Energy Exchange Control in Multiple Microgrids with Transactive Energy Management

Mohammadreza Daneshvar, Behnam Mohammadi-Ivatloo, Mehdi Abapour, and Somayeh Asadi

Abstract—**In recent years, the advent of microgrids with numerous renewable energy sources has created some fundamental challenges in the control, coordination, and management of energy trading between microgrids and the power grid. To respond to these challenges, some techniques such as the transactive energy (TE) technology are proposed to control energy sharing. Therefore, this paper uses TE technology for energy exchange control among the microgrids, and applies three operation cases for analyzing the energy trading control of four and ten microgrids with the aim of minimizing the energy cost of each microgrid, respectively. In this regard, Monte Carlo simulation and fast forward selection (FFS) methods are respectively exerted for scenario generation and reduction in uncertainty modeling process. The first case is assumed that all microgrids can only receive energy from the network and do not have any connection with each other. In order to maximize the energy cost saving of each microgrid, the second case is proposed to provide a positive percentage of cost saving for microgrids. All microgrids can also trade energy with each other to get the most benefit by reducing the dependency on the main grid. The third case is similar to the second case, but its target is to indicate the scalability of the models based on the proposed TE technology by considering ten commercial microgrids. Finally, the simulation results indicate that microgrids can achieve the positive amount of cost saving in the second and third cases. In addition, the total energy cost of microgrids has been reduced in comparison with the first case.**

Index Terms—**Transactive energy, renewable energy sources, energy exchange control, microgrid operation.**

I. Introduction

NOWADAYS, the use of electrical equipment is increasing due to the significant economic and environmental advantages of electrical energy. The operation of traditional power plants must be increased to supply enough energy with the aim of covering the increment of electricity consumption along with emerging new electrical systems. Increasing the production of fossil fuel based power plants or building new units in them leads to some fundamental concerns such as global warming and the reduction of non-renewable energy sources. These concerns become a specific motivation for researchers to propose reasonable solutions for the related challenges. Therefore, renewable energy sources (RESs) are introduced as the clean energy production units into the power grid. Because of the economic and environmental advantages of RESs, their technologies such as wind turbines and solar photovoltaic (PV) panels are quickly developed to be widely intended in the electricity generation process. Recent studies indicate that increasing the penetration of RESs (especially wind farms) in the power system can effectively reinforce the system reliability and stability [1]. This mutation in the electrical system field has led to the development of new concepts regarding energy management in smart grid and grid integration as well as their evaluations [2]. In this regard, smart grid with high penetration of RESs is divided into multiple microgrids in order to improve the energy supply for consumers and increase the system efficiency and reliability while facilitating the operation and integration of distributed energy resources (DERs) [3]-[5]. In other words, energy in multiple microgrids can be exchanged with the modern power grid to achieve some key advantages such as environmental friendliness, economic benefits, efficiency, reliability, and improvement of operation and control of the system [6], [7]. However, intermittences in RES generation have posed fundamental challenges regarding the optimal scheduling of electric power system. One of the most significant challenges is the optimal energy management and sharing between microgrids and power grid in the presence of numerous RESs [8]. Another one is the reliable energy supply, which can be considered as the essential support for modern civilization [9].

Recently, many studies have investigated the energy exchange analysis in microgrids. All of them have employed different approaches and techniques to control energy trading in microgrids. For example, [10] uses the formulation of prospect theory-based static game for the energy exchange among microgrids that are connected to the power plant, and various scenarios are also generated for the Nash equilibria. In [11], a game theory approach is used to encourage the microgrids for energy trading among themselves by providing the incentive programs. In this research, the proposed distributed mechanism is considered for the energy exchange of microgrid in a competitive market. In [12], the interactions between interconnected microgrids are intended by developing

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the scheduling and energy trading strategies. Similar to [11], [12] also uses the incentive-based programs for energy trading of microgrids to increase the benefits. In [13], the multi-objective intelligent energy management (MIEM) is proposed and the artificial intelligence techniques are applied to minimize the operation cost of microgrids. For battery scheduling in [13], the fuzzy logic expert system is employed and all uncertain parameters can be handled based on the proposed approach. In [14], a two-stage combined strategy is presented for the energy exchange by considering the electric vehicles as storage devices for multiple microgrid system. In addition, several dual variables are used for updating the price along with the presentation of a decentralized scheduling strategy based on the price signals for the microgrid controller. In [15], the multi-objective genetic algorithm is implemented for the energy management system of microgrids with the fuzzy inference system to maximize the automatic consumption of energy and reduce the fluctuations of energy trading in the network. In [16], a hybrid optimization model is employed to estimate the system configuration for the electrical renewables. Considering the uncertainties in electricity demand and environment changes, the sensitivity analysis is carried out and the effectiveness of the presented model is also evaluated in the case study with realistic data located in India. In order to establish the coordinated energy management between clustered microgrids and distribution systems, a two-level optimization model is proposed in [17] by employing the interactive game matrix for the power exchange control.

In addition to the mentioned studies, some studies have been conducted based on the powerful optimization methods to deal with various uncertainties in modeling the system. For example, a robust optimization approach is applied in [18] to overcome the challenges caused by the intermittent nature of the variable generation resources. Solar radiation and energy demand are considered as the uncertain parameters, which are modeled by the proposed optimization method with the piecewise linear curve incorporation. Simulation results of this study demonstrate that the expected operation cost is improved in the energy management of the combined cooling, heating and power (CCHP) microgrid using the robust optimization method compared with other deterministic optimization approaches. In [19], the probabilistic cost optimization model is proposed for the microgrids with several DERs considering the uncertain environment. The main goal of the probabilistic model is to optimize the decision making process in the microgrids which is related to the energy exchange with upstream grid and the amount of DER production.

Even though various studies have investigated the energy control and management of microgrids, most of them do not consider the key aspects related to the energy trading control such as adopting reliable techniques matched with advanced systems, which requires significant attention for providing acceptable condition for the smart network structure. In this regard, each of the mentioned references has used various techniques for the energy exchange and management in the microgrid, whereas none of them models the control of the energy exchange in microgrids and provide suitable condition with a powerful technique for the integration of DERs in microgrids. In addition, uncertainties in PV generation and wind speed forecasts in the control of energy trading between microgrids and power grid are not effectively considered.

Therefore, this paper focuses on the control of energy exchange and management considering the integration of numerous RESs. In this research, the transactive energy (TE) technology is applied to multiple microgrids in the smart grid to control and manage the energy sharing in a reliable and sustainable manner. TE technology is presented as a worthy contender in control, management, and coordination of intelligent systems for establishing the dynamic balance between the energy demand and supply sides. In this regard, the GridWise Architecture Council (GWAC) is responsible by the United States Department of Energy (DOE) to address the challenges of this technology in the energy trading market [20], [21]. Indeed, TE is defined by the GWAC as "a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using the value as a key operational parameter" [22]. In recent years, several effective studies have been conducted regarding TE technology with various objectives. For example, an analytical framework is presented in [23] based on the TE management with the aim of energy trading among neighboring households. However, this work is focused on the energy management of only several houses with limited features in the form of a residential microgrid. In [24], TE technology is employed for the integration of several villages to manage the energy sharing between villages with the aim of rural network electrification. In addition, a novel TE framework is presented in [25] for technical and economic analysis of distributed multi-energy systems with the aim of profit sharing between commercial participants. In [26], the features of TE and demand response programs are described to investigate the effectiveness of TE technology in establishing dynamic energy balance in the power grid.

In this paper, wind speed and solar radiation are considered as uncertain parameters and modeled with Weibull and Beta distributions, respectively. Generally, analytical approaches become less practical for the problems with higher complexity, but the Monte Carlo simulation method is a suitable method for the systems with various sizes or complexities because its efficiency does not depend on either the complexity or size of the problem [27]. Moreover, to reduce the time for solving the problem, the candidate scenarios with a high probability of occurrence in comparison with other scenarios should be effectively selected and used in the process of solving the stochastic problem. Fast forward selection (FFS) method is applied in this paper to select the scenarios that have the minimum distance in comparison with other scenarios with the Kantorovich distance protocol [28]. Therefore, the Monte Carlo simulation and FFS methods are used for the scenario generation and reduction, respectively.

To sum up, the main contributions of this paper are as follows: ① TE technology is applied for energy exchange control between multiple microgrids with each other and the main grid in a reliable manner; ② RES integration is effectively done with the aim of high usage of clean energy resources to mitigate greenhouse gas emissions; ③ uncertainty quantification is carried out by applying the Monte Carlo simulation and FFS techniques for scenario generation and reduction, respectively; ④ operation cases are proposed for the energy trading of multiple microgrids to minimize the operation costs considering the scalability issue.

The remainder of this paper is organized as follows: Section II presents the problem formulation. The simulation results are provided in Section III. Finally, the conclusions are described in Section IV with the summary of major findings.

II. Problem Formulation

A. Microgrid Architecture

In this paper, four microgrids are considered with the assumption that they are equipped only with RESs for electricity production. The solar PV panel, wind turbine, and battery storage are intended as the clean energy generation system [29]. The electricity trading between microgrids connected with each other and the power grid is illustrated in Fig. 1. As seen from this figure, the possibility of energy exchange is provided for the microgrids not only to establish energy sharing with the main grid but also to trade the energy between themselves at the local level. The production of wind turbine and solar PV panel can be sent back to the power grid, or be used in local energy exchange market (LEEM), battery storage, and electricity demand. In addition, battery storage can not only discharge for balancing the energy supply and demand in the emergency conditions but also receive or deliver the energy for its charging or discharging from the power grid and LEEM (other microgrids).

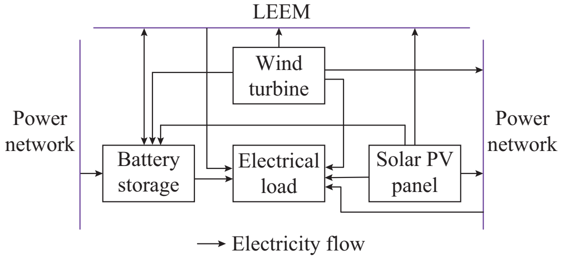

Fig. 1. Schematic diagram of microgrid.

The proposed architecture allows the microgrids to have energy trading in multiple ways. For example, at first, the microgrids can provide the energy demand through the energy production generated by RESs inside them. If the energy production of the microgrids is not enough for meeting the energy demand, the required energy can be received from other microgrids in LEEM. Indeed, LEEM is structured to realize the TE guidelines based on the general TE definition. LEEM is considered for meeting the energy demand of microgrids with the aim of reducing their dependency to the main grid as well as dynamic energy balancing, which is commensurate with the first part of the TE definition in [22]. This is done considering the minimization of the total energy cost of microgrids while improving the cost saving in the market interactions. Because RESs are used for energy production (environmental aspect) and the energy cost of microgrids is minimized (economic aspect), it is also commensurate with the second part of the TE definition in [22].

Therefore, LEEM is an appropriate mechanism to realize the economic and environmental goals of the proposed system based on the TE architecture. Moreover, since the TE principles are realized in the proposed cases based on the general TE definition, the mechanism is taken into account as the TE energy management paradigm, which can be applied for the energy exchange control of multiple microgrids in the smart grid. On the other hand, if LEEM has no enough potential to provide the energy demand of microgrids, the energy can be traded with the power grid to achieve the needed energy from it at the last step. These multiple ways for providing the energy demand of consumers increase the system reliability and demonstrate the capability of the proposed structure in meeting the energy loads. In addition, one of the main achievements made by establishing energy trading between multiple microgrids is that this mechanism can reduce the transmission power losses effectively. Indeed, the transmission power losses due to power exchanges with a nearby microgrid are less than that from the distant grid.

B. Objective Function and Constraints

The main goal of this paper is to minimize total energy cost of microgrids. In this regard, some constraints of microgrid devices and power grid should also be satisfied.

1) Objective Function

Minimizing the total energy cost is taken into account as the main objective of microgrids. The corresponding function consists of two terms for each microgrid including the cost of energy purchased from the power grid and the revenue of the energy sold to power grid with a negative sign, which is formulated as follows:

$$FC_i = \sum_t (Epm_{i,t} \cdot Ppm_t - Emp_{i,t} \cdot Pmp_t) \quad \forall i \tag{1}$$

where FC_i is the objective function for microgrid i; $Epm_{i,t}$ is the amount of electricity purchased from the power grid by microgrid i at time t; $Emp_{i,t}$ is the amount of electrical energy sold to the power grid by microgrid i at time t; and Ppm_t and Pmp_t are the electricity purchasing and selling prices at time t, respectively.

2) Constraints

Along with the minimizing of the objective function in (1), several operation and technical constraints should be considered, which are listed as follows.

1) Limitation of electricity balance

In each time, the amount of electricity generation and consumption must be matched according to the following constraint:

$$\begin{aligned} &Epm_{i,t} + Ewt_{i,t} + ESPV_{i,t} + Ebd_{i,t} \cdot \eta_{bd} + Elm_{i,t} = \\ &\quad Emp_{i,t} + El_{i,t} + \frac{Ebc_{i,t}}{\eta_{bc}} + Eml_{i,t} \quad \forall i, \forall t \end{aligned} \tag{2}$$

where $Ewt_{i,t}$ and $ESPV_{i,t}$ are the electricity generated by the wind turbine and solar PV panel in microgrid i at time t, respectively; $Ebd_{i,t}$ and $Ebc_{i,t}$ are the charging and discharging rates of battery storage for microgrid i at time t, respectively; η_{bd} and η_{bc} are two parameters representing the discharging and charging efficiencies of the storage system, respectively; $Eml_{i,t}(Elm_{i,t})$ is the electrical energy transmitted to (from) LEEM from (to) microgrid i at time t; and $El_{i,t}$ is the electricity load in microgrid i at time t.

2) Wind power model

Wind power is taken into account as one of the clean energy resources. The output power of the wind turbine depends on the wind speed under different conditions and its limitation is formulated as follows [30]:

$$Pwt_{i,t}=\begin{cases}0 & Vw_t<Vci_i, Vw_t>Vco_i\\ Pg_{t,\max}\cdot\left(\dfrac{Vw_t-Vci_i}{Vr_i-Vci_i}\right)^3 & Vci_i\le Vw_t\le Vr_i\\ Pg_{t,\max} & Vr_i\le Vw_t\le Vco_i\end{cases} \tag{3}$$

where $Pwt_{i,t}$ and $Pg_{t,\max}$ are the output and rated power of wind turbine in microgrid i at time t, respectively; and Vw_t, Vr_i, Vci_i, and Vco_i are the forecasted, rated, cut-in, and cut-out speeds of wind turbine in microgrid i at time t, respectively.

3) PV model

In recent years, as the solar PV panels are extensively used as clean energy generation equipment, they are considered for each microgrid in this paper, and the output power limitation of them should meet the following constraint [31].

$$ESPV_{i,t}\le SPV_i\cdot Sol_t\cdot\eta_{pv}\quad \forall i,\forall t \tag{4}$$

where SPV_i and η_{pv} are the size and efficiency of the solar PV panel in microgrid i, respectively; and Sol_t is the amount of solar radiation at time t.

4) Battery storage model

Generally, battery storage systems are used on an electrochemical basis for electricity storage at various levels. Some logical and technical constraints considered for these systems are as follows [32]:

$$MBc_{i,t}+MBd_{i,t}\le 1\quad \forall i,\forall t \tag{5}$$

$$Sb_i\cdot\delta_{B,\min}\le Eb_{i,t}\le Sb_i\quad \forall i,\forall t \tag{6}$$

$$Eb_{i,t}=Ibe+(Ebc_{i,t}-Ebd_{i,t})\Delta t\quad \forall i, t=1 \tag{7}$$

$$Eb_{i,t}-Eb_{i,t-1}=(Ebc_{i,t}-Ebd_{i,t})\Delta t\quad \forall i,\forall t\ge 2 \tag{8}$$

$$\delta_{Bc,\min}\cdot Sb_i\cdot MBc_{i,t}\le EBc_{i,t}\le\delta_{Bc,\max}\cdot Sb_i\cdot MBc_{i,t}\quad \forall i,\forall t \tag{9}$$

$$\delta_{Bd,\min}\cdot Sb_i\cdot MBd_{i,t}\le EBd_{i,t}\le\delta_{Bd,\max}\cdot Sb_i\cdot MBd_{i,t}\quad \forall i,\forall t \tag{10}$$

where $MBc_{i,t}$ and $MBd_{i,t}$ are the charging and discharging modes of the battery system in microgrid i at time t, respectively; Sb_i and $\delta_{B,\min}$ are the size of battery and coefficient for the minimum limitation of the storage system in microgrid i, respectively; $Eb_{i,t}$ is the amount of stored electrical energy in the battery in microgrid i at time t; Ibe is the initial electrical energy stored in the battery; Δt is the time interval, which is considered as 1 in this paper; $\delta_{Bc,\max}$ and $\delta_{Bc,\min}$ are the maximum and minimum amounts of charging limit of battery, respectively; and $\delta_{Bd,\max}$ and $\delta_{Bd,\min}$ are the maximum and minimum amounts of discharging limit of battery, respectively.

Equation (5) shows the battery storage systems should not be discharged and charged at the same time. Constraints (6)-(8) model the amount of electricity stored in battery with the definition of the allowable range. In addition, constraints (9) and (10) present the electrical energy charging and discharging limitations.

5) Constraints for LEEM

In the smart grid, microgrids can exchange energy with each other as well as with the power grid. In this paper, the other microgrids are considered as LEEM for each of the microgrids. The energy trading among the microgrids should be accomplished satisfying some operation constraints, which are listed as follows:

$$MElm_{i,t}+MEml_{i,t}\le 1\quad \forall i,\forall t \tag{11}$$

$$Elm_{i,t}\le X\cdot MElm_{i,t}\quad \forall i,\forall t \tag{12}$$

$$Eml_{i,t}\le X\cdot MEml_{i,t}\quad \forall i,\forall t \tag{13}$$

$$\sum_i Elm_{i,t}=\sum_i Eml_{i,t}\quad \forall t \tag{14}$$

where $MEml_{i,t}$ and $MElm_{i,t}$ are the modes of electrical energy contribution and transmission in microgrid i at time t, respectively; and X is a big number used in mixed integer programming.

According to (11), the status of receiving and transmitting energy between the microgrid and LEEM cannot be activated at the same time. For LEEM, the electricity transaction limitations are modeled in (12) and (13). The balance energy supply and demand constraint is enforced in (14).

6) Power grid constraints

Generally, transmission lines have limits in transmitting the power to various nodes throughout the electric power system. Therefore, constraints related to the power grid should be intended in modeling the networked microgrid problem. These constraints are given as:

$$P_{n,t}(\delta_t,V_t)+El_{n,t}=P_{n,t}^{Gen}\quad \forall n,\forall t \tag{15}$$

$$S_{n,m,t}(\delta_t,V_t)\le S_{n,m}^{Up}\quad \forall n,\forall m,\forall t \tag{16}$$

$$V_t^{\min}\le V_{n,t}\le V_t^{\max}\quad \forall n,\forall t \tag{17}$$

$$-\pi\le\delta_{n,t}\le\pi\quad \forall n,\forall t \tag{18}$$

where $P_{n,t}(\delta_t,V_t)$ and $P_{n,t}^{Gen}$ are the active power injection and production at node n at time t; $S_{n,m,t}(\delta_t,V_t)$ is the complex power flow between nodes n and m at time t; $S_{n,m}^{Up}$ is the maximum amount of complex power; $V_{n,t}$ and $\delta_{n,t}$ are the voltage magnitude and phase angle at node n at time t; $V_t^{\min}$ and $V_t^{\max}$ are the minimum and maximum voltage magnitudes, respectively.

C. Operation Cases for Microgrids

Three operation cases are proposed for the energy trading of microgrids based on TE management to evaluate the energy exchange control between the microgrids and power grid. Ten renewable microgrids are considered for the analysis of smart energy management. The energy exchange between microgrids and power grid is investigated in Case 1. In this case, the energy trading mode of each microgrid is assumed in the off state with the other microgrids, and the microgrids cannot share energy with each other. In other words, the main grid is the only reliable option for microgrids to provide the electricity demands. Case 2 is organized to provide proper conditions for microgrids to achieve a positive percentage of cost saving while minimizing the total cost of microgrids. In this case, microgrids can not only exchange energy with the power grid but also share energy with themselves, which will reduce the dependency on the power grid. Finally, Case 3 is presented for evaluating the scalability of the proposed model in Case 2. In this case, it demonstrates that the proposed TE-based model can be implemented effectively on the large-scale systems with numerous microgrids. All the energy trading conditions in Case 3 are similar to Case 2 except the number of microgrids (increasing from 4 to 10).

1) Case 1

In this case, all the microgrids are integrated with intermittent RESs and operate in the individual mode of energy trading. The control of energy exchange is not considered in the TE structure in this case. The problem formulation of this case is demonstrated as follows:

$$\begin{cases} \min FC_1 = \sum_i FC_{1,i} \\ \text{s.t. } (2)-(18) \\ \quad MElm_{i,t} = 0 \quad \forall i, \forall t \\ \quad MEml_{i,t} = 0 \quad \forall i, \forall t \end{cases} \tag{19}$$

where FC_1 is the total energy cost in Case 1; and $FC_{1,i}$ is the energy cost in Case 1 for microgrid i calculated by (1).

2) Case 2

Microgrids can trade energy with the power grid and other microgrids in this case. Four commercial microgrids are considered for energy trading evaluation in this case. The connection structure between microgrids and the power grid is illustrated in Fig. 2.

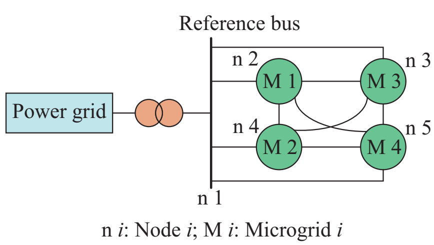

Fig. 2. Connection structure between microgrids and power grid in Case 2.

The TE management is employed to control the energy exchange, and it can not only minimize the total energy cost of microgrids but also provide the cost saving for microgrids. In other words, microgrids do not have energy loss when they operate in the TE architecture. The problem formulation of this case is listed as follows:

$$\begin{cases} \min FC_2 = \sum_i FC_{2,i} \\ \text{s.t. } (2)-(18) \\ \quad FC_{2,i} \le FC_{1,i} \quad \forall i \end{cases} \tag{20}$$

where FC_2 is the total energy cost in Case 2; and $FC_{2,i}$ is the energy cost in Case 2 for microgrid i calculated by (1).

3) Case 3

In this case, the formulation of the microgrids is the same with Case 2, hence it is not presented again.

III. Simulation Results

In this paper, each of the microgrids is equipped with one wind turbine (the rated power is 1.5 kW), and the required information about this system can be obtained from [30]. Wind speed and PV generation are considered as uncertain parameters to model the effects of them under real conditions. Therefore, Monte Carlo simulation is used for the generation of 2000 scenarios and the Weibull and Beta distributions are applied. Then, FFS method is employed for the reduction of generated scenarios to 20. Finally, the expected values are calculated and the numerical results are listed in Tables I and II for Case 2 and Case 3, respectively.

TABLE I
Simulation Results of Each Microgrid in Cases 1 and 2

Microgrid no.	Energy cost in Case 1 ($)	Energy cost in Case 2 ($)	Amount of cost saving ($)	Percentage of cost saving (%)
1	34.548	27.426	7.122	20.615
2	32.147	28.629	3.518	10.943
3	34.449	30.469	3.980	11.553
4	36.117	29.281	6.836	18.927
Total	137.261	115.806	21.455	15.631

TABLE II
Simulation Results of Each Microgrid in Cases 1 and 3

Microgrid no.	Energy cost in Case 1 ($)	Energy cost in Case 3 ($)	Amount of cost saving ($)	Percentage of cost saving (%)
1	34.763	18.249	16.514	47.504
2	32.147	21.248	10.899	33.904
3	34.447	22.212	12.235	35.518
4	36.117	16.793	19.324	53.504
5	35.245	18.049	17.196	48.790
6	43.342	23.467	19.875	45.856
7	30.724	14.970	15.754	51.276
8	58.473	40.320	18.153	31.045
9	28.717	17.285	11.432	39.809
10	36.625	25.834	10.791	29.463
Total	370.601	218.427	152.174	41.061

In this paper, ten microgrids located in Chicago, USA are selected for the assessment of energy trading between the microgrids and the power grid, and the related data can be found in [33]. In addition, June 1 is selected and hourly data of solar radiation is also used [34]. Therefore, the data of electricity price in the summer is used as selling and purchasing prices [24]. In order to model the proposed cases, the SBB solver of the GAMS software is chosen and other required parameters for this simulation can also be found in [32], [35].

In Tables I and II, the extracted simulation results prove the effectiveness of the TE technology simultaneously in minimizing the energy cost and the control of energy sharing. In other words, all microgrids can gain a positive percentage of cost saving with the TE paradigm, and the total cost of microgrids in Cases 2 and 3 is reduced compared to

Case 1. An exact evaluation of numerical results demonstrates that the total energy cost of microgrids in Cases 2 and 3 can be reduced by 15.631% and 41.061%, respectively, in comparison with Case 1 based on the TE architecture. However, the amount of obtained cost saving across the energy trading between microgrids has various magnitudes for all microgrids, which should be improved by the developed energy exchange models.

In addition, the control of energy trading in the system is effectively done based on the TE structure. An exact assessment of numerical results in Table II demonstrates that all microgrids have obtained the positive amount of cost saving in Case 3, which proves that the proposed TE-based model can be successfully implemented on the large-scale systems with numerous microgrids. Also, result assessment of Table I indicates that microgrid 1 has gained the most amount of cost saving among all microgrids. The purchasing electricity behavior of this microgrid from the power grid is illustrated in Fig. 3. In this figure, the amount of electricity purchased from the power grid is considered in Cases 1 and 2 for 24 hours. As shown in this figure, the electricity purchased from the main grid in Case 1 is greater than that in Case 2 at most of the time. In other words, the dependency of a microgrid on the main grid for meeting the electricity demand in Case 2 is less than that in Case 1.

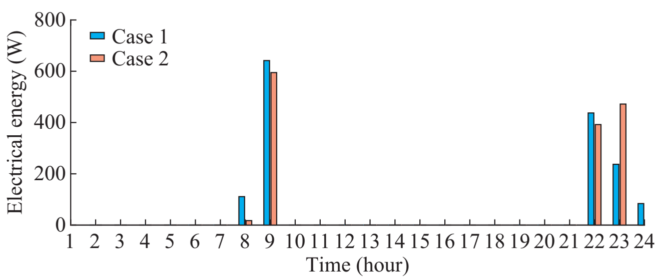

Fig. 3. Schematic diagram of electricity purchased from main grid in Cases 1 and 2.

In addition to the mentioned analysis, the electrical energy transmitted from LEEM to microgrids in Case 2 is demonstrated in Fig. 4. As shown in this figure, microgrids 4 and 2 have the most and least energy sharing, respectively. As the utilization potential of energy exchange is inadequate in LEEM, microgrid 2 has less cost saving than other microgrids.

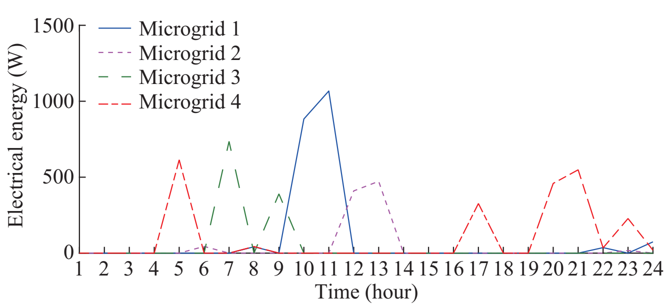

Fig. 4. Electrical energy sharing of microgrids in LEEM in Case 2.

The role of wind turbines, solar PV panels, LEEM, and main grid in meeting the daily electricity demand is shown in Fig. 5. As shown in this figure, the trade energy of microgrids in LEEM reduces the dependency on the main grid, especially at the peak-load time. Because of the high energy prices at peak-load time, the energy is purchased from the power grid by microgrids at other time when the energy price is low for minimizing the energy cost. In addition, the high potential of wind power in generating the electric energy is effectively used for selling energy by microgrids to the main grid at peak-load time when the energy price is at its maximum.

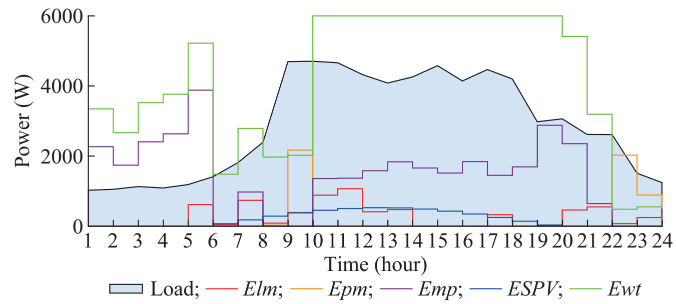

Fig. 5. Role of various resources in meeting electrical load in Case 2.

This operation of microgrids leads to the maximization of the profit in the energy exchange process based on the TE paradigm. However, because of the lower output of wind turbines at night (hour 21 to hour 24), the amount of energy sold to the main grid is also reduced, and the energy purchased from the power grid is required to meet the demand. On the other hand, a similar analysis is investigated for resources of microgrid in Case 3, which is illustrated in Fig. 6.

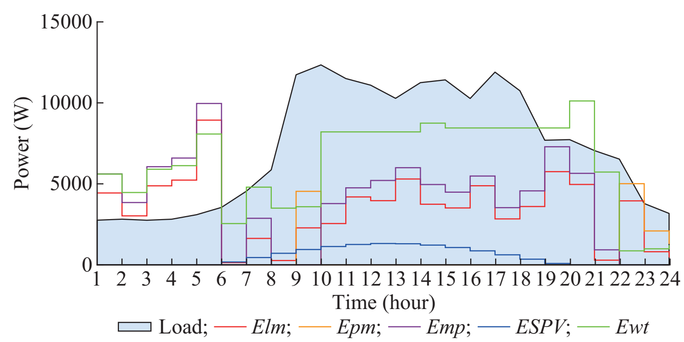

Fig. 6. Role of various resources in meeting electrical load in Case 3.

As shown obviously in this figure, the potential of the free energy trading possibility between the microgrids is effectively used for meeting the demand at the peak-load time when the electricity price is higher than in other hours. In this structure, all microgrids attempt to sell their surplus energy to the power grid at the time when the energy price is high and mutually purchase energy from the power grid at the time when the energy price is low. Moreover, the potential of clean energy resources is also used especially at peak-load time, not only to provide a large portion of demand but also to give an extra opportunity for microgrids to sell their surplus energy for minimizing the energy cost.

To sum up, given the obtained results in Case 3, the dynamic energy balance is met over the scheduling horizon and all microgrids can gain the positive amount of cost saving when they participate in LEEM and trade energy based on the TE paradigm. This proves that the proposed TE-based mechanism can be applied to a large number of renewable-based microgrids throughout the power grid. In other words, the proposed mechanism for the energy trading of microgrids is scalable and can be effectively employed in large-scale systems.

IV. Conclusion

In this paper, ten microgrids are considered for TE technology analysis in the network energy sharing with the three proposed operation cases. Each of the microgrids is only equipped with RESs for energy generation, so the energy production of them does not have any environmental problems. Simulation results of three cases show that all of the microgrids can achieve cost saving if they operate with the TE architecture. In addition, the total cost of microgrids is minimized from \$137.261 in Case 1 to \$115.806 in Case 2. The possibility of free energy trading, which is established between the microgrids based on the TE structure, can support the microgrids at all time (especially at peak-load time) to meet their energy demands and to sell energy to the power grid for their profit maximization. An exact assessment of the proposed model in Case 3 indicates the scalability feature of this model and demonstrates that the proposed model can be successfully applied in the power grid with a large number of microgrids considering the profit of each microgrid. Consequently, TE technology is recommended for the microgrids with high penetration of RESs for the control and management of optimal energy exchange in the power grid.

Each of the microgrids obtains various amounts of cost saving when the microgrids participate in the energy trading market. The percentage of the gained cost saving is not the same for all microgrids and the participation rate of microgrids is not considered in achieving the profit for them. Therefore, new operation models can be proposed considering the participation rate of microgrids in the market interactions or other models can be focused on proposing the new mechanisms for delivering the same percentage of cost saving for all of the participated microgrids in the market environment. On the other hand, security and reliability issues of the proposed models can be investigated in various case studies. In addition, the loss allocation issue as one important topic can be carefully analyzed in the TE models to provide better condition for achieving the cost saving for all microgrids. These topics will be studied as future works.

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