Optimal Coalition Formation between Multi-Microgrids Based on a Cooperative Game Theory Model with the Penetration of Renewable Energy Resources

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ABSTRACT:
A three-level scenario-based model for optimal operational planning in order to form a coalition between multiple microgrids is presented. The proposed model is based on the cooperative game theory method. Then the basis of the coalition is to achieve optimal cumulative energy management of all coalition participants. In the proposed model, At first, a bi-level problem is designed to give the optimal exchanges that happen between independent elements (e.g. an energy storage system and a wind power plant) and microgrids. The proposed model uses a cooperative game theory method in which the players try to find a way to achieve the highest profits for the whole coalition. The bi-level model is represented as an MPEC problem. After solving this problem and determining the number of exchanges, each of the local microgrids is operated separately from the perspective of the local operator in the third level of the introduced model. In this way, the amounts of production of electrical and thermal generation units and also the energy status of the system of storing energy are determined.

KEYWORDS: Multi microgrid, Coalition, Game theory, Scenario-based.

1. INTRODUCTION

With the introduction of the concepts of microgrids and the growth of distributed sources of power in the grid, power system planning has also changed. Energy management is one of the most important planning decisions that has been influenced by the distributed generation sources in microgrids [1].

Energy management in microgrids is usually carried out by local operators to provide the local loads taking into account technical and economic conditions. In addition, the system's central operator, despite the decisions of each local operator, tries to fulfill the constraints of the whole system.

Thus, appropriate decision making from the perspective of the central system operator despite independent decision making by local operators is one of the main challenges facing researchers, which is also addressed in this manuscript.

In recent years, many studies have proposed new methods for energy management of microgrids. In [2], a bi-level optimization model is proposed for energy management in a multi-microgrid system. The upper level models the coordination of microgrids with each other and with the network and the lower level is used for planning the operation of local and single microgrids.

Multiple microgrids connected to the distribution network are considered in [3] and a two-step sequential optimization algorithm is used for energy management. The upper-level objective function is to reduce losses, reduce bus voltage deviations, and reduce power fluctuations between microgrids and the distribution network. The lower-level objective function is made to optimize the overall expense of the multiple microgrids.

Authors in [4] employed an analytical target cascading theory and developed an optimal model of autonomous dynamic planning to be used in an automated system for distribution featuring microgrids. The exchange of power between the distribution network and microgrids can strengthen economic planning to ensure operation in a coordinated manner.

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In addition, in [5], the uncertainty of the output of the solar system is pictured in the exploitation of multiple grids as a structured model. Also in [6], the authors introduced a strategy for decision-making for the distribution network operator out of several grids in which the customers are asked to use different designs of network accountability to control the network.

The authors in [7] have used the theory of game to schedule the distribution network operation with several microgrids. In [8], a stochastic bi-level algorithm is used to plan and operate an active distribution network using several microgrids. In the first level, the objective function is used with the aim of minimizing the expense of energy received from the upstream network by locating and determining the size of the system for storing energy. In the second level, by defining technical indicators for the feasibility and quality of the optimal combinations obtained from the first level, these indicators are analyzed and the best answer is determined.

In a new approach, the reference [9] examines the effect of demand response programs on the optimal utilization of multiple microgrids in active distribution networks. The possibility of operating the microgrid with a multi-objective approach in the introduced model including technical indicators such as efficiency, power supply adequacy, reliability, and voltage profile, along with the costs of demand response transaction are evaluated. In [10] a method for creating cooperation between microgrids is proposed. In order to motivate collaboration between microgrids, a framework based on Stackelberg game theory for cooperation of microgrids called Microgrid Energy Trading Game (MGETG) has been proposed.

In [11], a multi-layer stochastic algorithm was introduced for managing energy taking into account load response, active losses, decreasing the emission of greenhouse gas, and lowering pollution and global warming along with overcoming the limits of renewable energy loads and sources.

Authors in [12] introduced a decentralized strategy for sequential control aimed at several microgrids in the island and connected networks. This strategy was designed to achieve a stable and optimize microgrids using the introduced strategy.

A strategy was proposed to optimize operation of several microgrids in peaks in [13]. The specifications of charging, discharging, generating, and transferring power in networks and grids and among the grids are given based on diverse load intervals and deficiency/add of power. Management of energy in a microgrid in 14] was based on a reliable optimization method and estimation of point.

In [15], the probabilistic planning of operation in a smart system of distribution was examined based on responsive loads. Renewable production planning and demand response in a microgrid has been analyzed in [16].

In [17], a three-level gameplay-based intelligent structure is presented to evaluate individual and collaborative strategies of electricity manufacturers, considering network and physical constraints.

The impact of network constraints on energy trading and how to share profits equitably are considered in [18] in the energy cooperation framework for community energy storage systems and prosumers.

An analytic approach to identify the best coalition among microgrids in multi-microgrid systems is proposed in [19]. The proposed model evaluates all of the strategies and ranks them from the viewpoint of microgrids.

In [20], to coordinate these energy transactions, a coalitional game theoretic energy transaction algorithm for networked microgrids is developed to improve energy exchange efficiency.

A tri-level energy management framework, including an improved payoff allocation scheme for the multi-vectored network microgrids system to ensure coalition and microgrids' collective and individual interests, respectively is proposed in [21].

In this paper, a new three-level energy management system using game theory is introduced for the optimal use of multiple microgrids (MMGs). Each element of the system in the model is taken as a player. Some measures are carried out independently by the players; however, specific activities are controlled by the control operator.

In the reviewed references, the coalition to maximize the profitability of multiple microgrids is sometimes solved using game theory. In these papers, only the maximization of the entire coalition is considered. But in the model proposed in this article, firstly, the optimal exchange with the upstream network and the exchange with other microgrids are determined using game theory in order to maximize the total profit of the coalition. After determining the production and exchange requirements based on the game theory, in the third level of the problem, the operation planning of each microgrid is done separately, taking into account the trading requirements considered in the first two levels (game theory). In this way, it is possible to modify the operation after determining the requirements of the coalition exchange, and this issue will be the main advantage compared to other existing authorities.

The key advantages of this model are listed below:

- To model the optimal Coalition Formation using an MPEC model (1st and 2nd levels).
- The correction reactions of microgrids is modeled to the answers of game problem (3rd level).
- Stochastic modeling of the optimal coalition formation problem.

This paper is arranged as follows; an introduction to the introduced model for the formation of coalition is given in Section 2 along with the development of the model. The results of the simulation are given in Section 3. Section 4 represents the conclusion.

2. MODEL DESCRIPTION

2.1. Model Structure

A novel model for optimal operation in a multiple microgrid is presented. The microgrids contain wind power plants (WPP), boiler (B), distributed conventional generation (DCG) unit, combined heat and power (CHP) unit, responsive load (RL), energy storage system (ESS), and Unresponsive load (UL).

The microgrids together form a multiple microgrid. The model is based on the assumption that multiple microgrids can form an alliance with independent energy storage system (IESS) and distributed generation (IDG). The purpose of forming a coalition is to achieve optimal cumulative energy management for all coalition participants. The energy management of the coalition participants is performed using the central operator.

The central operator, in order to achieve the optimal state of the whole coalition, determines how the coalition participants and the upstream network exchange energy. In this case, along with the technical specifications, the central operator will also consider the economic aspects of the whole coalition and will seek to increase the profits of the whole coalition. Here, game theory is used to model the problem from the perspective of the central operator for energy management of coalition. The introduced model relies on cooperative game method. Through this, the players can find a standard strategy to increase the benefits of the whole coalition.

The coalition contains N + 2 players including N microgrid and independent energy storage and distributed generation. In this system, a wind farm is considered as independent distributed generation.

According to Fig. 1, at first, a bi-level problem is resolved from the stand point of central operator to find the obligations of players. The obligation consists of the level of energy exchange between the players taking part in the upstream network and the coalition.

After determining the obligations by the problem solved by the central operator, the local operators control the energy and the optimum use of resources found in the local microgrids. This is done independently for local microgrids. It is possible to formulate and solve this problem as a way to optimize one for the local microgrids. Therefore, the third level contains N-independent optimization problems.

2.2. Proposed formulation

In order to formulate the scenario-based coalition energy management, first the formulation will be presented for each of the players. For this purpose, further formulation is performed for local microgrids and then for independent distributed generation sources (wind farm) and independent energy storage system. After that, the higher level of the problem will be formulated. The uncertainties of the wind power plants productions in the introduced model are modeled through a method of reduction and generation of a scenario. Here, scenarios are generated for the wind power plants productions, the model of autoregressive integrated moving average based on the historical data is used. Also, for scenario reduction, the fast-forward selection algorithm is utilized [22].

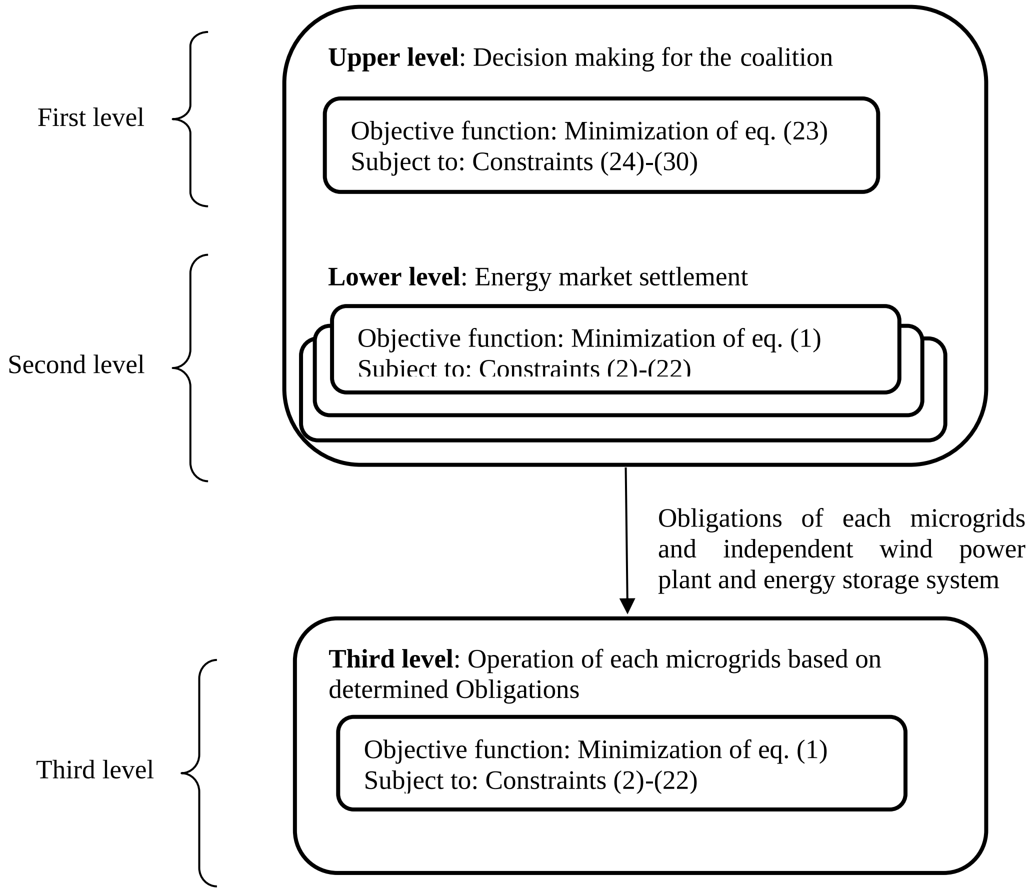

Fig. 1. The proposed model.

2.2.1 Local microgrids formulation

Each microgrid to participate in the coalition is designed to minimize operating costs as follows:

$$min\sum_{s=1}^{N_s}\sum_{t=1}^{24}\left\{\begin{array}{c}\overbrace{MC_i^c\times P_{ist}^c}^{1}+\overbrace{MC_i^{CHP}\times P_{ist}^{CHP}}^{2}+\overbrace{MC_i^B\times H_{ist}^B}^{3}\\ +\overbrace{MC_i^{ch}\times P_{ist}^{ch}+MC_i^{dis}\times P_{ist}^{dis}}^{4}\\ +\overbrace{\beta_i^{DR}\times P_{ist}^{DR}}^{5}+\overbrace{\alpha_t\times\left(P_{it}^{buy}-P_{it}^{sell}\right)}^{6}\end{array}\right\} \qquad (1)$$

In (1), term 1 determines the expense of power generation by the source of distributed generation. term 2 calculates the cost of generating power by the CHP. The cost of heat generation by the boiler is determined by term 3. The price of operating the energy storage system in discharge and charge modes is given by term 5. Demand response and power exchange costs are determined by terms 5, and 6, respectively.

Local microgrid limitations are:

Distributed conventional generation unit constraints:

The production capacity of a conventional power plant unit is restrained as follows [23].

$$\underline{P_i^c}\le P_{ist}^c\le\overline{P_i^c} \qquad \forall i,\forall s,\forall t \qquad (2)$$

The power changing rate of the standard power plant in microgrid *i* is modeled as follows:

$$P_{ist}^c-P_{ist-1}^c\le RU_i^c \qquad \forall i,\forall s,\forall t \qquad (3)$$

$$P_{ist-1}^c-P_{ist}^c\le RD_i^c \qquad \forall i,\forall s,\forall t \qquad (4)$$

The amount of pollution resulting from the generation of electrical energy through a standard power plant in microgrid *i* is determined linearly and in proportion to the production energy as follows:

$$E_{ist}^c=P_{ist}^c\times ER_i \qquad \forall i,\forall s,\forall t \qquad (5)$$

CHP unit constraints:

The limitation of the production capability of the CHP unit is as follows [24]:

$$\underline{P_i^{CHP}}\le P_{ist}^{CHP}\le\overline{P_i^{CHP}} \qquad \forall i,\forall s,\forall t \qquad (6)$$

The power changing rate of the CHP unit in microgrid *i* is limited as follows:

$$P_{ist}^{CHP} - P_{ist-1}^{CHP} \leq RU_i^{CHP} \qquad \forall i, \forall s, \forall t \qquad (7)$$

$$P_{ist-1}^{CHP} - P_{ist}^{CHP} \leq RD_i^{CHP} \qquad \forall i, \forall s, \forall t \qquad (8)$$

The CHP unit pollution is the same as the standard power plants, which is:

$$E_{ist}^{CHP} = P_{ist}^{CHP} \times ER_i^{CHP} \qquad \forall i, \forall s, \forall t \qquad (9)$$

The level of generated heat in the CHP in microgrid *i* is determined as follows:

$$H_{ist}^{CHP} = P_{ist}^{CHP} \times HR_i^{CHP} \qquad \forall i, \forall s, \forall t \qquad (10)$$

Boiler constraints:

The generation of heat in the boiler in microgrid *i* is limited as follows [25]:

$$0 \leq H_{ist}^{B} \leq \overline{H_i^{B}} \qquad \forall i, \forall s, \forall t \qquad (11)$$

The amount of pollution produced by the boiler will be obtained as follows:

$$E_{ist}^{B} = H_{ist}^{B} \times ER_i^{B} \qquad \forall i, \forall s, \forall t \qquad (12)$$

Energy storage system constraints:

The energy storage system state is determined as follows [26]:

$$E_{ist}^{s} = E_{ist-1}^{s} + \eta_i^{s,ch} \times P_{ist}^{ch} - \frac{1}{\eta_i^{s,dis}} \times P_{ist}^{dis} \; \forall i, \forall s, \forall t \qquad (13)$$

The energy stored each day is given as follows:

$$E_{is24}^{s} = E_{is0}^{s} \qquad \forall i, \forall s \qquad (14)$$

The power balance relationship in the energy storage is determined as follows:

$$\sum_{t=1}^{24} \eta_i^{s,ch} \times P_{ist}^{ch} = \sum_{t=1}^{24} \frac{1}{\eta_i^{s,dis}} \times P_{ist}^{dis} \; \forall i, \forall s \qquad (15)$$

The storage energy limit is formulated as follows:

$$\underline{E_i^{s}} \leq E_{ist}^{s} \leq \overline{E_i^{s}} \qquad \forall i, \forall s, \forall t \qquad (16)$$

The power of discharging and charging of the energy system is limited as follows:

$$0 \leq P_{ist}^{ch}, P_{ist}^{dis} \leq \overline{P_i^{s}} \qquad \forall i, \forall s, \forall t \qquad (17)$$

Flexible load constraints:

Flexible load response capability is limited as follows:

$$0 \leq P_{ist}^{DR} \leq \overline{P_i^{DR}} \qquad \forall i, \forall s, \forall t \qquad (18)$$

General microgrid constraints:

The equilibrium relationship of electrical power in the microgrid is formulated as follows:

$$P_{ist}^{c} + P_{ist}^{CHP} + P_{ist}^{dis} + P_{ist}^{w} + P_{ist}^{DR} + P_{it}^{buy} = P_{ist}^{ch} + P_{ist}^{fl} + P_{ist}^{vl} + P_{it}^{sell} \qquad \forall i, \forall s, \forall t \qquad (19)$$

Energy exchange capability is limited by the constraint below:

$$0 \leq P_{it}^{buy}, P_{it}^{sell} \leq \overline{P_i^{trade}} \qquad \forall i, \forall t, \forall s \qquad (20)$$

The heat balance relationship in every microgrid is formulated as follows:

$$H_{ist}^{B} + H_{ist}^{CHP} = H_{ist}^{l} \qquad \forall i, \forall s, \forall t \qquad (21)$$

The pollution for each microgrid is limited as follows.

$$E_{ist}^{B} + E_{ist}^{c} + E_{ist}^{CHP} \leq \overline{E_{it}} \qquad \forall i, \forall s, \forall t \qquad (22)$$

2.2.2 Modeling the Coalition Problem

The upper-level objective function is given to minimize the cumulative operation expense of the coalition members:(23)

$$min \sum_{s=1}^{N_s} \sum_{t=1}^{24} \left(\left(\sum_{i=1}^{N} \left(\begin{array}{c} \overbrace{MC_i^{c} \times P_{ist}^{c}}^{1} + \overbrace{MC_i^{CHP} \times P_{ist}^{CHP}}^{2} + \\ \overbrace{MC_i^{B} \times H_{ist}^{B}}^{3} + \overbrace{MC_i^{ch} \times P_{ist}^{ch} + MC_i^{dis} \times P_{ist}^{dis}}^{4} \\ + \overbrace{\beta_i^{DR} \times P_{ist}^{DR}}^{5} + \overbrace{\alpha_t \times \left(P_{it}^{buy} - P_{it}^{sell}\right)}^{6} \end{array} \right) \right) + \begin{array}{c} \overbrace{MC_c^{c,ch} \times P_{ts}^{c,ch} + MC_c^{c,dis} \times P_{ts}^{c,dis}}^{7} + \\ \overbrace{\alpha_t \times \left(P_t^{c,buy} - P_t^{c,sell}\right)}^{8} \end{array} \right) \qquad (23)$$

Terms 1 to 6 have already been introduced and are similar to Equation (1). In (23), the seventh term determines the expense of discharging and charging the storage system. The eighth term determines the expense of exchanges with the upstream network. The upper level limits are given below.

Independent Energy storage system constraints:

Charge state of the independent system of energy storage is determined as follows:

$$\mathrm{E_{ts}^{cc}} = \mathrm{E_{ts-1}^{cc}} + \eta^{\mathrm{c,ch}} \times \mathrm{P_{ts}^{c,ch}} - \frac{1}{\eta^{\mathrm{c,dis}}} \times \mathrm{P_{ts}^{c,dis}} \qquad \forall \mathrm{t}, \forall \mathrm{s} \qquad (24)$$

The energy stored in the independent system of energy storage in each day is:

$$E_{s24}^{cc} = E_{s0}^{cc} \tag{25}$$

The balance relationship for the independent energy storage system is:

$$\sum_{t=1}^{24} \eta^{c,ch} \times P_{ts}^{c,ch} = \sum_{t=1}^{24} \frac{1}{\eta^{c,dis}} \times P_{ts}^{c,dis} \qquad \forall s \tag{26}$$

Energy constraint for the independent energy storage system is:

$$\underline{E^{cc}} \le E_{ts}^{cc} \le \overline{E^{cc}} \qquad \forall t, \forall s \tag{27}$$

The power of discharging and charging of the independent system of energy storage is limited as follows.

$$0 \le P_{ts}^{c,ch}, P_{ts}^{c,dis} \le \overline{P^{cc}} \qquad \forall t, \forall s \tag{28}$$

The limits of power balance for the entire coalition are:

$$\begin{aligned}&\sum_{i=1}^{N}\left(P_{ist}^{c} + P_{ist}^{CHP} + P_{ist}^{dis} + P_{ist}^{w} + P_{ist}^{DR} + P_{it}^{buy}\right) \\ &+P_{ts}^{c,dis} + P_{ts}^{wc} + P_{t}^{c,buy} \\ &= \sum_{i=1}^{N}\left(P_{ist}^{ch} + P_{ist}^{fl} + P_{ist}^{vl} + P_{it}^{sell}\right) + P_{t}^{c,ch} \\ &+ P_{t}^{c,sell} \qquad \forall t, \forall s\end{aligned} \tag{29}$$

The exchange of power with the upstream network is restrained by:

$$0 \le P_{t}^{c,buy}, P_{t}^{c,sell} \le \overline{P^{c,trade}} \qquad \forall t, \forall s \tag{30}$$

In this paper, to solve the coalition problem, modeling the problem from a bi-level model is proposed. Decisions at the upper level are made about how to exchange players from the central operator's perspective. The operational choices at the lower level are made for local microgrids. Thus, we will face mathematical program with equilibrium constraints (MPEC). This problem was solved using the main-dual method for conversion where a strong double equation replaces the complementary conditions [27].

2.2.3 Third-level formulation of the proposed model

The 1st and 2nd levels are solved as a bi-level problem (MPEC problem). The output of the MPEC model will be the exchange energy of the microgrids participating in the alliance with each other and the upstream network. By solving the bi-level optimization problem mentioned in the upper pages, highlighting the obligations of the microgrids, energy storage system, and independent wind power plant, in the 3rd level, we can determine the way each microgrid is operated. It is represented as a one-level optimization from the standpoint of the local operators. Thus, the problem formulation is like to that of section 2.2.1.

3. NUMERICAL RESULTS

To show the proposed model capabilities, a system with three microgrids, one independent wind power plant, and one independent system for energy storage is considered. The general structure of the model is pictured in Fig. 1. Tables 1 to 5 present the features of standard power plants, energy storage system, boiler, and CHP in the microgrids. Fig. 2 illustrates the electrical loads in the microgrids. Fig. 3 also represents the flexible loads in the microgrids. Fig. 4 illustrates the thermal loads in the microgrids. The generations of the wind power plants in the microgrids in a sample day are depicted in Fig. 5. The output of the independent wind power plant in a sample day is shown in Fig. 6. It is assumed that the highest interchange capability in microgrids and exchange with the upstream network is equal to 2 MW. The maximum pollution production per hour is assumed to be 1000 lb.

Table 1. Conventional power plants properties.

Microgrid	ER_i (lb/kwh)	RD_i^c (kW/h)	RU_i^c (kW/h)	$\overline{P_i^c}$ (kW)	$\underline{P_i^c}$ (kW)	MC_i^c ($/kW)
1	0.012	3000	3000	7000	0	0.1
2	0.013	2000	2000	6000	0	0.12
3	0.015	3000	3000	7000	0	0.09

Table 2. CHP properties.

Microgrid	HR_i^{CHP}	ER_i^{CHP} (lb/kwh)	RD_i^{CHP} (kW/h)	RU_i^{CHP} (kW/h)	$\overline{P}_i^{CHP}$ (kW)	$\underline{P}_i^{CHP}$ (kW)	MC_i^{CHP} ($/kW)
1	1.85	0.014	1000	1000	3000	0	0.11
2	1.9	0.013	1000	1000	4000	0	0.13
3	1.95	0.014	1500	1500	5000	0	0.125

Table 3. Boiler properties.

Microgrid	ER_i^{B} (lb/kwh)	$\overline{H}_i^{B}$ (kW)	MC_i^{B} ($/kW)
1	0.01	2000	0.038
2	0.011	1500	0.042
3	0.012	1800	0.04

Table 4. Energy storage system properties.

Microgrid	$\overline{P}_i^{s}$ (kW)	$\overline{E}_i^{s}$ (kWh)	$\underline{E}_i^{s}$ (kWh)	$\eta_i^{s,dis}$	$\eta_i^{s,ch}$	MC_i^{dis} ($/kW)	MC_i^{ch} ($/kW)
1	100	500	0	0.95	0.95	0.01	0.01
2	100	400	0	0.95	0.95	0.01	0.01
3	150	600	0	0.95	0.95	0.01	0.01

Table 5. Independent energy storage system properties.

$\overline{P}_i^{s}$ (kW)	$\overline{E}_i^{s}$ (kWh)	$\underline{E}_i^{s}$ (kWh)	$\eta_i^{s,dis}$	$\eta_i^{s,ch}$	MC_i^{dis} ($/kW)	MC_i^{ch} ($/kW)
100	300	0	0.95	0.95	0.01	0.01

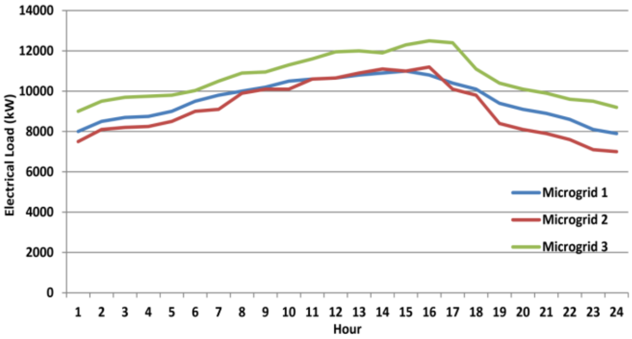

Fig. 2. Electrical load in microgrids.

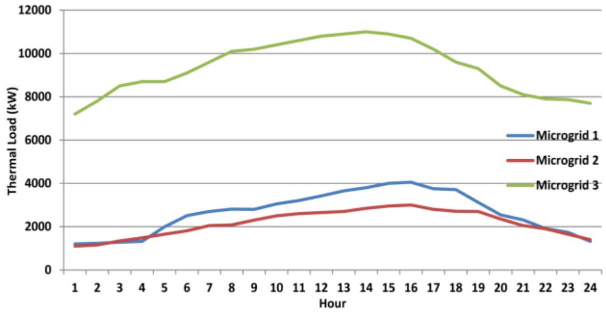

Fig. 4. Thermal load in microgrids.

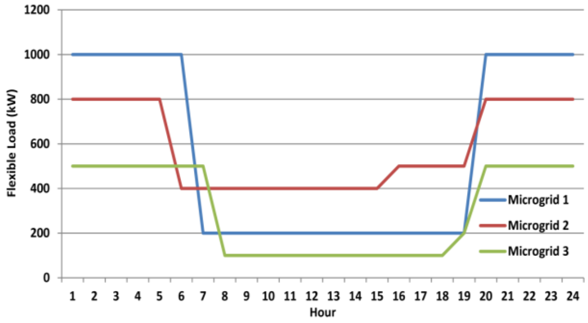

Fig. 3. Flexible load in microgrids.

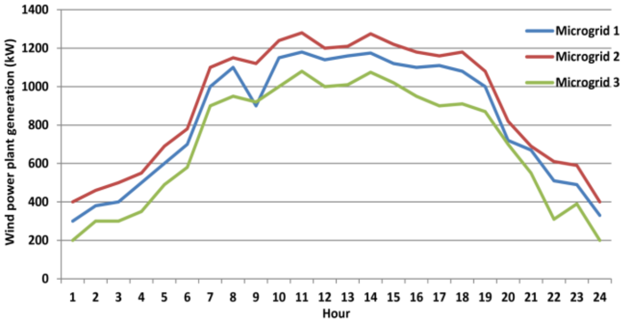

Fig. 5. Wind power plant generation in microgrids.

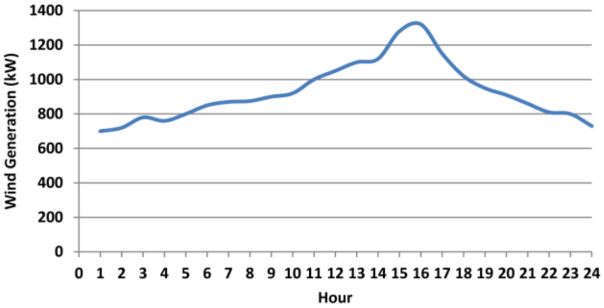

Fig. 6. Independent wind power plant generation.

The scenarios of the wind power generations are generated by the explained procedure in subsection 2.2.2 using MATLAB software. Then, the scenario reduction process is performed to achieve ten scenarios. Through solving the MPEC problem in GAMs, the bi-level model output, the amount of exchange between different microgrids, as well as the coalition exchange with the upstream network will be determined. The findings indicated that the 1st and 2nd microgrids receive energy and the 3rd microgrid supplies energy. The energies received by the 1st and 2nd microgrids are presented in Figs. 7 and 8, respectively. The energy supplied by the 3rd microgrid is illustrated in Fig. 9. The results also show that the coalition will deliver energy to the upstream grid. The energy delivered to the upstream grid is presented in Fig. 10. The charge condition of the independent storage for a scenario with high probability is also shown in Fig. 11. The results show that this energy storage system is charged about hours 1, 3, 6, and 8 and discharged at 11, 13, 15, and 16 hours.

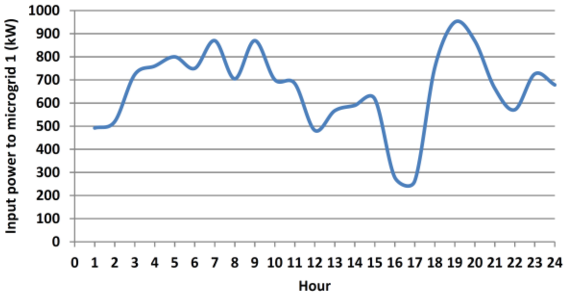

Fig. 7. Input power to microgrid 1.

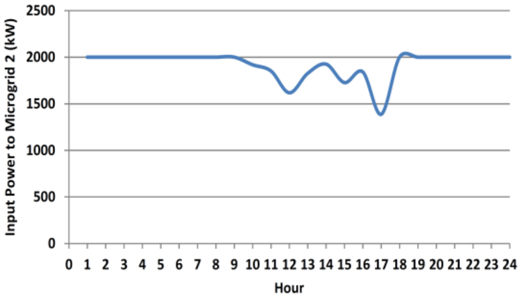

Fig. 8. Input power to microgrid 2.

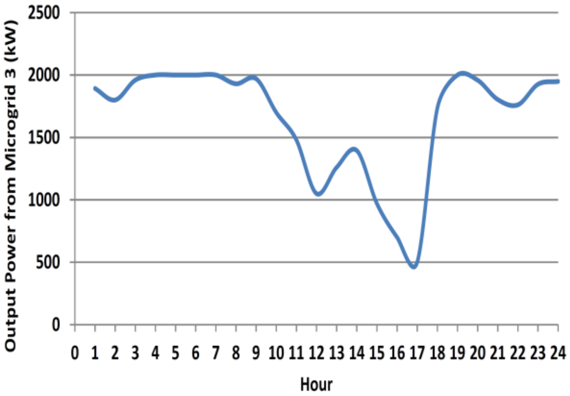

Fig. 9. Output power from microgrid 3.

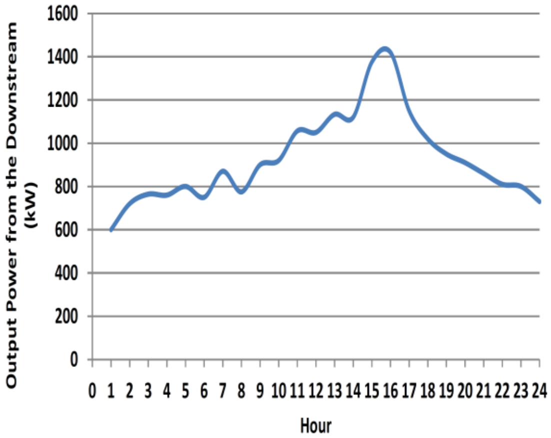

Fig. 10. Coalition output to the upstream network.

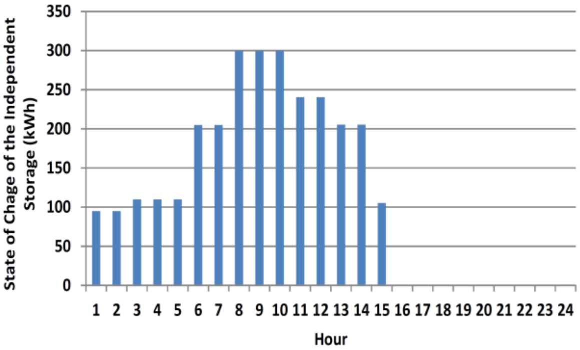

Fig. 11. State of charge of the independent energy storage system.

By resolving the MPEC model, the volumes of exchange between microgrids are taken as the input of the one level problem for microgrids operation. The problems are solved in GAMs. Fig. 12 shows the standard power plants generation in microgrids for a scenario with high probability. The productions of CHPs in this scenario are displayed in Fig. 13. Also, the charge conditions of the systems of energy storage in the microgrids are illustrated in Figs. 14, 15, and 16.

The system for energy storage in microgrid needs 1 to 6 hours to charge and 12 to 16 hours to discharge. The energy storage in microgrid 2 needs 1 to 4 hours to charge, 12 to 16 hours to discharge. The energy storage in microgrid 3 is charged at hours 4 to 8 and discharged at hours 13 to 16. The reason for discharging the energy storage systems between hours 12 to 16 is due to the significant electrical energy consumed during these hours. Without an energy storage system, more electrical energy would have to be received from other microgrids or the upstream network in order to supply electrical demands.

Studies show that the boilers are not produced during the 1st and 2nd microgrids. If so, the thermal loads are generated by the CHP units. However, in their microgrid, along with the CHP unit, heat is also generated by the boiler. The boiler's thermal energy during the third microgrid in the case of a high probability is illustrated in Fig. 17.

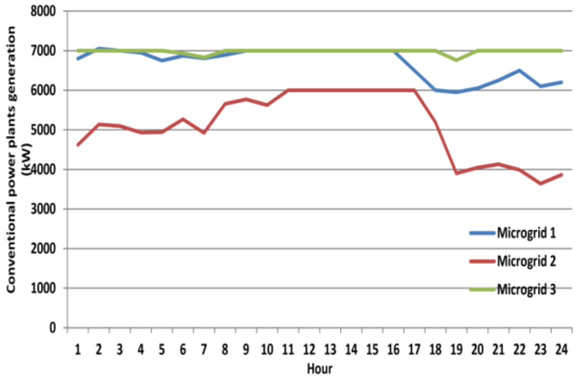

Fig. 12. Conventional power plants generation in microgrids.

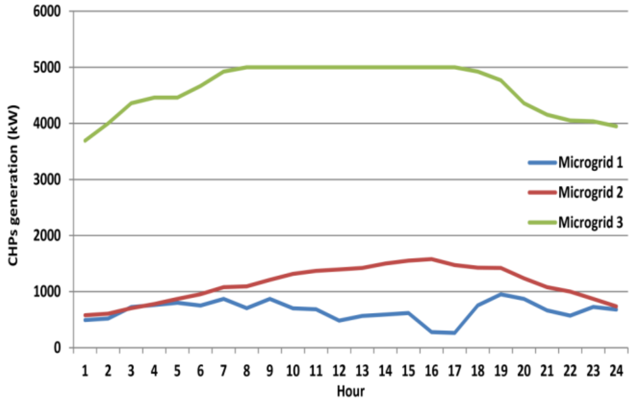

Fig. 13. CHP units generation in microgrids.

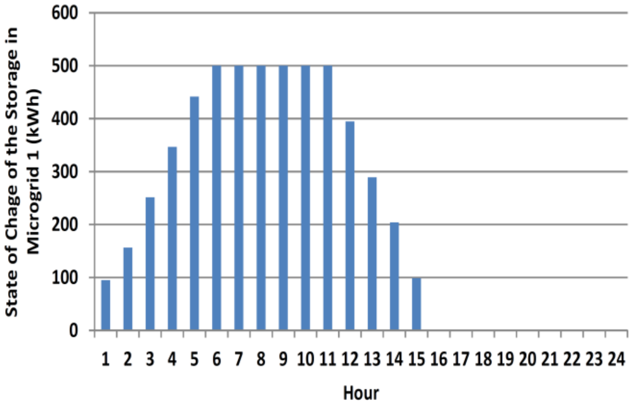

Fig. 14. State of charge of the energy storage system in microgrid 1.

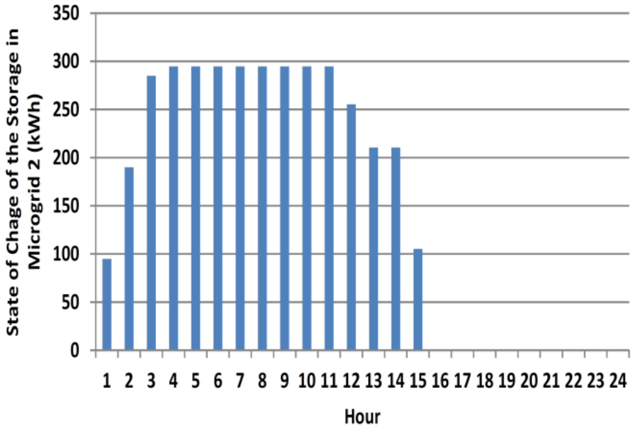

Fig. 15. State of charge of the energy storage system in microgrid 2.

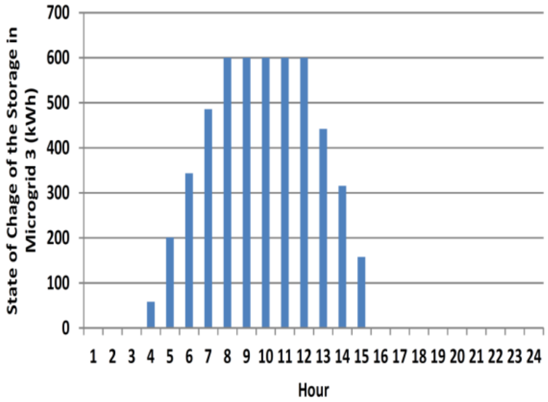

Fig. 16. State of charge of the energy storage system in microgrid 3.

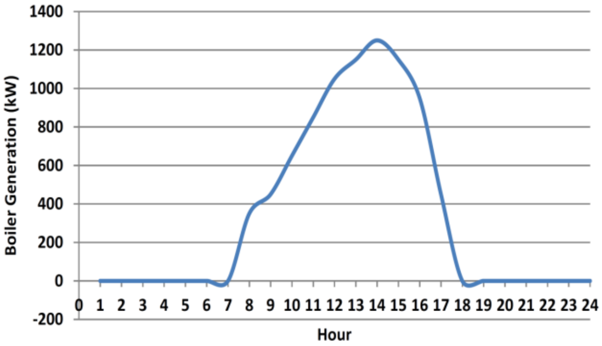

Fig. 17. Thermal energy generation by the boiler in microgrid 3.

4. CONCLUSION

A novel scenario-based model is presented for more efficient operation planning of several microgrids system beside a number of independent elements. The independent elements include a system of energy storage and a wind power plant. In order to consider the decision independence of microgrids and independent elements, the problem is modeled using the game theory. In fact, microgrids and independent elements as the main players can create a coalition and decide on the operation planning to meet the local demand and also exchange power with other produces and the main grid. To this end, the model was implemented at three diverse levels and how to operate the electrical and thermal energy resources and the energy storage systems has been determined. The findings indicated that along with providing local electrical and thermal consumption, it is possible to deliver energy to the upstream network and make more profit.

Nomenclature	
Indices	
i	Microgrids index
t	Hour’s index
s	Index of scenarios
Constants	
N	Microgrids number
Ns	Scenarios number
MC_i^c	Marginal expenses of the standard generation unit distributed in microgrid *i*
MC_i^{CHP}	Marginal expenses of the CHP in microgrid *i*
MC_i^B	Marginal expenses of the boiler in microgrid *i*
MC_i^{ch}	Charging marginal expenses of the systems used for storing energy in microgrid *i*
MC_i^{dis}	Discharging marginal expenses of the system used for storing energy in microgrid *i*
β_i^{DR}	Cost received by the flexible load per unit of power in the microgrid
α_t	Exchange power cost at time *t*
$\overline{P_i^c}$	The highest limitation of generation of distributed standard unit of generation in microgrid *i*
$\underline{P_i^c}$	The lowest limitation of generation of distributed standard unit of generation in microgrid *i*
RU_i^c	Ramping up of the standard distributed production unit in microgrid *i*
RD_i^c	Ramping down of the standard distributed production unit in microgrid *i*
ER_i	Rate of pollution of the standard distributed production unit in microgrid *i*
$\overline{P_i^{CHP}}$	Highest limitation of electrical production of CHP unit in microgrid *i*
$\underline{P_i^{CHP}}$	Lowest limitation of electrical production of CHP unit in microgrid *i*
RU_i^{CHP}	The CHP unit ramp-up in microgrid *i*
RD_i^{CHP}	The CHP unit ramp down in microgrid *i*
ER_i^{CHP}	The CHP unit rate of pollution in microgrid *i*
HR_i^{CHP}	The CHP unit heat rate in microgrid *i*
$\overline{H_i^B}$	The highest limitation of CHP unit heat generation in microgrid *i*
ER_i^B	Boiler rate of production pollution in microgrid *i*
$\eta_i^{s,ch}$	Performance of charging the system of energy storage in microgrid *i*
$\eta_i^{s,dis}$	Efficiency of discharging the system of energy storage in microgrid *i*
$\underline{E_i^s}$	Lowest capacity of energy storage in microgrid *i*
$\overline{E_i^s}$	Highest capacity of energy storage system in microgrid *i*
$\overline{P_i^s}$	Highest limitation of power in the system for storing energy in microgrid *i*
$\overline{P_i^{DR}}$	Highest power lowered by flexible load in microgrid *i*
$\overline{P_i^{trade}}$	Highest power to trade for microgrid *i*
$\overline{E_{it}}$	Highest allowable pollution for microgrid *i* at hour *t*
$MC^{c,ch}$	The marginal expenses of charging the independent system for storing energy
$MC_c^{c,dis}$	The marginal expenses of discharging in the independent system for storing energy
$\overline{P^{c,trade}}$	The highest tradable power with upstream network

Variables	
P_{ist}^{c}	Distributed standard production unit in microgrid *i* at *t* and scenario *s*
P_{ist}^{CHP}	Electrical production of CHP in microgrid *i* at *t* and scenario *s*
H_{ist}^{B}	Thermal generation of CHP in microgrid *i* at *t* and scenario *s*
P_{ist}^{ch}	Energy storage system charging power in microgrid *i* at *t* and scenario *s*
P_{ist}^{dis}	Energy storage system discharging power in microgrid *i* at *t* and scenario *s*
P_{ist}^{DR}	Reduced power by flexible load in microgrid *i* at *t* and scenario *s*
P_{it}^{buy}	Procured energy by microgrid *i* at *t*
P_{it}^{sell}	Sold energy by microgrid *i* at *t*
E_{ist}^{c}	Generated pollution by standard unit in microgrid *i* at *t* and scenario *s*
E_{ist}^{CHP}	Produced pollution by CHP unit in microgrid *i* at *t* and scenario *s*
H_{ist}^{CHP}	Generation of heat of CHP in microgrid *i* at *t* and scenario *s*
E_{ist}^{B}	Generated pollution in the boiler in microgrid *i* at *t* and scenario *s*
E_{ist}^{s}	Energy charge state in microgrid *i* at *t* and scenario *s*
P_{ist}^{fl}	Inflexible demand power in microgrid *i* at *t* and scenario *s*
P_{ist}^{vl}	Flexible demand power in microgrid *i* at *t* and scenario *s*
H_{ist}^{l}	Heat demand in microgrid *i* at *t* and scenario *s*
$P_{ts}^{c,ch}$	Power charge in independent system of energy storage at *t* and scenario *s*
$P_{ts}^{c,dis}$	Power discharge in independent energy storage system at *t* and scenario *s*
$P_{t}^{c,sell}$	Power sold to the upstream network at *t*
$P_{t}^{c,buy}$	Supplied power by the upstream network at hour *t*
P_{ts}^{wc}	Produced energy in independent wind power plant at *t* and scenario *s*

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