ENERGY MANAGEMENT OF MICROGRID WITH EMISSION LIMITATIONS UNDER UNCERTAINTY

Amir ABDOLLAHI
SKED CO[1] – Iran
a.abdollahi@uk.ac.ir

Abdolvahid MAHDAVINIA
SKED CO – Iran
Avmnia@yahoo.com

Hooman KHALOIE
SBUK[2] – Iran
h,khaloie@eng.uk.ac.ir

Mehran MOHAMMADNEJAD
SBUK – Iran
m.mohammadnejad@eng.uk.ac.ir

ABSTRACT

This paper introduces an enhanced energy management framework providing an optimal operation strategy in a microgrid (MG). This framework is able to provide the required energy for variable loads with the objective function of minimizing energy cost and greenhouse gas (GHG) emission. The energy cost in the problem formulation is considered as the cost of providing energy by MGs own distributed energy resources(DERs) and energy storage systems (ESSs) and the cost of exchanged power with the upstream grid. In such conditions, the output power of resources such as wind turbines (WTs) and photovoltaics (PVs) is uncertain. We have considered the uncertainties associated with PV and WT output power through using a point estimate method (PEM). The proposed energy management framework is formulated for a daily load demand profile. The proposed model has been implemented in GAMS software. The model is validated through a test system and the outcomes illustrate the advantages, applicability, and challenges of utilizing the proposed model. After applying this framework on a typical MG, the optimum power allocation of DERs (such as CHP, FC, PV, and WT), ESSs and exchanged power with the upstream grid is obtained.

INTRODUCTION

Nowadays, microgrids (MGs) play an essential role in achieving a higher level of reliability, resiliency, energy efficiency and power quality in power systems [1]. A microgrid is a group of interconnected loads and distributed energy resources (DERs) that can either be connected or only benefit from its own DERs and energy storage systems (ESSs) in disconnected mode [2]. Various types of DERs such as CHPs (combined heat and power), FCs (fuel cells), PVs (photovoltaic) and WTs (wind turbines) can be used in MGs to reduce operational cost and greenhouse gas (GHG) emission. In such conditions, proposing a coordinated energy management framework for supplying MG load with upstream grid seems crucial. For this purpose, an energy management framework can determine the optimal power allocation of DERs, ESSs and exchanged power from the main grid. In this regard, in [3] authors have proposed a microgrid energy management method to specify the optimal strategy of electricity and heat generation, purchases, sales, and consumptions. The authors have benefited from various tasks to diminish the operational cost. In [4], EV batteries have been used as energy storage systems in managing energy consumption and generation of a grid-connected microgrid. in this work, an inhomogeneous continuous-time Markov chain method has been applied to deal with the uncertainty of available capacity of parking lots. In [5], and IGDT-based framework is developed to address the energy management problem of a sample microgrid. The upstream grid price is considered as the uncertain parameter which is modeled using IGDT. This paper presents a novel probabilistic framework for energy management of a microgrid with respect to emission limitations. For this purpose, the uncertainty associated with real-time energy market price, WTs and PVs power output are covered using a PEM.

METHODOLOGY

The considered MG contains WT, PV, FCs, CHP, and ESS. Our framework attempts to present an optimal economic/environmental power dispatch while the optimal power trading with the upstream grid is in the model. In MG energy management system, we seek to supply electrical load while concerning about GHG emission limitations. In order to minimize the total operating cost of the MG, an appropriate binary 0/1 state is applied into DERs. As mentioned before, the uncertain parameters of our problem are real-time energy market price, WTs and PVs output power which are modeled using 2m+1 PEM. The concept of PEM is described in the following section.

THE 2M+1 POINT ESTIMATE METHOD

PEM is used when the probability function of an uncertain input variable is not completely valid due to lack of information. Therefore, these probability functions can be approximated by means of few statistical moments of the uncertain input variables (i.e., mean, variance, …), a fewer level of information would be needed. 2m PEM and 2m+1 PEM are two types of point estimate method which have widely been employed to handle the uncertainties associated with input random

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[1] South Kerman Electrical Power Distribution Company
[2] Shahid Bahonar University of Kerman

variables. The 2m+1 scheme is more accurate than the 2m scheme due to considering one additional function evaluation than the 2m PEM. It should be noted that 2m+1 PEM method has been applied in the introduced framework. The PEM focuses on the *concentrations.* Concentrations are statistical data of input random variables. The 2m+1 PEM assigns 3 concentration points (s=1,2,3) to every input random variable. Assuming Y=F(X) as the objective function and X{x_1, x_2,.., x_n} as the input random variable, the output result would be obtained by twice applying F to each input random variable and one more appraisal for the mean value of all input random variables (μ_{xi}). As the result, the objective function would be solved 2m+1 times. Consequently, in case of facing *n* uncertainties, the following steps describe the 2m+1 PEM method.

I. Set *i*=1;

II. Calculate the skewness $\lambda_{i,3}$ and kurtosis $\lambda_{i,4}$ using equations (1) and (2).

$$\lambda_{i,3} = \frac{E\left[(x_i - \mu_{xi})^3\right]}{(\sigma_{xi})^3} \qquad (1)$$

$$\lambda_{i,3} = \frac{E\left[(x_i - \mu_{xi})^4\right]}{(\sigma_{xi})^4} \qquad (2)$$

III. Calculate the standard location $\xi_{i,s}$ and their relevant weights $\omega_{i,s}$ according to equation (3).

$$\xi_{i,s} = \frac{\lambda_{i,3}}{2} + (-1)^{3-s}\sqrt{\lambda_{i,4} - \frac{3}{4}{\lambda_{i,3}}^2}, \qquad S=1,2$$

$$\xi_{i,3} = 0$$

$$\omega_{i,s} = \frac{(-1)^{3-s}}{\xi_{i,s}(\xi_{i,1} - \xi_{i,2})}, \quad S=1,\ 2$$

$$\omega_{i,3} = \frac{1}{n} - \frac{1}{\lambda_{i,4} - {\lambda_{i,3}}^2} \qquad (3)$$

IV. Specify the concentration points $x_{i,s}$ according to the following equation.

$$x_{i,s} = \mu_{xi} + \xi_{i,s}\sigma_{xi} \qquad (4)$$

V. It should be noted that for *s=3,* $x_{i,3}$ would be equal to μ_{xi}. This case leads to one additional calculation $f(\mu_{x1}, \mu_{x2}, ..., \mu_{xn})$. The corresponding weight to current calculation should be updated according to the following equation.

$$\omega_0 = \sum_{i=1}^{n}\omega_{i,3} = 1 - \sum_{i=1}^{n}\frac{1}{\lambda_{i,4} - \lambda_{i,3}^2} \qquad (5)$$

VI. Calculate the moments of Y.

$$E(Y) = \omega_0 f(\mu_1, ..., \mu_n) + \sum_{i}\sum_{s=1}^{2}\omega_{i,s}Y_{i,s} \qquad (6)$$

PROBLEM FORMULATION

The goal of the microgrid energy management system is to minimize the operating cost. In the proposed objective function, the operating costs include generating power by DERs, total power exchanging cost with the upstream grid, start-up costs of DERs and finally charging/discharging cost of ESSs. The objective function of microgrid energy management according to the aforementioned descriptions, could be formulated as follows:

$$MinF(x) = Min\sum_{t=1}^{T}\cos t =$$

$$Min\sum_{t=1}^{T}\left\{\begin{array}{l} \sum_{j=1}^{N_j}\{u_{DERj}(t).P_{DERj}(t).C_{DERj}(t)\} \\ + \sum_{k=1}^{N_k}\{u_{ESSk}(t).P_{ESSk}(t).C_{ESSk}(t)\} \\ + P_{gr}(t).C_{gr}(t) - P_{gs}(t).C_{gs}(t) \\ \end{array}\right\} \qquad (7)$$

Where u_{DERj} and u_{ESSk} stand for the online status of *jth* DER and kth ESS, respectively. P_{DER_j} and P_{ESSk} represent the generated power by *jth* DER and kth ESS. C_{DER_j} and C_{ESSk} are the costs of providing power by the *jth* DER and kth ESS. P_{gr} and P_{gs} represent the received and sold power from/to the upstream grid. C_{gr} and C_{gs} stand for the cost of receiving and selling power from/to upstream grid. The objective function (7) constraints are as follows.

$$\sum_{t=1}^{T}\left\{\sum_{j=1}^{N_j}P_{DERj}(t) + \sum_{k=1}^{N_K}P_{ESSk}(t) + P_{gr}(t) - P_{gs}(t)\right\} = \sum_{t=1}^{T}\left\{\sum_{l=1}^{N_L}P_L(t)\right\} \qquad (8)$$

$$\begin{array}{l} E\_CO_{2B}P_B(t) \le E\_CO_{2B}{}^{\max}(t) \\ E\_SO_{2B}P_B(t) \le E\_SO_{2B}{}^{\max}(t) \\ E\_NO_{xB}P_B(t) \le E\_NO_{2B}{}^{\max}(t) \end{array} \qquad (9)$$

$$\textbf{\textit{Where}}\ B = [DERj, ESSk, Grid]$$

$$P_{Grid}(t) = P_{gs}(t) - P_{gr}(t) \qquad (10)$$

$$P_{DERj}^{\min}(t) \le P_{DERj}(t) \le P_{DERj}^{\max} \qquad (11)$$

$$P_{ESSk}^{\min}(t) \le P_{ESSk}(t) \le P_{ESSk}^{\max} \qquad (12)$$

Constraint (8) is the power balance limit which enforces the total load demand to be supplied at each hour. Constraint (9) ensures that the emission limitations are met. The considered emissions include carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x). In other words, each unit should not exceed the emission limitation pertaining to each gas in *kg* at each hour. Equation (10) represents the main grid net power. In order to ascertain that each DER and ESS works in the allowed zone, the technical limitations are assigned as constraints (11) and (12). Furthermore, the next constraint that should be considered in the MG formulation is for charging and discharging rate of the ESSs according to the following expression.

$$W_{ESS}(t)=W_{ESS}(t-1)+P_{ch}\times(\Delta t)\times\eta_{ch}-\frac{P_{dis}}{\eta_{dis}}\times(\Delta t) \qquad (13)$$

Where $W_{ESS}(t)$ and $W_{ESS}(t-1)$ are the quantity of the stored energy in the storage system at hour *t* and *t-1*, respectively. P_{ch} and P_{dis} are the allowed rates of charge and discharge during a certain time interval Δt. η_{ch} and η_{dis} are the battery efficiency rates for charging and discharging interval.

The most significant constraint to prevent battery damage is the upper and lower level of stored energy inside a battery.

$$W_{ESS}^{\min}\le W_{ESS}(t)\le W_{ESS}^{\max} \qquad (14)$$

Where $W_{ESS}^{\min}$ and $W_{ESS}^{\max}$ are the minimum and maximum of the energy storage system, respectively. Also, the charging and discharging rates must exceed their specified characteristics through each interval Δt according to the following equation.

$$P_{ch}\le P_{ch}^{\max}, \qquad P_{dis}\le P_{dis}^{\max} \qquad (14)$$

The proposed method has implemented in General Algebraic Modeling System (GAMS) and solved using DICOPT solver with a laptop computer with core i5 CPU and 4 GB of RAM.

NUMERICAL RESULTS

The proposed energy management system for a typical MG has been executed. The considered MG contains DERs and ESSs whose technical information exist in Table 1. The reason why the provided power from wind and PV are more expensive than other DERs is due to discounting the investment and O&M cost over the lifelong divided by the yearly electricity production.

The maximum emission of each DER and ESS should not exceed from 17 kg of CO_2, 7e-3 kg of SO_2 and 5e-3 NO_x at each hour *t*. Also, the considered emission factors of the provided power from the utility grid are 0.95 kg/KWh of CO_2, 3.5e-4 kg/KWh of SO_2 and 2e-4 kg/KWh of NO_x.

Table 1. DER and ESS technical information

MG system	CHP	FC	Wind	PV	ESS
Price ($/KWh)	0.57	0.38	0.98	0.86	0.43
CO_2 (kg/KWh)	0.46	0.28	0	0	0.006
SO_2 (kg/KWh)	$0.69e^{-6}$	$2.9e^{-6}$	0	0	$1.85e^{-7}$
NO_x (kg/KWh)	$11e^{-5}$	$8e^{-6}$	0	0	$1.23e^{-6}$
P_{min} (KW)	2	1	0	0	-22
P_{max} (KW)	55	40	20	25	22

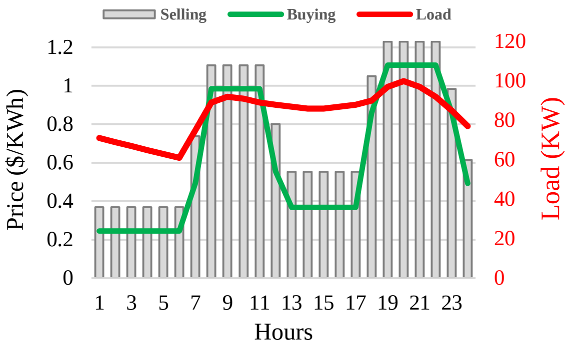

Fig. 1. Real-time selling/buying energy price and electric load profile

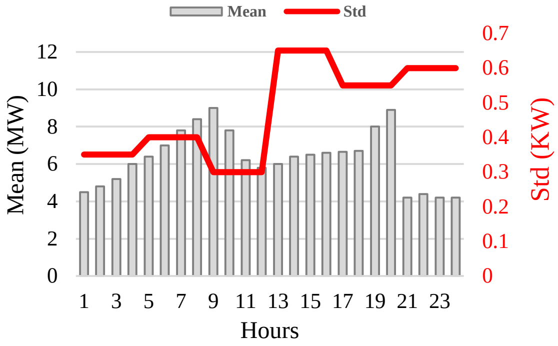

Fig. 2. Wind stochastic characteristics

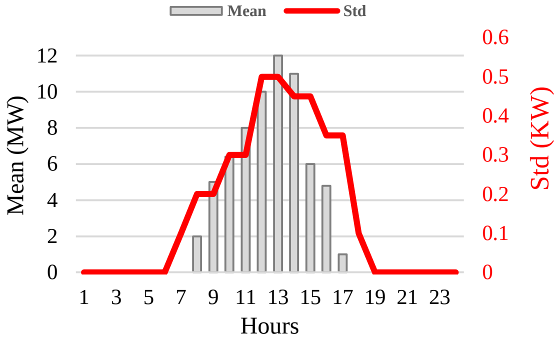

Fig. 3. PV stochastic characteristic

The information of load demand profile and main grid tariff are provided in Figure 1. The power trade tariff is assumed to be for common residential usage. The Stochastic parameters of Wind and PV power output are illustrated in Figures 2 and 3. All the information mentioned above are educed from Ref. [6]. In order to examine the validity of the proposed framework, the MG energy management problem is solved with a condition that the capacity of tie lines between MG and upstream grid is 50 kW.

The expected total operating cost of MG is $835.72 per a day. The optimum power allocation of the studied MG is provided in Table 2. As it can be seen from this Table, during the first seven hours of the day, most of the load is provided by FC and upstream grid due to their lower energy price in comparison with other existing sources. In the next hours, due to MG load growth as well as rising

Table 2. Optimum MG Power Allocation

Hour	FC (kW)		CHP (kW)		Wind (kW)		PV (kW)		Ch/Disch (kW)		Grid (kW)	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1	19	0	2.00	0	0	0	0	0	0	0	50.00	0
2	21.25	1.33	2.00	0	0	0	0	0	-4.25	1.33	50.00	0
3	19.94	1.58	2.00	0	0	0	0	0	-4.94	1.58	50.00	0
4	16.50	1.87	2.00	0	0	0	0	0	-3.50	1.87	50.00	0
5	15.36	1.13	2.00	0	0	0	0	0	-4.36	1.13	50.00	0
6	13.36	1.45	2.00	0	0	0	0	0	-4.36	1.45	50.00	0
7	25.53	0.41	2.00	0	0	0	0	0	-2.53	0.41	50.00	0
8	40.00	0	44.06	2.25	8.40	0.40	0	0	4.16	0.62	-7.20	2.40
9	40.00	0	45.66	3.57	9.00	0.30	2.00	0.20	4.10	0.29	-8.71	3.22
10	40.00	0	44.93	1.55	7.80	0.30	5.00	0.20	4.30	0.57	-11.23	1.89
11	40.00	0	46.73	2.00	6.20	0.30	6.40	0.30	3.90	0.21	-14.70	2.60
12	40.00	0	2.00	0	0	0	0	0	-1.00	0.40	47.00	0.40
13	39.00	0.81	2.00	0	0	0	0	0	-4.00	0.81	50.00	0
14	38.23	0.20	2.00	0	0	0	0	0	-4.23	0.20	50.00	0
15	38.23	0.20	2.00	0	0	0	0	0	-4.23	0.20	50.00	0
16	39.13	0.57	2.00	0	0	0	0	0	-4.13	0.57	50.00	0
17	39.70	0.42	2.00	0	0	0	0	0	-3.70	0.42	50.00	0
18	40.00	0	46.16	1.02	0	0	0	0	0	0	3.83	1.02
19	40.00	0	45.68	0.73	8.00	0.55	0	0	4.00	0	-0.67	0.35
20	40.00	0	46.06	0.16	8.90	0.55	0	0	4.16	0.12	0.87	0.43
21	40.00	0	45.56	0.92	4.20	0.60	0	0	4.00	0.16	3.41	1.45
22	40.00	0	45.92	0.73	4.60	0.60	0	0	4.02	0.36	-2.43	1.69
23	40.00	0	45.83	0.23	0	0	0	0	3.02	0.23	-3.57	0.11
24	40.00	0	2.00	0	0	0	0	0	0	0	35.00	0

upstream grid energy price, we witness an increment in DER output power. During the aforementioned hours, in order to reduce its expenses, can sell its surplus production to upstream grid. It should be noted that the FC output during these hours reach to its maximum production capacity because it has the lowest energy price among all DERs. It is worth mentioning that our ESS charging process is accomplished when the upstream grid energy price, as well as MG load, are low, but the ESS discharging process is done when the MG load demand is at its peak values. Also, it can be seen from this table that MG benefits from wind power output during hours 8-11 and 19-22 while facing peak consumption hours of the MG.

CONCLUSIONS

In the present paper, a microgrid energy management framework is established for a typical MG. The proposed framework not only considers the emission limitations in order to reduce the GHG pollutants but also tries to minimize total operation cost through achieving an optimum power allocation of MG. In this framework, the stochastic nature of uncertain input parameters is modeled using an accurate and fast platform called 2m+1 point estimate method (PEM). The considered uncertain parameters include real-time buying and selling market energy price, wind and PV power output. The results demonstrate that MG prefers to buy energy from the upstream grid during low grid energy price. With an increase in MG load and as well as a growth in purchasing cost of energy from the upstream grid, the microgrid tends to take advantage of its own resources. Also, the MG decides to charge its ESSs during low energy price in order to diminish its dependency to the upstream grid by discharging ESSs during high grid energy prices.

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