JJEE
Jordan Journal of Electrical Engineering

Volume 7, Number 2, June 2021
Pages 166-178
ISSN (Print): 2409-9600, ISSN (Online): 2409-9619

Energy Management in Multiple Micro-Grids Considering Uncertainties of Load Using Hierarchical Multi-Agent System

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Received: February 10, 2021 *Revised: March 11, 2021* *Accepted: March 16, 2021*

***Abstract*—** A micro-grid (MG) is an active low-voltage grid that includes renewable energy sources and different types of loads. Given that MGs consist of different distributed energy resources (DER), energy storage systems and different load types, integration of a distribution network and several distributed energy sources leads to creation of a multiple MG (MMG) system. In this paper, an energy management system (EMS) is proposed and implemented in JADE software environment to operate - considering load uncertainties – MMG with optimal power of distributed energy sources and optimal consumer loads with minimum cost based on hierarchical multi-agent system (HMAS). The obtained results reveal that the proposed EMS is capable of establishing energy management of distributed and storage energy resources in MMGs with the minimum possible cost.

***Keywords*—** Multiple micro-grid; Energy management system; Hierarchical multi-agent systems; Optimization; Uncertainties.

1. INTRODUCTION

The concept of energy management started with the advanced metering infrastructure (AMI) to improve on demand side management. However, with the emergence of Internet of Things (IoT) and advancement in communication technologies, energy management solutions have gained renewed interest to provide more flexibility to user as well as to offer intelligent services. A micro-grid (MG) is an independent, controllable and single energy system that consists of different load types, energy storages and control devices, and in which distributed generation (DG) and energy storage (ES) are connected directly parallel to the user's side. Smart network tries to prepare advanced control technology for the electrical power systems in different levels of production, transmission, and consumption. By applying the information technology concepts, conventional electrical power systems would be transformed to much safer, more flexible and highly efficient networks. In [1], researchers investigated a home energy management system design that focused on the use of IEEE 802.15.2 and Zigbee for user demand response and load management. In [2], authors proposed a hardware design system for home energy management using sensing technology and machine learning algorithm, to enable users achieve real time price response control over residential loads. In [3], the focus was on scheduling method that allows cost-effective delivery of power to appliances taking into account real time prices. In [4], a discussion has been made on a new approach regarding the integration of DG units in distribution networks in order to reduce the consumers peak demand. Logenthiran et al. reviewed the operation scheme of an industrial load, which participates in distributed resources (DR), considering the electricity price and the labor costs [5].

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Article's DOI: 10.5455/jjee.204-1612950717

In [6], a multi-agent control strategy for island mode has been presented. It adopted coordination of multi-agent platform, including level agent coordination, different regions agents and various agents of the components used in coordinated control strategy. This system has been implemented in order to indicate control strategy feasibility using Java programming language. In [7], a decentralized control structure - based on a multi-agent system (MAS) for automatic utilization of MG and using power electronic interface - has been proposed. It is presented in a system consisting of four distributed energy sources and has been shown using Matlab/Simulink environment.

Furthermore, a hierarchical control model, using a multi-agent system (MAS) for utilization of a MG through power electronic interface, has been developed [8]. Five types of agents including grid agent, central agent, generation agent, load agent, and cutoff agent were designed to be utilized using MATLAB and SIMULINK software. Researchers in [9] composed a conceptual approach of a MAS for controlling distributed energy resources (DERs) in MGs. Three types of agents, including regional agent (RA), local agent (LA), and service agent (SA) were defined. In addition, a two-layer control strategy was proposed for achieving local autonomy and global optimization in both the grid and island modes. In [10], a MAS based on control structure for MG has been presented. The structure's architecture included cooperative methods in order to achieve the goals defined by the user. In addition, researchers in [11] designed and created a new oriented hierarchical multi-agent distributed control system for MG conceptually. This MAS consisted of the management of several MGs agent, the control of MG agent, and the local agent. The entire system was interrelated through CORBA technology. Researchers in [12] offered a general framework for controlling MG based on MASs and a multi-agent confirmatory learning algorithm for automatic utilization in island mode of MG. Similarly, a completely distributed MAS based on reconstruction algorithm has been presented in [13]. It dealt with the distributed algorithm for determining coefficients. Researchers of [14] examined the design of MG energy resources which can supply the required energy of load for one year without outage. This caused oversizing of MG, suggesting that energy management system (EMS) must be designed in a way that prevents overcharging in energy storage devices.

On the other hand, authors tested the process of transitioning power systems toward smart grids (SG) and integrated advanced control methods, advanced measurement technologies, and telecommunication grids for the current power grid [15]. MG is a management structure and an innovative control at distribution level that supports the implementation of SG concept at distribution system level. According to [16], the problems of energy management of a MG, regardless of energy resources, are very variable. Therefore, in MG, the speed of updating orders must be high enough in order to track unexpected load changes as well as distributed generations with time constants close to time constants of the control system. This approach leads to reduced amount of exchanged information and, thereby, decreasing the demand for an expensive communication grid. In addition, distributed EMS-MG provides plug and play capability for additional installation of DER units and loads in the MG. Furthermore, researchers in [16] implemented a distributed EMS-MG based on MAS for a MG using MATLAB simulation software. However, given the limitations of simulation platform, a simple negotiation mechanism was used between the limited agents and functions of EMS-MG. In order to realize multi-objective management of

MGs in different time proportions, in the related architecture and coordination design, there is a need to integrate EMS-MG information in the cross sections between different controls. In [17], a multistep hierarchical optimization algorithm based on a MAS considering adjustable power and demand response for reducing operational cost of multiple MG (MMG) systems through MAS, has been proposed. However, given the limitations of the simulation platform, a simple negotiation mechanism between the limited agents and functions of EMS-MG has been used. In order to realize multi-objective management of MG in different time proportions, in the related architecture and coordination design, there is need to integrate EMS-MG information in the cross sections between different controls. In [18], a multistep hierarchical optimization algorithm based on a MAS considering adjustable power and demand response for reducing operational cost of MMG systems through MAS has been proposed.

Developing a proper model for the energy storage system (ESS) to achieve feasible and optimized results is necessary. Several models for planning of storage systems in MGs have been proposed [19, 20]. In [21], the researchers properly modeled an ESS with respect to operational constraints and limitations. In recent years, researchers proposed new techniques for scheduling of MGs. Researchers in [22] suggested a new modeled version of Symbiotic Organisms Search (SOS) to increase its total search ability in the local and global searches. In their research, several types of DGs and also an ESS have been modeled.

In this paper, for scheduling optimized energy management of the MG considering uncertainties of load by hierarchical multi agent system (HMAS), different scenarios have been followed in order to solve the optimization problem. The proposed EMS is implemented in JADE software environment for MMGs based on HMAS. The aim of this paper is to find the optimized power of DER units including wind turbines (WTs), micro-turbines (MTs), ESS as well as the consumer consumption pattern.

2. ENERGY MANAGEMENT BASED ON HMAS

In this section, the recommended MG structure is presented. Then, the agents and their tasks and relationships to each other are determined and the algorithm and strategy of MMG energy management has been presented by hierarchical MAS based on JADE platform. HMASs are more successful in controlling the DERs due to reliable communication and organized structure. For reliable operation in a MG, continuous monitoring and controlling should proceed for wind power, solar power, battery levels, loads and dynamic pricing. So, it is very important to process the best logical algorithm to get the most optimized solution considering all aspects such as safety, economy, and stability. Fig. 1 illustrates the developed system for performance of the proposed MMG algorithm which contains an ESS, WT, MT and consumer (C).

The MG is connected to the upstream grid and exchanges energy with it. The MG manager has the task of utilizing the MG. Further an agent has been considered for each of the units, with the responsibility of local control of the unit under its supervision. The recommended HMAS includes the agents of WT, ESS, MT, loads, MG management agent and upstream grid agent.

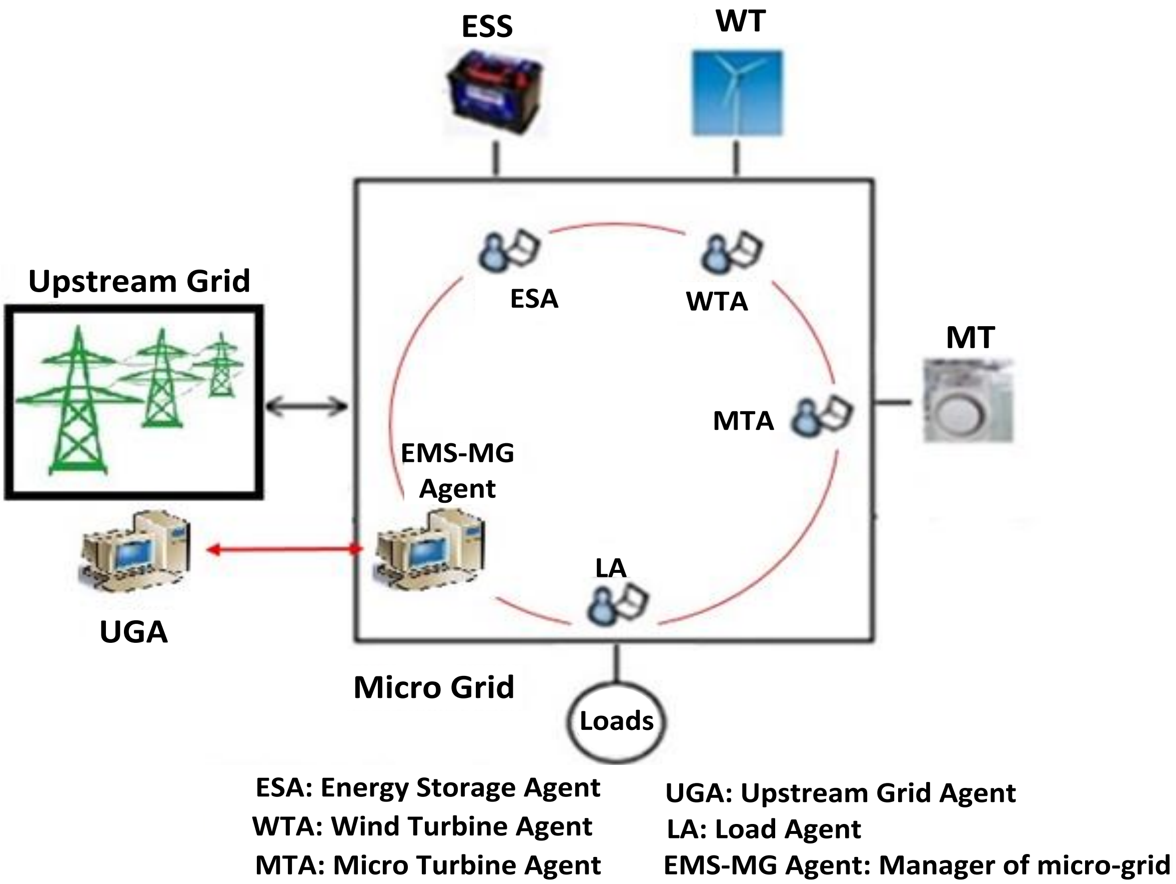

Fig. 1. Configuration of developed system.

Fig. 2 shows the structure of the proposed EMS-MMG. Based on the above requirements, the EMS-MG can be divided into three participants at three levels: i) the manager of MG agent, ii) the control agent and iii) the local agent.

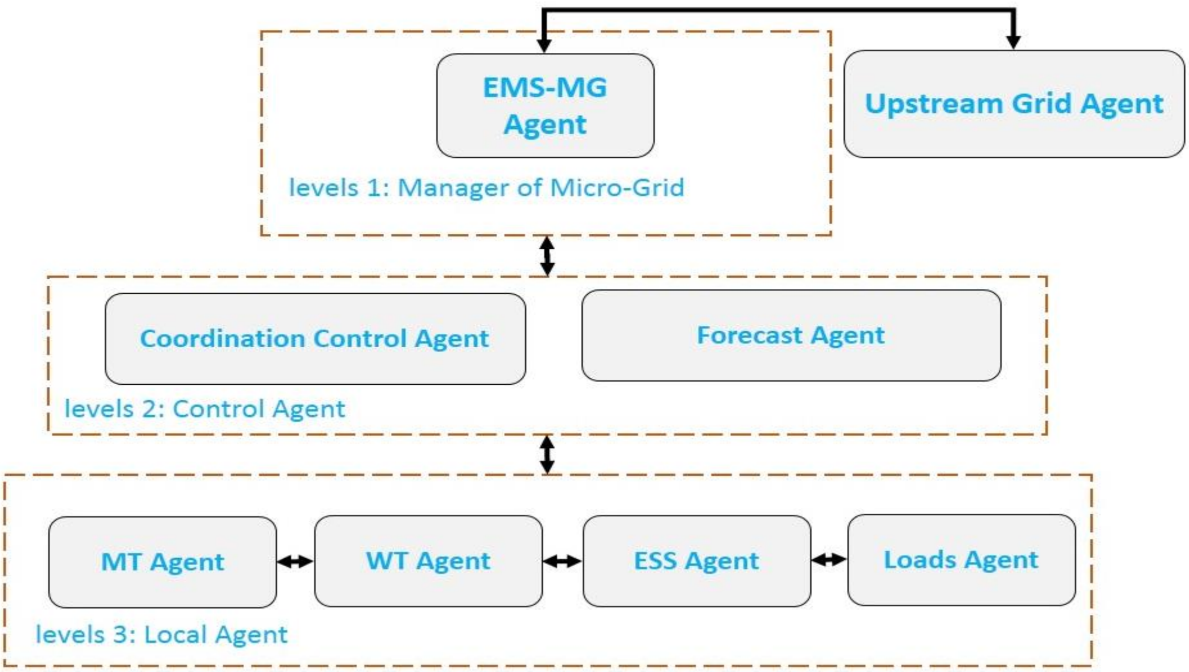

Fig. 2. The proposed HMAS structure.

Agent of the high level is as a measurement agent, which is designed to optimize the entire system. Agents of the medium level act as measurement agents that are designed to change the performance modes between the agents in order to enhance reliability and flexibility of DERs. The forecast agent performs very-short term consumers' forecast for each load based on both historical and real-time data using the proposed algorithms. The forecast agent is dedicated to data collection, including live weather data from the national weather forecasting station and electricity consumption data from the energy monitoring system. The agents of low level operate as combinatory agents including reactive and measuring layers. The reactive layer has been defined as the layer of recognition, understanding, and action, which is of top priority for rapid response to environmental emergency conditions. The measuring layer has been defined as the layer of supposition, tendency, and concept which is of high intelligence for planning how to operate the agents in order to achieve the set goals.

3. ENERGY MANAGEMENT SYSTEM

The challenge in planning MMGs with load responses and the consideration of uncertainty in availability of renewable energy have led to complexity of the problem.

Considering the importance of balancing an active power in the MMGs, it is assumed that the control center, at any time, has to deal with the problem of lack of production and the imbalance of active power. In the case of consumer collaboration in the load response plan, the assumption is that there exists 1.5-2 times the cost of MTs production to maintain the balance and stability of the pattern.

In order to validate the method of energy management of MMG based on the MASs, a MMG has been modeled in JADE software environment. The reason of using JADE is that it conforms to the FIPA standards and creates a space where the programmer can directly focus on the design of the operating system. The platform created by JADE allows users to easily focus on controlling and monitoring the power balance in the MG. JADE is a platform that facilitates the implementation of MASs and includes:

a) Runtime environment where JADE agents are enabled
b) Library of programming classes used to develop agents
c) Collection of graphical tools.

The base of the work is in the way in which different types of loads - that are active in encouraging-base project - are directed to upstream power network by smart agents. The MAS in this work includes responsive, managing, and upstream agents which carry their responsibilities in an efficient way. In this work, JADE has been used to manage the encouraging based loads since it is in line with the FIPA standards and helps the programmer to focus on designing the agents. Moreover, the JADE platform helps individuals to control and monitor the MGs. The encouraging-based system of power distribution network is a device consisting of software and hardware. The software has been designed to make the connections between electrical servers. The hardware consists of sensors, data loggers and modules which obtain the information from the upstream networks in the encouraging based managing system. The responses are done by the help of data loggers and sensors. The method of electrical and informational interactions of the mentioned MG is shown in Fig. 3 and the JADE settings are exhibited in Table 1.

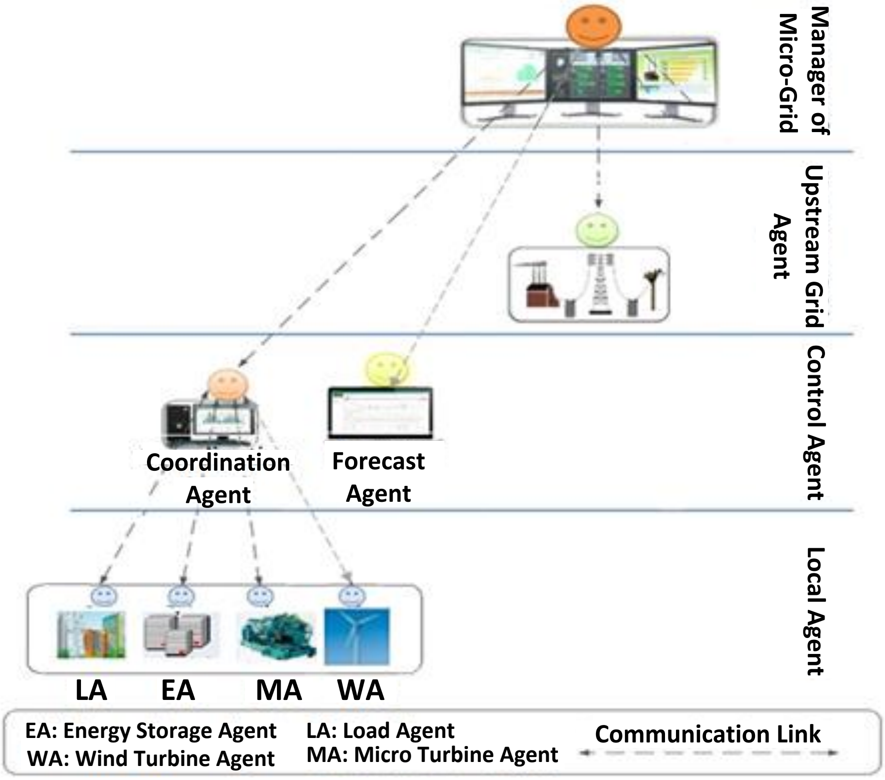

Fig. 3. Configuration of the proposed system.

Table 1. JADE settings.

Number of agents	Initial population size	Generations	Cross over rate	Mutation rate
7	3000	100	0.95	0.1

Optimizing the operation of the distribution network - including several MMGs and DERs, ESS - with consideration of uncertainty and types of loads are carried out in the following steps:

a) Collecting data of loads and WT
b) Scheduling the forecast for DERs amount and load considering uncertainty
c) Implementing the proposed method
d) Determining the optimal values.

As depicted in Fig. 3, the MG manager has information and interactions with the upstream grid manager and is responsible for coordination of the units with each other. The MT agent, after calculation of the cost of its generated power, announces the cost and the range of generated power to the MG's manager during the next 24 hours. The WT also informs the MG's manager about its magnitude of generated power along with its cost in the next 24 hours. The storage unit is considered for reducing the cost of utilization and supply of load power of the MG and is placed subordinate to the MG manager agent. Further, the load agent, according to incentive-based response plan, determines its range of power reduction and announces it to the MG's manager. The agent of upstream grid also announces the prices of the upstream grid within the next 24 hours to the MG manager.

The MG manager, after processing and optimizing the plan, determines the amount of charge and discharge of the storage in the next 24 hours, and also determines the extent of reductions of loads' use in the next 24 hours. It informs the MT agent about the amount of generated power of MTs. It further determines the magnitude of power required for exchange with the upstream grid and announces it to the related agent.

4. METHODOLOGY

In the proposed method, MG tries to minimize the total costs considering the technical constraints of MGs. In order to implement the mathematical model, the objective function is explained in order to maximize the profit of available units and meet the constraints. It is worth to note that in order to perceive the useful role of the storage device of the MG more clearly, the problem is investigated in a 24 h time period.

$$F(x) = \sum_{t=1}^{24} \left[\sum\nolimits_{a} P_{MT}^{t} B_{MT}^{t} + \sum\nolimits_{b} P_{WT}^{t} B_{WT}^{t} + \sum\nolimits_{c} P_{ESS}^{t} B_{ESS}^{t} \right] + P_{GRID}^{t} B_{GRID}^{t} \quad (1)$$

In this relation, a is the number of MTs, b is the number WTs, c is the number of ESS, $P_{MT}(t)$ is the active power generation of ith MT unit, $B_{MT}(t)$ is the bid of ith MT unit at hour t, $P_{WT}(t)$ is the active power generation of ith WT unit, B_{WT} (t) is the bid of ith WT unit at hour t, $P_{ESS}(t)$ is charge/discharge power of the jth battery at hour t, $B_{ESS}(t)$ is the bid of jth battery at hour t, $P_{GRID}(t)$ is the active power which is bought (sold) from (to) the utility at hour t and $B_{GRID}(t)$ is the bid of the utility at hour t.

Eq. (1) is the objective function of the problem. It includes the cost operation for the use of MTs, the cost of charging and discharging storage device, the cost of exchanging power with the upstream network and the cost of responsive loads. In this paper, the objective is to determine the optimal power of distributed energy sources and optimal power reduction of consumer loads based on HMAS using Gravitational Search Algorithm (GSA) in MMG. Fig. 4 shows the problem-solving flowchart.

The law of universal gravitation is one of the four basic forces in nature. It is one of the fundamental forces in nature. The gravitational force is proportional to the product of the mass, and is inversely proportional to the square of the distance. The gravitational force between two objects is calculated by:

$$F = G \frac{M_1 M_2}{R^2} \quad (2)$$

where F is the gravitational force between two objects, G is the gravitational constant, M_1 and M_2 are the masses of the objects 1 and 2, respectively and R is the distance between these two objects.

The GSA should make the moving particle in space into an object with a certain mass. These objects are attracted through gravitational interaction between each other, and each particle in the space will be attracted by the mutual attraction of particles to produce accelerations. Each particle is attracted by other particles and moves in the direction of the force. The particles with small mass move to the particles with great mass, so the optimal solution is obtained by using the large particles. The GSA can realize the information transmission through the interaction between particles. The GSA optimization procedure proceeds as follows:

Step 1: Initialize the positions and accelerations of all particles, the number of iterations and the parameters of the GSA

Step 2: Calculate the fitness value of each particle and update the gravity constant according to the equation of the universal gravitational constant

Step 3: Calculate the quality of the particles based on the obtained fitness values and the acceleration of each particle to find the optimal solution

Step 4: Calculate the velocity of each particle and update the position of that particle

Step 5: Return to step 2 if the termination condition is not satisfied. Otherwise, the output constitutes the optimal solution.

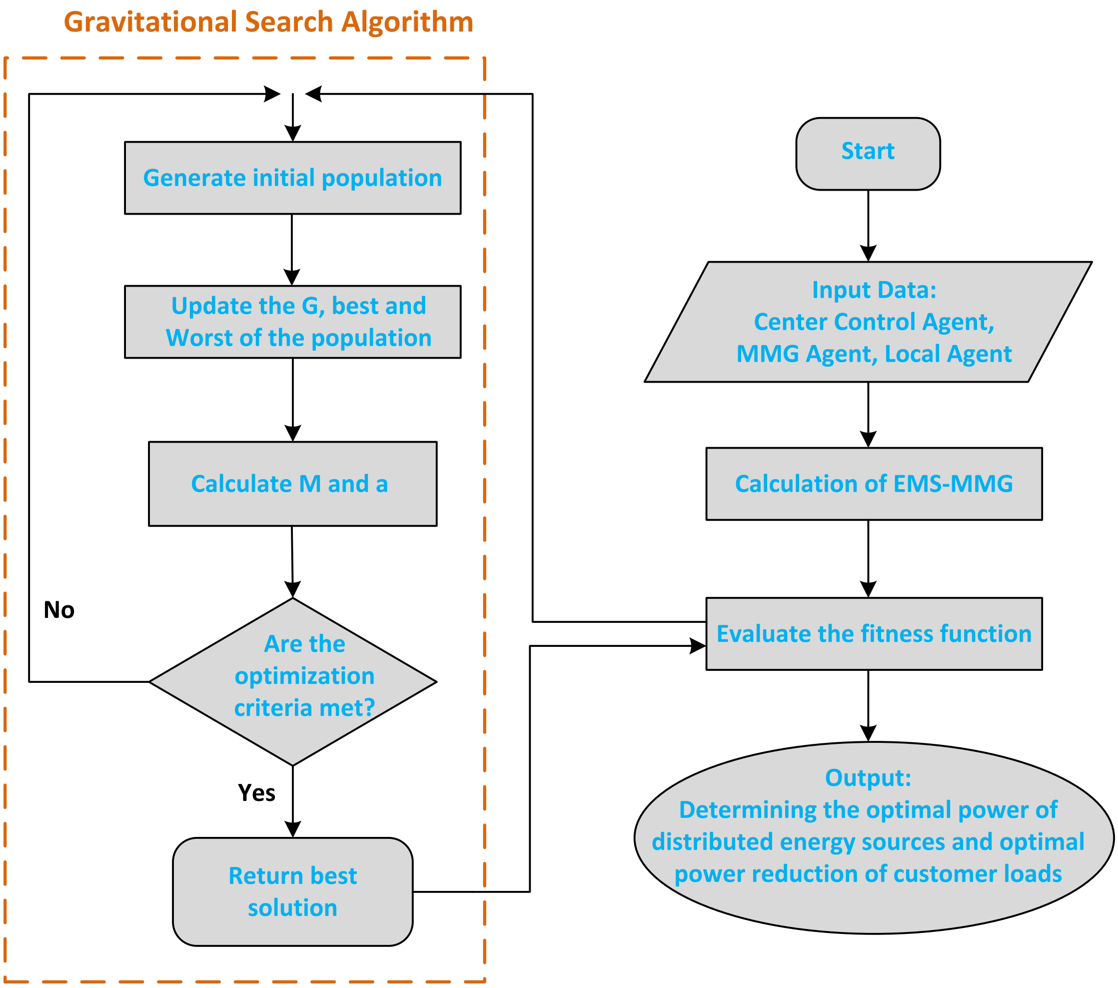

Fig. 4. Flowchart of the EMS strategy.

5. RESULTS AND DISCUSSION

In order to perform the simulations, the considered test system constitutes a MG structure that consists of a wind unit with a nominal power of 15 kW and a speed variation rate between Vci = 0 m/s to Vco = 25 m/s plus a MT that contains three units with a nominal power of 35 kW in addition to ESS that contains ten batteries with maximum charging and a discharge power of 30 kW, each as exhibited in Tables 2 and 3. The load consists of a 27 kW residential consumer, a 36 kW commercial consumer, and 33 kW industrial consumer as listed in Table 4. In Fig. 5, a profile of total power generation and total power demand for two demand scenarios is shown.

Table 2. Characteristics of the DG units.

Type	Number of Units	Max Capacity [kW]
WT	1	15
MT	3	35

Table 3. Characteristics of ESS.

Number	Min-Max SOC [kWh]	Max Charge/Discharge Power [kW]	Charge/Discharge Efficiency
10	5-100	-30 / +30	0.9

Table 4. Characteristics of the loads.

Type	Daily Peak [kW]	Max Capacity in hour [kW]
Industrial	610	33
Commercial	607	36
Residential	457	27

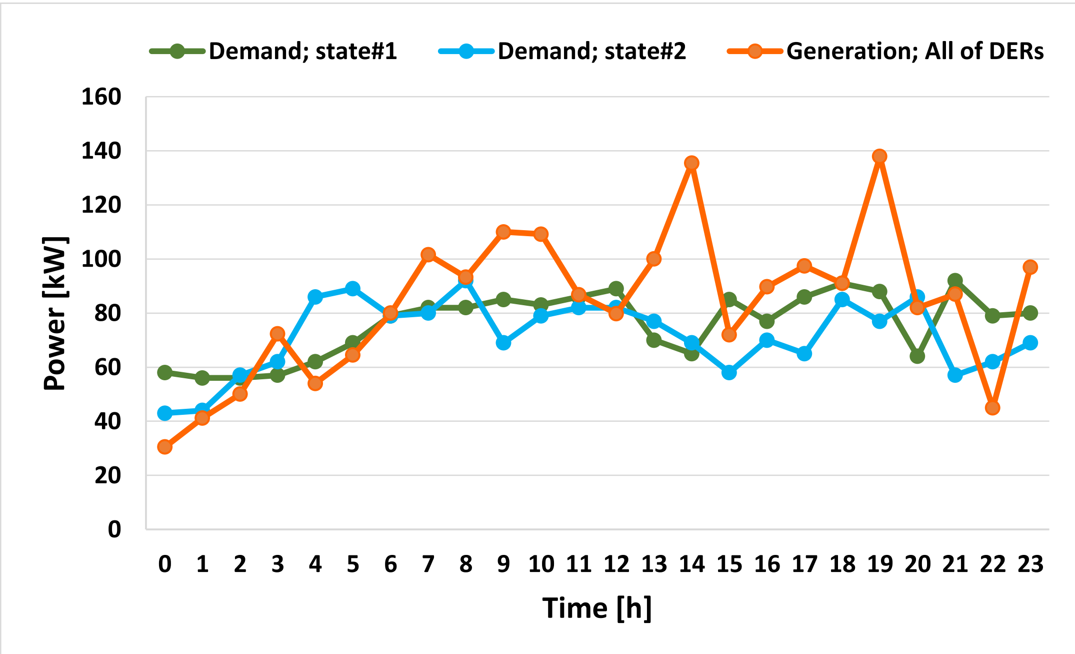

Fig. 5. Hourly profile of total power generation and demand.

The performance scenario of EMS of the MMG during the next 24 hours for different generations and consumptions has been simulated. The purpose of hierarchical MAS in all scenarios is that the most optimal energy exchange between MG and upstream grid occurs. Also, another goal is to determine the most appropriate power generated for distributed energy sources, storage, resources and the amount of power reduction of different types of loads with the lowest possible cost during a 24-hour period.

We have tested two scenarios of the consumers' load patterns on the proposed grid. In each of the two scenarios, MMGs are connected to the upstream network and the energy storage unit, MT unit, and WT feed the responsive residential, commercial, and industrial consumers. Figs. 6 and 7 exhibit the hourly planning of the MG for the first and the second scenarios, respectively.

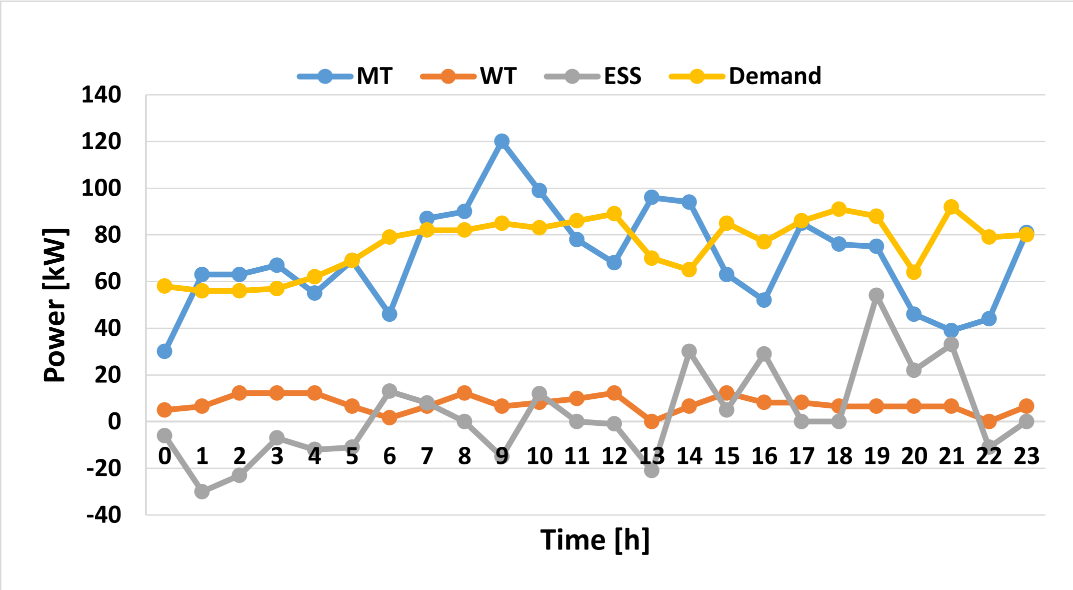

Fig. 6. Hourly planning of the MG with the proposed method for the first scenario.

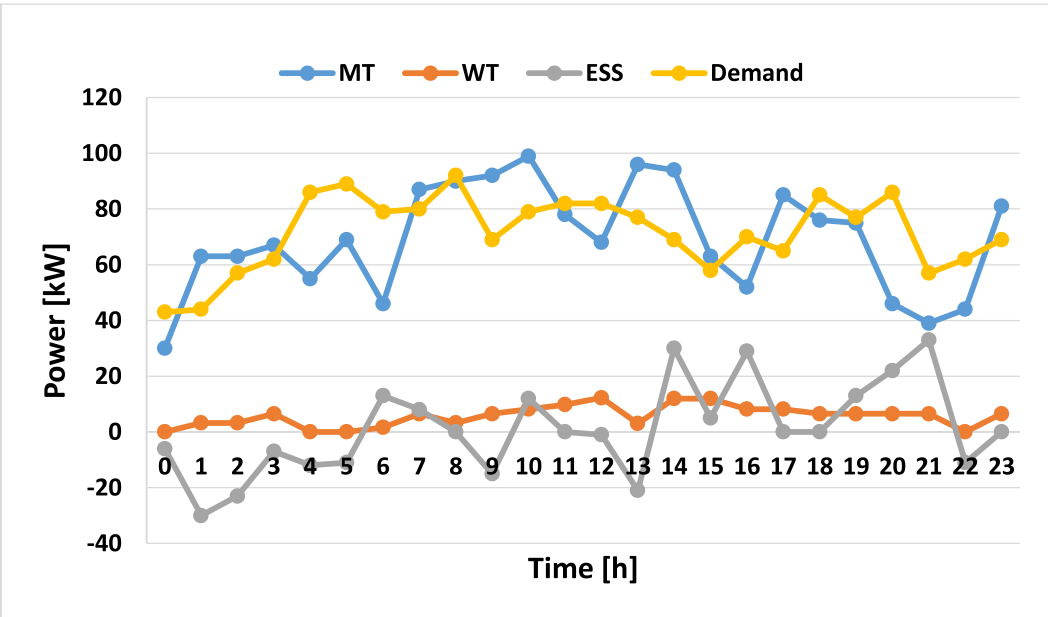

Fig. 7. Hourly planning of the MG with the proposed method for the second scenario.

According to the results, the total net emission of scenario 1 and 2 are 1176 kg and 1506.9 kg, respectively. Due to utilizing the maximum available power of WT, scenario 2 has the lowest net emission. Therefore, using the GSA - to minimize the objective function with the goal of optimizing the problem variables (production capacities of scattered production resources) with the condition that all system components must meet the constraints of the problem - the optimal power production in the MG is obtained and compared to that obtained using the particle swarm optimization algorithm [23] as exhibited inTable 5.

Table 5. Expected optimal power production in the sample MG.

Time [h]	With GSA		With PSO [23]	
	WT+ESS+MT [kW]	Grid [kW]	WT+ESS+MT [kW]	Grid [kW]
1	1.7	30	1.3	30
2	1.7	30	1.3	22
3	1.7	30	1.3	17
4	1.7	30	1.7	30
5	1.7	30	1.7	30
6	0.9	30	2.3	30
7	1.7	30	5.7	30
8	2.3	6.5	3.3	9
9	5.7	-19.5	4.7	-15.7
10	10.1	-20	9.1	-20.6
11	18.7	-30	11.7	-30
12	21.4	-30	17.4	-30
13	25.9	-30	3.9	-21.9
14	24.3	-30	2223	-30
15	9.7	-23	6.7	-15.7
16	7.3	-15	2.3	-11.3
17	2.7	-7	5.7	-5
18	1.7	21	5.7	22
19	1.3	30	17	30
20	1.7	15.2	1.3	21
21	1.3	-13	1.5	-13.3
22	1.3	-20	2	-19
23	0.9	30	1.3	30
24	0.6	30	1.7	30

All DG units generate power within their production range, or are satisfied in all the above terms (equations and inequalities). The results of Table 5 show that a large part of the load is supplied by the grid between 1 to 8 hours, due to the lower power cost rate by the above units than other units. The market price is higher at 9 to 17, 21 and 22 hours, and the extra power generated by the MG is sent to the upstream grid. By reducing the presence of WTs and micro turbine systems in power generation, the total cost will be reduced due to the higher power tariffs of these two units.

The proposed strategy initially charged the ESS and, then, responded to the power shifted from the previous stage. Since the deficit power levels during the power deficit periods were lower than the minimum value of the MT, the proposed strategy does not add MT and WT to the grid and compensates for this deficit by discharging the EES. Finally, since the required power is greater than the maximum discharging capacity of the storage, it will shift the load to the next intervals.

6. CONCLUSIONS

In this paper, a HMAS was discussed for modeling an energy management of MMGs consisting of distributed energy sources including WT, MT, ESS and various types of loads considering uncertainties of load. EMS strategy for MMGs with a new objective function for optimized performance of the MMG has been presented and implemented based on HMAS in JADE software environment. The results of simulating different possible states of the recommended model showed that the recommended method has been able to establish energy management of distributed and storage energy resources in MMGs with the minimum possible cost.

Acknowledgement: The authors would like to express their gratitude to the Islamic Azad University, Kahnooj Branch, Iran for financial, administrative, and technical support.

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