Delta P_{ER_{i,j}} + \frac{1}{T_{ER_{i,j}}} b_{ER_{i,j}} u_{ER_{i,j}} \tag{4}$$

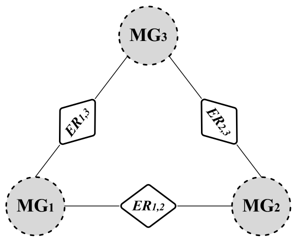

Figure 2. Annular connection of MGs.

Different from the model proposed in Subsection A, the power change of AC bus in MGs cannot be described by the form of (3). Based on the power flow hypothesis, we describe each MG's power deviation (ΔP_1, ΔP_2 and ΔP_3) as (5) (time t omitted).

$$\begin{cases} \Delta P_1 = \Delta P_{PV_1} + \Delta P_{WTG_1} + \Delta P_{BES_1} + \Delta P_{MT_1} + \Delta P_{FC_1} \\ \qquad -\Delta P_{L_1} - \Delta P_{ER_{1,2}} - \Delta P_{ER_{1,3}}, \\ \Delta P_2 = \Delta P_{PV_2} + \Delta P_{WTG_2} + \Delta P_{BES_2} + \Delta P_{MT_2} + \Delta P_{FC_2} \\ \qquad -\Delta P_{L_2} + \Delta P_{ER_{1,2}} - \Delta P_{ER_{2,3}}, \\ \Delta P_3 = \Delta P_{PV_3} + \Delta P_{WTG_3} + \Delta P_{BES_3} + \Delta P_{MT_3} + \Delta P_{FC_3} \\ \qquad -\Delta P_{L_3} + \Delta P_{ER_{1,3}} + \Delta P_{ER_{2,3}}. \end{cases} \tag{5}$$

If the system stability of one particular MG can be ensured, in the sense that its frequency stability is better than that of the other MGs, a star-shaped topology could be used to form an EI [11], as shown in Fig. 3. In this case, MG_1 not only guarantees the power balance of itself, but also maintains the system stability of the remaining interconnected MGs. We use (1), (4) and (6) to describe the dynamics of such component in EI scenario. The robustness of the whole EI system relies heavily on MG_1. The failure of MG_1 may cause the whole system blackout, if the remaining MGs cannot provide enough power. This is regarded as a limitation of the star-shaped topology.

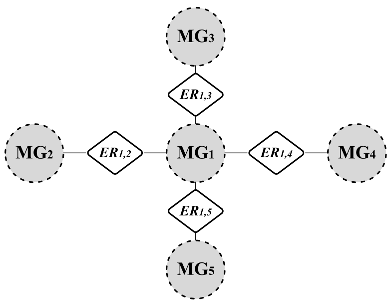

Figure 3. Star-shaped topology of EI.

$$\begin{cases} \Delta P_1 = \Delta P_{PV_1} + \Delta P_{WTG_1} + \Delta P_{BES_1} + \Delta P_{MT_1} + \Delta P_{FC_1} \\ \qquad -\Delta P_{L_1} - \Delta P_{ER_{1,2}} - \Delta P_{ER_{1,3}} - \Delta P_{ER_{1,2}} - \Delta P_{ER_{1,3}}, \\ \Delta P_i = \Delta P_{PV_i} + \Delta P_{WTG_i} + \Delta P_{BES_i} + \Delta P_{MT_i} + \Delta P_{FC_i} \\ \qquad -\Delta P_{L_i} + \Delta P_{ER_{1,i}}, \qquad i = 2, 3, 4, 5. \end{cases} \tag{6}$$

In Fig. 4, we give an example of a generalized EI topology based on annular connections of multiple MGs. Each MG is connected with at least two other ones, ensuring that the EI system shall be able to operate normally even if failure occurs in any MG or ER. Let us consider a case in which MG_k is about to be connected to the existing EI, and it is connected with the two adjacent MGs, for example, MG_i and MG_j, via $\text{ER}_{i,k}$ and $\text{ER}_{j,k}$, respectively. In this scenario, energy between any two MGs can be transmitted following multiple paths.

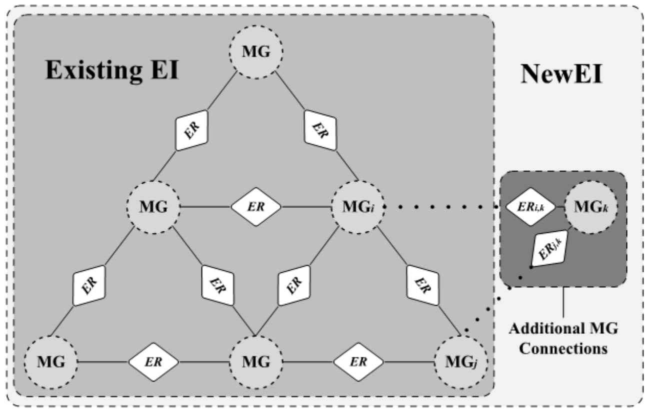

Figure 4. A genralized EI topology.

Let H be the set of numbers of MGs transmiting energy directly to MG_i, and G be the set of numbers of MGs receiving energy directly from MG_i. We can describe the dynamics of the genralized EI topology with (1), (4) and (7).

$$\begin{aligned} \Delta P_i = {} & \Delta P_{PV_i} + \Delta P_{WTG_i} + \Delta P_{BES_i} + \Delta P_{MT_i} + \Delta P_{FC_i} \\ & -\Delta P_{L_i} + \sum_{h \in H} \Delta P_{ER_{h,i}} - \sum_{g \in G} \Delta P_{ER_{i,g}}. \end{aligned} \tag{7}$$

III. PROBLEM FORMULATION AND SOLUTION

In this section, we formulate a stochastic optimal control problem to minimize the EI operation cost. In addition, we provide a numerical solution to our stochastic optimization problem.

A. Stochastic Optimal Control Problem Formulation

It can be seen that (5), (6) and (7) describing different EI topologies are essentially the same. For illustrative purpose, we provide the mathematical system modeling and stochastic optimization problem formulation based on a series-shaped EI model. For notation simplicity, let us denote: (time t omitted)

$$
\begin{aligned}
x_L &= [\Delta P_{L_1} \quad \Delta P_{L_2} \quad \cdots \quad \Delta P_{L_n}]',\\
x_{PV} &= [\Delta P_{PV_1} \quad \Delta P_{PV_2} \quad \cdots \quad \Delta P_{PV_n}]',\\
x_{WTG} &= [\Delta P_{WTG_1} \quad \Delta P_{WTG_2} \quad \cdots \quad \Delta P_{WTG_n}]',\\
x_{MT} &= [\Delta P_{MT_1} \quad \Delta P_{MT_2} \quad \cdots \quad \Delta P_{MT_n}]',\\
x_{FC} &= [\Delta P_{FC_1} \quad \Delta P_{FC_2} \quad \cdots \quad \Delta P_{FC_n}]',\\
x_{BES} &= [\Delta P_{BES_1} \quad \Delta P_{BES_2} \quad \cdots \quad \Delta P_{BES_n}]',\\
x_f &= [\Delta f_1 \quad \Delta f_2 \quad \cdots \quad \Delta f_n]',\\
x_{ER} &= [\Delta P_{ER_{1,2}} \quad \Delta P_{ER_{2,3}} \quad \cdots \quad \Delta P_{ER_{n-1,n}}]',\\
u_{MT} &= [u_{MT_1} \quad u_{MT_2} \quad \cdots \quad u_{MT_n}]',\\
u_{FC} &= [u_{FC_1} \quad u_{FC_2} \quad \cdots \quad u_{FC_n}]',\\
u_{ER} &= [u_{ER_{1,2}} \quad u_{ER_{2,3}} \quad \cdots \quad u_{ER_{n-1,n}}]'.
\end{aligned}
$$

Introducing $x = [x_L, x_{PV}, x_{WTG}, x_{MT}, x_{FC}, x_{BES}, x_f, x_{ER}]'$, and $u = [u_{MT}, u_{FC}, u_{ER}]'$, we obtain a state space system as shown in (8) (time t omitted).

$$
\begin{cases} \mathrm{d}x = (Ax + Bu)\mathrm{d}t + \sum_{i=1}^{m} (C_i x + D_i)\mathrm{d}w_i(t), \\ x(0) = x_0. \end{cases} \tag{8}
$$

To minimize the operation cost of EI, extending the lifetime of the BES devices is essential, since they are relatively expensive [20]. As over-charge and over-discharge would reduce the lifetime of BES devices [20], mathematically, the value of $\int_0^T \sum_{i=1}^n \Delta P_{BES_i}^2 \, dt$ shall be minimized [17].

In an EI, HVDC technology is widely used in power transmission between two interconnected MGs. Since electric energy has to be transformed into high voltage direct current before transmission, the power loss caused by AC-DC transformation, DC-AC transformation and voltage level change can be regarded as one of the main operating cost of the EI [21]. In our considered model, we use power change of $ER_{i,i+1}$ to characterize the power change of the dynamic transmission process between MG_i and MG_{i+1}, denoted as $\Delta P_{ER_{i,i+1}}$. In this sense, $\int_0^T \sum_{i=1}^n \Delta P_{ER_{i,i+1}}^2 \, dt$ also needs to be controlled to a relatively low level.

On the other hand, the power balance of each AC MG is the premise of safety operation. Thus, large power deviation of AC bus frequency shall be avoided [22]. So, the value of $\int_0^T \sum_{i=1}^n \Delta f_i^2 \, dt$ shall be kept in a small scale.

Besides, in practical engineering scenario, the sizes of controllers designed in MTs, FCs and ERs are limited by the parameters of the power electronic device. Oversized u_{MT_i}, u_{FC_i} and $u_{ER_{i,i+1}}$ may cause excessive loss of MTs, FCs and ERs [17]. Thus, the sum of the values of $\int_0^T \sum_{i=1}^n u_{MT_i}^2 \, dt$, $\int_0^T \sum_{i=1}^n u_{FC_i}^2 \, dt$ and $\int_0^T \sum_{i=1}^n u_{ER_{i,i+1}}^2 \, dt$ shall not be large.

Consider a finite time period from time 0 to time T, based on the above discussion, our aim is to minimize the sum of k_x and k_u defined in (9) and (10), respectively, in addition to the terminal conditions (11).

$$
k_x(t) = \sum_{i=1}^{n} \left[\left(\varepsilon_1 \Delta P_{BES_i}^2 + \varepsilon_2 \Delta P_{ER_{i,i+1}}^2 + \varepsilon_3 \Delta f_i^2 \right) \right], \tag{9}
$$

$$
k_u(t) = \sum_{i=1}^{n} \left[\varepsilon_4 \left(u_{MT_i}^2 + u_{FC_i}^2 + u_{ER_{i,i+1}}^2 \right) \right], \tag{10}
$$

$$
K_T = \sum_{i=1}^{n} \left[\varepsilon_1 \Delta P_{BES_i}^2(T) + \varepsilon_2 \Delta P_{ER_{i,i+1}}^2(T) + \varepsilon_3 \Delta f_i^2(T) \right]. \tag{11}
$$

where scalars ε_1, ε_2, ε_3 and ε_4 are system weighting coefficients. We define the cost function $J(0, x_0; u)$ by (12).

$$
J(0, x_0; u) = \mathbb{E}\left\{ \int_0^T [k_x(t) + k_u(t)] dt + K_T \right\}. \tag{12}
$$

The problem of minimizing the operation cost in EI equals to finding an optimal solution u^* such that $J(0, x_0; u)$ is minimized subject to system (8).

B. *Problem Solution*

Let us rewrite the cost function $J(0, x_0; u)$ in the form of a linear quadratic control (LQ) problem's criteria as follows:

$$
J(0, x_0; u) = \mathbb{E}\left\{ \int_0^T [x(t)'Qx(t) + u(t)'Ru(t)] \, dt + x(T)'Hx(T) \right\}. \tag{13}
$$

The stochastic optimal control problem (minimizing (13) subject to (8)) is solved with the deep learning approximation approach introduced in [23]. In this approach, the continue-time system (8) is converted into a discrete-time system. At each time step, a multi-layer perceptron with batch normalization layers is used to obtain the controller corresponding to the system state. With the approximation ability of neural networks, we are able to overcome the *curse of dimensionality*. Since the neural network is trained with stochastic gradient descent method, the controller obtained is usually a sub-optimal solution to the considered stochastic control problem.

IV. NUMERICAL SIMULATION

To show the feasibility of our proposed method, in this section, some numerical simulations are studied within a three-MG series-shaped EI topology for illustrative purpose.

Fig.1 with (1)-(3) can be used to describe such special scenario properly. In this sense, we have $n = 3$. The system parameters are shown in Table I according to practical engineering scenarios. We assume that, the value of weighting coefficients ε_1, ε_2, ε_3 and ε_4 in the cost function (12) is 10, 150, 500 and 14, respectively. The initial state x_0 of the system is a zero vector.

TABLE I. SYSTEM PAEAMETERS

Parameter	Value	Parameter	Value	Parameter	Value
T_{L_1}	1.3	T_{L_2}	3.8	T_{L_3}	2.4
T_{PV_1}	1.8	T_{PV_2}	1.1	T_{PV_3}	1.5
T_{WTG_1}	2.3	T_{WTG_2}	2.2	T_{WTG_3}	1.7
T_{MT_1}	0.14	T_{MT_2}	1.2	T_{MT_3}	1.9
T_{FC_1}	0.16	T_{FC_2}	0.8	T_{FC_3}	0.9
T_{BES_1}	0.11	T_{BES_2}	0.16	T_{BES_3}	0.13
r_{L_1}	1.9	r_{L_2}	1.7	r_{L_3}	1.8
r_{PV_1}	1.6	r_{PV_2}	1.4	r_{PV_3}	1.5
r_{WTG_1}	1.9	r_{WTG_2}	1.9	r_{WTG_3}	1.7
b_{MT_1}	2.5	b_{MT_2}	3.1	b_{MT_3}	2.9
b_{FC_1}	2.6	b_{FC_2}	2.4	b_{FC_3}	2.2
r_{BES_1}	1.0	r_{BES_2}	0.9	r_{BES_3}	1.1
D_1	0.002	D_2	0.005	D_3	0.008
M_1	2.2	M_2	2.3	M_3	2.0
$T_{ER_{1,2}}$	0.9	$b_{ER_{1,2}}$	1.9	s_{L_1}	0.4
$T_{ER_{2,3}}$	0.9	$b_{ER_{2,3}}$	1.2	s_{PV_1}	0.4
s_{WTG_1}	0.4	s_{L_2}	0.4	s_{PV_2}	0.4
s_{WTG_2}	0.4	s_{L_3}	0.4	s_{PV_3}	0.4
s_{WTG_3}	0.4				

The following results are obtained via *Python*. Fig. 5 shows the stochastic power deviations of loads, PV units and WTGs in the EI system, all of which have relatively strong randomness.

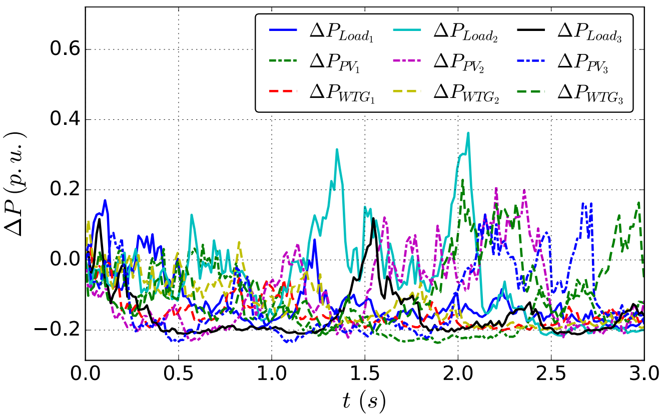

Figure 5. Power deviations of loads, PV units and WTGs.

To show the efffectiveness of the sub-optimal controller u^* obtained with the solution introduced in Section III-B, frequency deviations of the AC bus in each MG with and without the sub-optimal controllers are shown in Fig. 6. The frequnecy deviations in MGs under controller u^* are denoted as $\Delta f_1^*, \Delta f_2^*$ and Δf_3^*, respectively. While the frequency deviations without controlling are denoted as Δf_1^0, Δf_2^0 and Δf_3^0. The results presented in Fig. 6 show that the frequency deviations are effectively regulated when controller u^* is implemented to the system. In Fig. 7 and Fig. 8, we see that power deviations of BES devices and ERs are controlled within a relatively low level successfully.

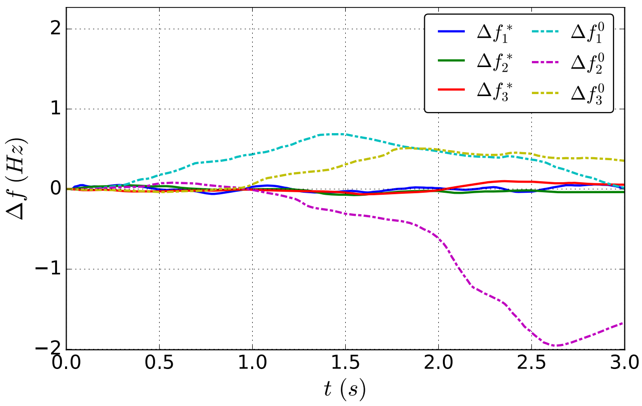

Figure 6. Frequency deviations.

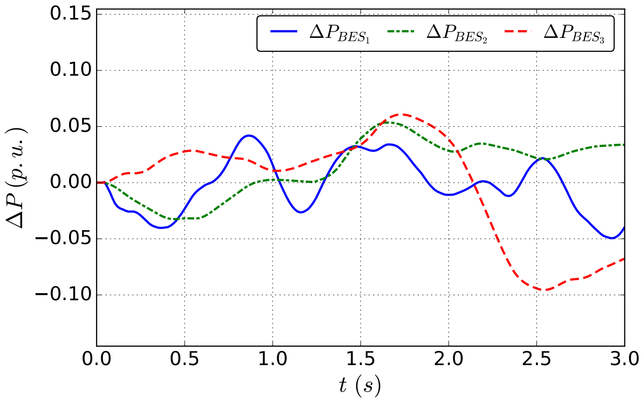

Figure 7. Power deviations of BES devices.

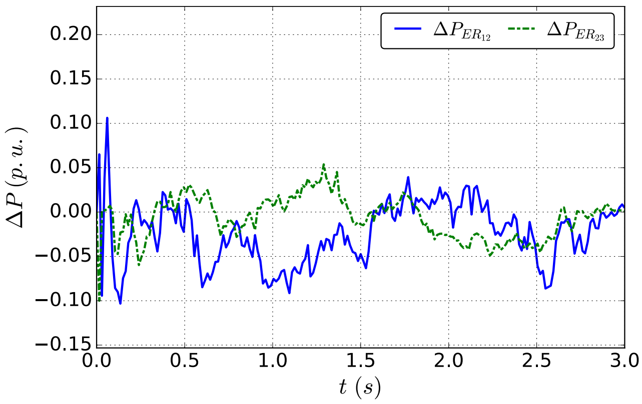

Figure 8. Power deviations of ERs.

In Fig. 9, according to the presented power deviation of MTs and FCs, we claim that over control is avoided.

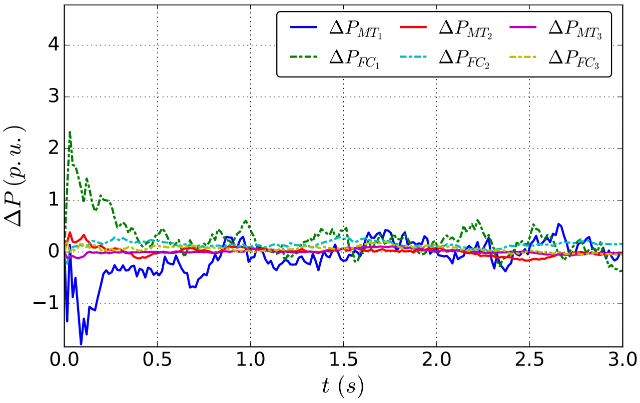

Figure 9. Power deviations of MTs and FCs.

Based on the above simulation results, we claim that the obtained sub-optimal controller successfully achieves the predesigned control target.

V. Conclusion

In this paper, a stochastic optimal control scheme is investigated for the problem of operation cost management in EI. The physical EI scenario is modeled as a stochastic dynamic system, and the operation cost includes cost of BES devices, the transmission loss, the risk from AC bus frequency deviation and the additional cost involved by the controllers. Such stochastic optimal control problem is solved numerically. In the future, we shall study the operation cost optimization problem for EI in which the communication time delay and system parameter uncertainties are taken into consideration.

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