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Optimal Power Dispatch of Multi-Microgrids at Future Smart Distribution Grids

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***Abstract*—In this paper, future distribution network operation is discussed under assumption of multimicrogrids (MMGs) concept. The economic operation of MMGs is formulated as an optimization problem. A stochastically and probabilistic modeling of both small-scale energy resources (SSERs) and load demand at each microgrids (MGs) is done to determine the optimal economic operation of each MGs with minimum cost based on the power transaction between the MGs and main grids. The balance between the total power generation in each MGs and the load demand is determined regarding the sold or purchase power either by MG or by main grid. Based on the results, the mean, standard deviation, and probability density function of each generated power with SSERs is determined considering optimization constraints. A statistical analysis for generated power and costs is given. The power interchange between MGs is considered. The particle swarm optimization is applied to minimize the cost function as an optimization algorithm. Results show that it is possible to regulate the power demand and power transaction between each MGs and the main grid. Moreover, it is indicated that the power sharing between MGs with main grid can reduce the total operation cost of the future distribution network.**

***Index Terms*—Economic dispatch, load demand, microgrid (MG), particle swarm optimization (PSO), probability, small-scale energy resource (SSER).**

I. Introduction

FUTURE distribution grids may include some microgrids (MGs), which can regarded as small-scale energy zones (SSEZs) with many uncertainties both in generation and load. This SSEZ can be regarded as MG. One of the basic components of MGs is small-scale energy resources (SSERs). Optimal operation and planning of future smart distribution grids is a challenging problem with many uncertainties. Based on market operation of MMGs, the optimal scheduling of MMGs is an important topic that regulates the transaction of the power between each MGs and main grid. The global electrical energy demand is seen to be increasing in recent years. Conventional power networks are facing the problems of reduction of fossil fuel resources. Wind and solar are two of the main energy sources that utilized in many parts of the world. Integration of SSERs will help to better utilization of the existing power networks, reduction of fossil-based fuels consumption, and reduction of network losses and improve system reliability. However, higher penetration of SSERs causes some technical and nontechnical problems such as power quality, reliability, power management, total network efficiency, and interconnection of network [1]. The name of the future power grid is smart grid that satisfies the electrical infrastructure and intelligent information networks [2], [3]. A MG is a section of the grid with a combination of multiply SSERs [including renewable energy sources like solar photovoltaic (PV), wind turbine (WT)], energy storages, and loads. The MG is operated in two grid-connected and isolated types [4]. In grid-connected mode, the MG remains connected to the main grid either totally or partially, and imports or exports power from or to the main grid. In case of any disturbance in the main grid, the MG switches over to stand-alone mode while still feeding power to the priority loads.

From the MG energy management point of view, the economic scheduling of generation units, storage systems, and loads is a crucial task, where the optimization algorithms can be the most important issue that can be regarded as a major component of distribution management system, this management is carried out using the MG central controller by receiving/sending signals to local controllers. In order to leave behind centralized control center that makes too complicated to process with variety of data and controls in MGs, [5] uses decentralized multiagent platform for optimal dispatch problem. The application of multiagent system on microgrids operation is addressed in numerous works that makes the most benefits of system operations [6], [7]. Economic dispatch problem can be divided into two groups. One is static dispatch that solve for any separated time without regarding the relations between time periods in order to obtaining the optimal solution [8]. The another method is dynamic dispatch that considers a discrete time system with finite time period [9], [10].

There is important difference between the optimization of a MG and conventional economic dispatch problem [11]. At present, there are some researches on MG optimal energy dispatch. In the grid-connected mode, the optimal energy dispatch is analyzed in MG [12] and the effect of time-of-use electricity price and electric energy transaction are considered. To consider the decentralized optimal power dispatch strategies in [13], the sharing of marginal cost of each power source is done through iterative and communication. In [14], the real-time energy optimization scheduling method is proposed in independent operation mode of MG.

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The economic dispatch optimization problem is solved with different methods in literature [15], [16]. For example [15] uses particle swarm optimization (PSO) algorithm in grid-connected mode of MG and multiobjective optimization problem without considering sold and purchase power is regarded in economic dispatch problem [16]. Chaotic quantum genetic algorithm [17], [18], ant colony [19], differential evolution algorithm [20], Tabu search, genetic algorithm [21], and niching evolutionary algorithm [22] are methods that used in optimal dispatching problem.

One of the important issues in the MGs is management of load demand with power sharing capability [23]. In order to achieve a minimum operation cost and application of SSERs with best manner, the performance of the smart energy management system is studied in [24]. Balancing of demand-supply in MGs by using power electronic devices as controlled generators with locally monitoring of frequency and voltage is studied in [25] and [26]. In [27], a tuning fuzzy system (TFS) is applied to improve the energy demand forecasting in MG by a simplified economic dispatch model. The TFS is applied to prediction model to note the actual load changes. In some paper, stochastic fluctuation of load and power regulation margin is applied for multiobjective economic dispatch (ED) model [28]. In [29], MG management system is extended in a stochastic framework and uncertainties in load demand and generation by renewable sources are considered and two stage stochastic programming methods is used to optimize MG operations effectively. Because of uncertainties in load demand and intermittent behavior of power generation by PVs and winds it can cause operational challenges to maintain the generation-load balance. In [30], the economic dispatch algorithm is solved by an unconventional, stochastic optimization method. In [31], load demand management of interconnected MGs is described as a power dispatch optimization problem. The demands and supplies are assumed as random variables varying over the time but without any consideration on their probability density functions (PDFs). In [32], multiagent system is applied to regard a decentralized operation of MGs. By this system, the market operation of MG model and the interaction among MGs is modeled. Lyapunov optimization method has answered both of MG electricity scheduling and energy management problems in [33]. In this paper, concept of quality of service in electricity (QoSE) is the base of smart energy management. This concept with energy storage systems management issues are converted into stability problem using both of QoSE and battery virtual queues. Based on MG concept and also because of penetration of SSER into power networks, the unit commitment (UC) problem is encountered with new challenges. Zhao *et al.* [34], using duality-based method, first transformed UC problem into a convex optimization problem and then subgradient-based algorithm is proposed to achieve the optimal UC solution. In [35], the proposed MG-based co-optimization planning problem and annual reliability sub-problem consider as mixed-integer programming problem. Minimization of total system planning cost is assumed as cost function. The proposed model for random component outages is analyzed with numerical simulations method such as Monte Carlo method. Goals of [36] are minimization of battery life loss, power generation costs, and maximization of life time characteristics of batteries. The multiobjective function in this paper is solved with NSGA-II algorithm. Hemmati *et al.* [37] have minimized the costs of power generation, operation, and maintenance of MG using a new multicross learning-based chaotic differential evolution algorithm. This algorithm searches all dimensions of solution space of continuous decision variables. The load consumption and generated power by WT and PV have probabilistic behaviors in 24 h. In [38], these uncertainties are modeled with two point estimate method (2 PEM). Mentioned method uses two deterministic points on both sides of the average value (μ) of the related distribution function for all random variables. The optimization of operation costs and emission is considered as multiobjective function in [39]. In this paper, charging and discharging scheduling model of electric vehicles on cost function is studied that reduce both of operation cost and pollutant emissions.

It should be mentioned that the duty of each MG is to create balance between supply and demand. In other word, in simple economic dispatch problem power generation sources such as SSERs and diesel generators produce power in order to supply load demand and with increasing or decreasing fuel in diesel generators, the balance between supply and demand is provided. But considering MGs concept in smart grids, the balance between generation and load is done through power exchanging between MGs as well as main grid so that the total cost of power generation in each MG as well as the total cost of power exchanging between MGs and main grid be optimized. This paper solves the optimal power dispatch problem considering uncertainties in load and probabilistic modeling of generated power by renewable SSERs. In order to deal with these uncertainties, PDF is considered for power generation parameters. The problem is solved with PSO algorithm. The power generation at each MG and main grid, the purchased and sold power by each MG and the power transaction between each MG and main grid are analyzed based on operation and maintenance (O&M) cost.

II. MG Architecture

A MG is a new model for MV or LV distribution networks that includes SSERs and new technologies such as PHEVs and energy storages. MG networks can be connected to the main or external grid and supplies or absorbs power to the load demand both in MG or main grid. In this paper, a distribution network with three MGs is analyzed. Each MG or SSEZ consists of three SSERs. The SSER units which is used include PV, WT, micro gas turbine (MT), fuel cell (FC), and combined heat and power (CHP). The structure of SSEZs is indicated in Fig. 1.

III. Probabilistic Analysis Method

At present, high penetration of SSERs into distribution grids affect operation and planning of the power systems. In WTs and PV power generation, wind speed, and solar radiation are prime energy sources, respectively. Because of stochastic behavior of wind speed and sun irradiance, power generation

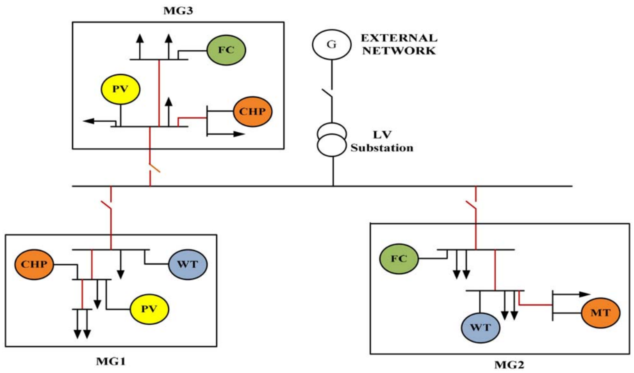

Fig. 1. Structure of network with three MGs (SSEZ).

of the above energy resources undergoing significant uncertainties. Uncertainties analysis of the impact of SSERs such as WT and PV units on current power systems based on deterministic methods is complicated scenario. Although the deterministic analysis of power systems is a common used in electric utilities, the probabilistic analysis of power systems at presence of uncertainties is a very powerful tool for optimal operation and planning of power systems. In probabilistic analysis, input data have PDF and these data can be described by cumulative distribution function (CDF). Consequently, the obtained results from probabilistic analysis are also presented in PDF and CDF forms. Probabilistic analysis is applied in calculation of probabilistic load flow (PLF) [40] in that authors are performed a good review on PLF problem. It is also applied into short-term and long-term planning [41]. One of the problems which has stochastic and probability behavior at presence of SSERs is ED. Considering uncertainties in load consumption and generated power by generation units, ED problem is analyzed using probabilistic method.

In this paper, PDF is considered for input data such as load, generated power by SSERs, purchased and sold powers by MGs, cost of transaction, and costs O&M. Hence, the output results are represented in framework of PDF and CDF.

IV. System Model

A. Power Model

1) Load Demand Model: In deterministic load model for a MG, it is supposed that the load of each MG is constant at any study period. Because of variable nature of load, it is suitable to model the stochastic behavior of the load. This modeling can be achieved either by measured data analysis or by application of mathematical model. The MG load behavior is modeled as a normal distribution function. In this case, the MG load is defined by a mean value (μ) and standard deviation (σ) as

$$f(P_l) = \frac{1}{\sqrt{2\pi} \times \sigma} \exp\left(-\frac{(P_l - \mu)^2}{2 \times \sigma^2}\right). \tag{1}$$

To model the load variation in a given period, a predefined number of load samples based on normal distribution with mean μ and standard deviation σ are generated to model the load uncertainty. The MGs loads at each sample are calculated by (2). In this circumstance, load of each MG has random variable behavior.

2) SSERs Power Generation Model:

a) WT power generation model: Generated power by WT depends on wind speed. The wind speed varies every minute, hour, day, and season of the year, which highlights the importance of a probability model. The Weibull distribution is used to represent the distribution for the wind speed for long-term planning purposes [42]. Weibull PDF is as follows:

$$f_v(v) = \begin{cases} \frac{\beta}{\alpha} \times \left(\frac{v}{\beta}\right)^{\rho-1} \times e^{\left(\frac{v}{\alpha}\right)\beta} & v \geq 0 \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

In (2) α, β, and v are shape parameter of Weibull function, scale parameter of this function, and wind speed, respectively. The wind speed is prime energy source and must be converted into power based on

$$P_G(v) = \begin{cases} P_r \times \left(\frac{v_{\text{cut-out}}^n - v^n}{v_{\text{cut-in}}^n - v_r^n}\right) & v_{\text{cut-in}} \leq v \leq v_r \\ P_r & v_r \leq v \leq v_{\text{cut-out}} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where $P_G(v)$ and P_r are generated power of WT at speed v, respectively. $v_{\text{cut-in}}$, $v_{\text{cut-out}}$, and v_r are WT parameters. Theses parameters are low cut, high cut, and rated speed of WT. Parameter n describes the rate of characteristic curve between $v_{\text{cut-in}}$ and v_r. Maximum value of generated power by WTs is considered 250 kW.

b) PV power generation model: Solar radiation and air temperature are two important parameters for power generation in PV. These parameters are variable in any time of day. In this paper, irradiance and air temperature are modeled by normal distribution function for a given time. The properties of the PV in operation conditions differ from the standard condition (G_{STC} = 1000 W/m^2, T_c = 25 °C). The PV modules are tested at standard test condition (STC). The output power of the module can be calculated as follows [43]:

$$P_{pv} = P_{\text{STC}} \times \frac{G_{\text{ING}}}{G_{\text{STC}}} \times (1 + k(T_c - T_r)) \tag{4}$$

where P_{pv} and P_{STC} are output power of the module at irradiance G_{ING} and rated power at STC respectively. T_c and T_r are cell and air temperature, respectively. k is maximum power temperature coefficient. The rated power of PVs is 250 kW.

B. Cost Model

1) WT and PV Cost Model: The cost of primary energy often determines the cost of generated power by SSERs. In WT and PV, wind and solar radiation are primary energies respectively with zero fuel costs. For the cost function of WT and PV units, only O&M costs are considered. In this paper, the costs of O&M are supposed 0.1095 ($/kWh) and 0.1368 for PVs and WTs, respectively at every samples. It should be mentioned that all samples have been considered only for one-time interval. The costs of O&M ($C_{\text{O\&M}}$) for WT and PV are as follows:

$$C_{\text{O\&M},\ WT,\ s} = K_{\text{O\&M}} \times P_s. \tag{5}$$

TABLE I
CHARACTERISTICS OF GENERATION UNITS

MG number	1			2			3		
Unit type	PV	CHP	WT	WT	MT	FC	PV	CHP	FC
Minimum value of generated power (kw)	0	150	0	0	100	100	0	150	100
Maximum value of generated power (kw)	250	500	250	250	500	250	250	500	250
O&M cost ($/kwh)	0.1095	0.088	0.1095	0.1095	0.088	0.016	0.1095	0.088	0.016

*P*s is generated power of PV or WT units considering sample *s*.

2) FC Cost Model: In FC, hydrogen is combined with oxygen and electricity, heat, and water is produced. Produced electricity is a dc current and to connect this unit into MG, it is necessary to use power electronic devices. FC can produce electricity as long as fuel is being provided. The efficiency of FC (η_s) in sample s depends on output power in same sample. The efficiency of FC will be lower if the output power be increased. The cost of generated power by FC achieve from

$$\text{Cost}_{\text{FC},s} = \frac{C_{nl}}{L} \times \frac{P_s}{\eta_s}. \tag{6}$$

In this paper, C_{nl} and L are 0.76 \$/m^3 and 9.7 kWh/m^3. These parameters describe natural gas price value (\$/m^3) and low-hot value (kWh/m^3), respectively. The O&M costs for FC are calculated based on (6). The value of $\text{K}_{\text{O\&M}}$ for FC is considered 0.016 (\$/kWh).

3) MT Cost Model: MTs are small high-speed gas turbines. The size of MT is from 25 to 500 kW [45]. A MT supplies input mechanical energy for the MT generator system, which is converted by the generated to electricity energy. Unlike FC, the efficiency of MT increases with increase of supplies power. The cost function of generated power of MT is calculated by (7) and O&M costs are obtained by (6) for each sample. The value of $\text{K}_{\text{O\&M}}$ is considered 0.088 (\$/kWh) for MT

$$\text{Cost}_{\text{MT},s} = \frac{C_{nl}}{L} \times \frac{P_s}{\eta_s}. \tag{7}$$

4) CHP Cost Model: CHP system is an economical type of power delivery method that provides electricity and heat at the same time. In MT units with CHP performance, the efficiency of MT increase and the fuel cost of MT decrease to a great extent. The fuel cost of MT with CHP performance is as follows:

$$\text{Cost}_{\text{CHP},s} = \text{Cost}_{\text{MT},s} - B_{\text{CHP},s} \tag{8}$$

$$B_{\text{CHP},s} = \text{Cost}_{\text{MT},s} \times \frac{\varepsilon_{\text{rec}}(\eta_{T,s} - \eta_{e,s})}{\eta_b} \tag{9}$$

where $B_{\text{CHP},s}$ is cost reduction of generated power by MT in sample s, because of using exhaust gas heat. ε_{rec} is heat recovery factor. η_T, η_e, and η_b are total efficiency of CHP, electrical efficiency of MT and efficiency of boiler, respectively. On the other hand, composition of (8) and (9) concludes as

$$\text{Cost}_{\text{CHP},s} = \text{Cost}_{\text{MT},s} \times \left(1 - \frac{\varepsilon_{\text{rec}}(\eta_{T,s} - \eta_{e,s})}{\eta_b}\right). \tag{10}$$

$\text{Cost}_{\text{MT},s}$ obtains from (7). In this paper, ε_{rec} and η_b are assumed to be 0.95 and 0.80, respectively.

5) Modeling of Purchased and Sold Powers Cost: In this paper, all MGs are connected into main grid. So, all of them are able to inject power into grid, which in that, the MGs take money from network. By selling power to grid, the costs of MGs operation are reduced that is an economical operation. If one of the MGs be unable to supplies own load demand, it can purchase electrical power from main grid. The purchased and sold cost of MGs is described as

$$\text{Cost}_{\text{pur,sm}} = \sum_i c \times P_{\text{buy,smi}} \tag{11}$$

$$\text{Cost}_{\text{sell,sm}} = \sum_i d \times P_{\text{sell,smi}}. \tag{12}$$

In the above equations, $\text{Cost}_{\text{pur,sm}}$ and $\text{Cost}_{\text{sell,sm}}$ are purchased and sold powers costs of MG m in sample s, respectively. $P_{\text{buy,smi}}$ and $P_{\text{sell,smi}}$ are purchased and sold powers by ith unit of MG m in sample s, respectively. Based on Fig. 1, each MG consist three units. The cost of transaction of powers between MG and external grid is described as

$$\text{Cost}_{\text{trans},ms} = \text{Cost}_{\text{pur},ms} - \text{Cost}_{\text{sell},ms}. \tag{13}$$

In the proposed paper, c and d are purchased price and sold price, respectively. The value of c and d, respectively, are 0.16 and 0.12 (\$/kWh) for all MGs. Table I shows some mentioned characteristics of MGs.

V. PROBLEM FORMULATION

The MG optimization problem is rather similar to the ED with traditional generation units. The purpose of ED problem is minimization of cost function of generation considering equality and inequality constraints.

A. Objective Function

ED is a nonlinear problem. Objective function includes generated power, purchased and sold power, and O&M costs. In this problem, the cost of power generation must be minimized. The total energy cost for providing energy to consumers is equal to the summation of the energy costs of MGs. The objective function is as follows:

$$\text{Min} : \text{OF} = \sum_s F_s \tag{14}$$

$$F_s = \sum_i \text{Cost}_{\text{gen,si}} + \sum_m (c \times P_{\text{buy,sm}} - d \times P_{\text{sell,sm}}) + \text{Cost}_{\text{O\&M},s} \tag{15}$$

$$\text{Cost}_{\text{gen,si}} = \text{Cost}_{\text{gen,MT,si}} + \text{Cost}_{\text{gen,FC,si}} + \text{Cost}_{\text{gen,CHP,si}} \tag{16}$$

$$\text{Cost}_{\text{O\&M},s} = \text{Cost}_{\text{O\&M},WT,s} + \text{Cost}_{\text{O\&M},PV,s} + \text{Cost}_{\text{O\&M,MT},s} + \text{Cost}_{\text{O\&M,FC},s} + \text{Cost}_{\text{O\&M,CHP},s}. \tag{17}$$

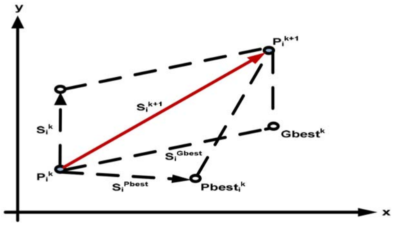

Fig. 2. Path of the particles movement.

In (14), OF is objective function that is summation of function F. Function F is optimized for each samples separately by PSO algorithm. Indeed F is a $[1 \times s]$ function or matrix. In this paper, $\mathrm{Cost}_{\mathrm{gen,si}}$ is the cost of generated power buy unit i at sample s.

B. Problem Constraints

1) Power Balance Constraint: The total real-power generation plus purchased power from external grid must balance the predicted power demand plus the sold power to main grid, at any sample of PDF

$$P_{l,s} + \sum_m P_{\mathrm{sell,sm}} = \sum_i P_{\mathrm{gen,si}} + \sum_m P_{\mathrm{buy,sm}}. \quad (18)$$

2) Inequality Constraint: In this paper, upper and lower constraint is considered for generated power of SSERs. These constraints are applied into power transaction between MGs and main grid

$$P^{\mathrm{si}}_{\mathrm{Min,gen}} < P^{\mathrm{si}}_{\mathrm{gen}} < P^{\mathrm{si}}_{\mathrm{Max,gen}} \quad (19)$$
$$P^{\mathrm{sm}}_{\mathrm{Min,pur}} < P^{\mathrm{sm}}_{\mathrm{pur}} < P^{\mathrm{sm}}_{\mathrm{Max,pur}} \quad (20)$$
$$P^{\mathrm{sm}}_{\mathrm{Min,sell}} < P^{\mathrm{sm}}_{\mathrm{sell}} < P^{\mathrm{sm}}_{\mathrm{Max,sell}}. \quad (21)$$

The optimal dispatch problem in (14) is minimized with PSO algorithm considering equality and inequality constraints.

VI. Review of PSO Algorithm

The main idea of the PSO algorithm is inspired first by Kennedy and Eberhart [46] in 1995. The idea is suggested from offensive particles movement such as birds or fish. When the birds want to move, they use present position and neighbor's birds' position in order to reach bird with the best position. In PSO algorithm, instead of birds or fish, particles do this paper. According to Fig. 2, any of particles are described with two vectors S_i and x_i. In every movement steps of particles population, every particle is updated by two values. First value is the best previous position of particle i that called p-best and evaluated by using fitness function. Second value is the best particle among all p-bests that called g_{best}. By finding these values, any of particles update their new velocity and position by following relations:

$$S_i^{k+1} = W \times S_i^k + c_1 \times r_1 \times \left(p_{\mathrm{best}_i} - x_i\right) + c_2 \times r_2 \times (g_{\mathrm{best}} - x_i) \quad (22)$$

$$x_i^{k+1} = x_i^k + S_i^{k+1} \quad (23)$$

$$W = W_{\max} - \frac{(W_{\min} - W_{\max})}{\mathrm{iter}_{\max}} \times \mathrm{iter} \quad (24)$$

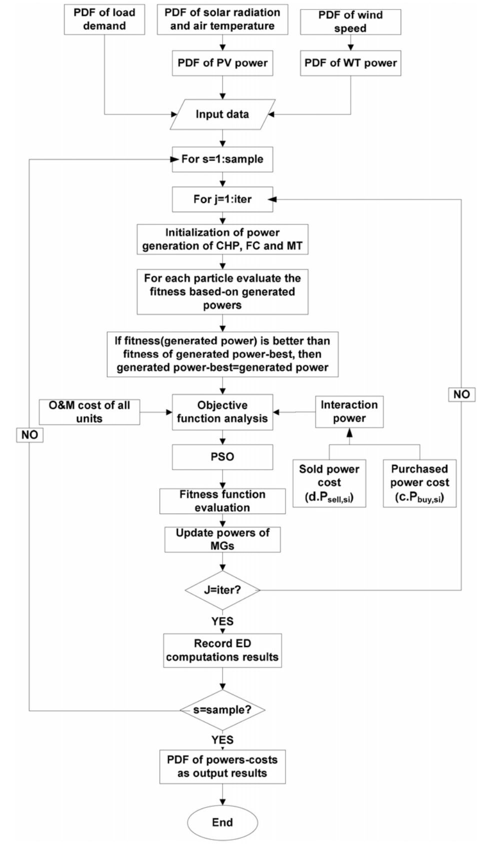

Fig. 3. Flowchart of implementation of PSO on probabilistic ED.

TABLE II
PSO Parameters Used for Systems

Iteration Number	500
Number of Particles	250

where

$c_1,\ c_2$ acceleration constant in the range [0, 2];
$r_1,\ r_2$ uniform random value in the range of [0, 1];
$P_{\mathrm{best}i}$ best previous position of particle 3i;
g_{best} best particle among all P_{best};
$S_i,\ x_i$ velocity and position vectors of particle i, respectively;
k number of iterations;
W inertia weight factor;
Iter current iteration number;
$W_{\min}, W_{\max}$ minimum and maximum inertia weights factor.

PSO algorithm can be described as follows.

Step 1 (Initialization): The velocity and position vectors are initialized randomly.

Step 2 (Update Velocity): The velocity vector of the all particles is updated by using equation.

Step 3 (Position Update): The position vector of the all particles is updated by using equation.

Step 4 (Memory Update): $P_{\mathrm{best}i}$ and g_{best} are updated as follows:

$$\text{If}:\quad F(p_i) < F\left(p_{\mathrm{best}_i}\right); \quad p_i \rightarrow p_{\mathrm{best}_i} \quad (25)$$
$$\text{If}:\quad F(p_i) < F(g_{\mathrm{best}}); \quad p_i \rightarrow g_{\mathrm{best}}. \quad (26)$$

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TABLE III
STATISTICAL ANALYSIS OF GENERATED POWERS AND COSTS

MG number	Unit type	Mean (μ) of power (KW)	STD (σ) of power (KW)	Mean (μ) of cost of power ($/h)	STD (σ) of cost of power ($/h)	Mean (μ) of operation and maintenance cost ($/h)	STD (σ) of operation and maintenance cost ($/h)
MG1	PV	122.87	54.19	28.25	11.46	13.45	5.93
	CHP	321.64	102.69			28.30	9.04
	WT	93.43	89.35			10.23	9.78
MG2	WT	79.86	85.66	104.47	26.81	8.74	9.38
	MT	289.92	111.34			25.51	9.80
	FC	172.94	43.09			2.77	0.69
MG3	PV	119.52	44.91	60.36	14.78	13.09	4.92
	CHP	310.53	99.97			27.33	8.80
	FC	179.24	42.48			2.87	0.68

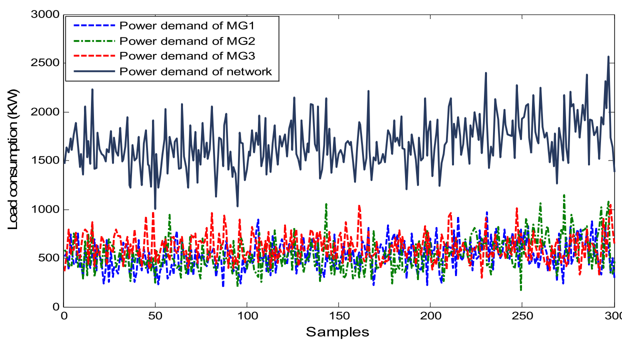

Fig. 4. Load demand of MGs 1, 2, and 3 and network.

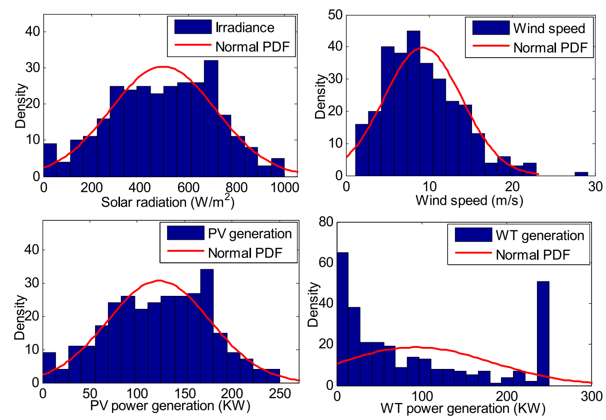

Fig. 5. Probabilistic modeling of PV and WT primary input and generated power in MG1.

The flowchart of solving probabilistic optimal power dispatch problem with PSO is illustrated in Fig. 3 graphically. According to the flowchart, a PDF function is used for load, wind speed, solar irradiation, and air temperature, so these input variables are defined as probabilistic variables. Based on correlation between network input and output variables, the output of the network parameters show probabilistic behavior. To explain this, for example, Fig. 5 is illustrated the probabilistic modeling of both wind speed and solar irradiation and consequently the probabilistic modeling for wind and solar power in MG1.

VII. SIMULATION RESULTS AND DISCUSSION

In this section, distribution of power problem among loads of MGs is tested on proposed MMG network. Fig. 1 shows the structure of MMG network with three MGs. Each MG consists three SSERs to power generation. All basic data for simulation are mentioned in the rest of this paper.

The aim of this paper is to solve the optimal power dispatch of MMGs at the presence of SSERs such as WT, PV, FC, and CHP for a given hours. Because of the intermittent behavior of some renewable energy resources and load variation this paper is done based on uncertainty in input data.

To model the uncertainty of wind speed and solar irradiation the historical measured data for 100 days (93 days of summer and the first week of autumn) with three samples for each hours ($3 \times 93 + 3 \times 7$ samples) at 12 h of each day, is used as practical data to model the distribution function of wind speed and solar irradiation. As an economic dispatch problem this paper is solved the MMG economic dispatch problem

TABLE IV
VALUES OF PARAMETERS IN WT AND PV

WT	P_r=250KW	$V_{cut\text{-}in}$=2m/s	V_r=14m/s	$V_{cut\text{-}out}$=25m/s
	n=3	$\alpha = 2$	$\beta = 10$	-
PV	P_{STC}=250KW	G_{STC}=1000W/m^2	K=0.001	Tc= 25$^\circ C$

based on measured data of 12 h. This problem is solved for only 12 h of the day. Based on the above discussion, there are approximately 300 ($3 \times 93 + 3 \times 7 = 300$) samples for each hours.

The load demand of each MGs and main grid is illustrated in Fig. 4.

In this paper, each MG is modeled as a small disco with capability of power interchange between each MG and also between each MG and the main grid. To consider the effect of power generation cost in each MG, it is assumed that the characteristic of SSERs such as size, and technology of WT, PV, and FC is different. Based on the above discussion, the cost of per kilowatt generated power by each SSERs at each MG is different. Indeed, this paper is modeled as a multi-area economic dispatch problem in market operation of power system that each MG is seem as a virtual power plant. In this case, the probabilistic economic dispatch problem is solved using PSO as a heuristic optimization algorithm. The characteristics of PSO algorithm is described in Table II. Based on this figure and Table III, the mean cost of generated power in MG1 is lower than MG2 and MG3, because MG1 has two DG

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TABLE V
STATISTICAL ANALYSIS OF POWER TRANSACTION AND COSTS

	Related to purchased power				Related to sold power				Related to interaction power	
MG number	μ of purchased power (KW)	σ of purchased power (KW)	μ of purchased power cost ($/h)	σ of purchased power cost ($/h)	μ of sold power (KW)	σ of sold power (KW)	μ of sold power cost ($/h)	σ of sold power cost ($/h)	μ of interaction cost ($/h)	σ of interaction cost ($/h)
MG1	184.18	70.33	29.47	11.25	191.84	79.72	23.02	9.57	6.45	10.98
MG2	193.54	77.81	30.97	12.45	195.89	80.76	23.51	9.69	7.46	11.49
MG3	215.12	66.12	34.42	10.58	214.38	73.96	25.72	8.88	8.69	11.16

TABLE VI
STATISTICAL ANALYSIS OF POWER TRANSACTION AND COSTS IN INTERCONNECTED MMGS MODE

State	MG1				MG2				MG3			
Power-Cost	From or to MG2	From or to MG3	From or to network	Total	From or to MG1	From or to MG3	From or to network	Total	From or to MG1	From or to MG2	From or to network	Total
μ of purchased power (KW)	43.28	48.18	34.20	125.65	31.48	31.29	0	62.76	27.72	36.00	106.82	170.54
μ of purchased power cost ($/h)	22.62				10.67				27.29			
μ of sold power (KW)	31.48	27.72	23.87	83.06	43.28	36.00	0	79.27	48.18	31.29	86.27	165.74
μ of sold power cost ($/h)	11.63				10.31				19.89			

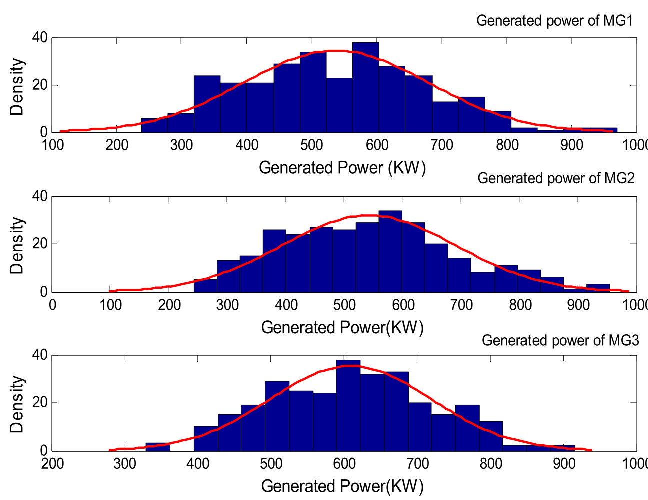

Fig. 6. PDF of generated power of MGs.

units, WT and PV, and these units have no cost about power generation. Besides, the sum of generated power by MGs in Fig. 6 must be equal with total power generation of network at any sample.

Table III describes the powers, costs of power, and O&M costs of each units based on mean and standard deviation of 300 samples.

The density of generated power at each MGs, is shown in Fig. 6.

Using obtained costs of generated power, O&M, and transaction powers between main grid and each MG, the total cost of each MG can be described as follows for any sample:

$$\mathrm{Cost}_{\mathrm{MG}} = \sum_i \mathrm{Cost}_{\mathrm{gen},i} + \sum_m (c \times P_{\mathrm{buy},m} - d \times P_{\mathrm{sell},m}) + \mathrm{Cost}_{\mathrm{O\&M}}. \quad (27)$$

In this paper, ED problem is solved considering PDF for some parameters of power generation. Proposed example solves ED problem at presence of load demand and renewable SSERs uncertainties. The results includes the total cost at any states of generated and transaction powers. The probabilistic analysis about ED has a good prospect in operation, planning, unit commitment problem studies, etc. PDF of the purchased and sold powers of MGs gives an insight vision to the dispatcher to evaluate the risk of change in system total cost with respect the variation in load and SSER power. This value at risk for purchase and sold power can be calculated and can be useful for dispatchers. The mean value of the PDF can use as the power with high probability of the appearance. Indeed, in this case, it is possible to evaluate the forecasting errors in load, wind, and solar short-term scheduling.

In Table IV, the values of parameters of WT and PV units are given that are used in simulation.

Table V describes the purchased and sold powers, costs of purchased and sold power, and transaction costs between MGs and external grids based on mean and standard deviation of samples. In this table to calculate the transaction cost, (14) is used for each MG. The purchased and sold powers of MGs are indicated in Fig. 7. The CDF of total costs of network as PDF and CDF are shown in Fig. 8.

To consider the power transfer capability at interconnected MG, the simulation is repeated and the results are given in Figs. 9 and 10. Moreover, in Table VI, the detail of the analysis is given. For this case, the power transaction between two MGs as well as each MG and the main grid are given. Comparing Tables V and VI is clear that total cost of operation is lower in case of interconnected MMG operation.

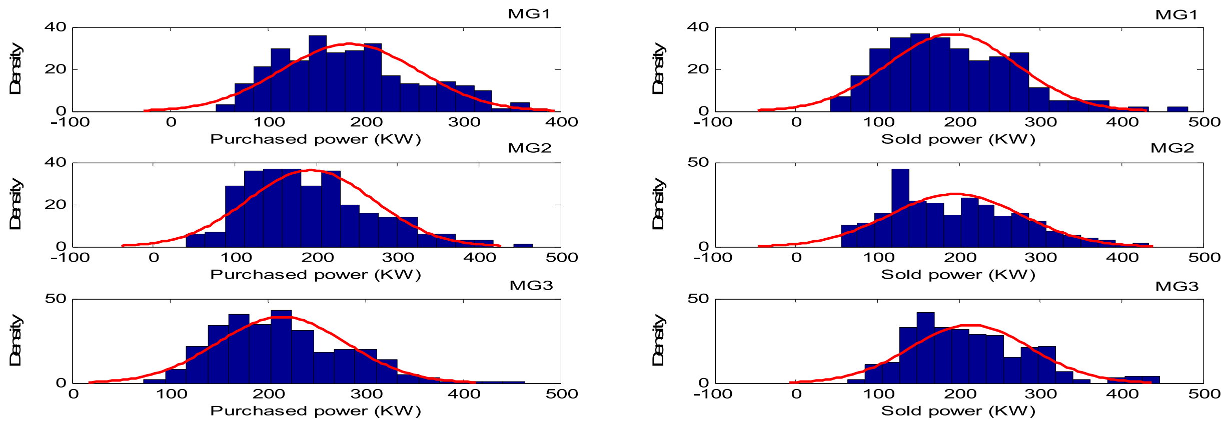

Fig. 7. PDF of purchased and sold powers.

TABLE VII
STATISTICAL ANALYSIS OF POWER TRANSACTION AND COSTS IN MMGS MODE WITH LOSSES

MG number	Unit type	Generated power (kW)	Cost of generated power ($/h)	Purchased power (kW)	Cost of purchased power ($/h)	Sold power (kW)	Cost of sold power ($/h)
MG1	With Loss	534.96	32.78	69.14	12.44	119.98	16.80
	Without Loss	441.52	26.28	125.65	22.62	83.06	11.63
MG2	With Loss	584.01	113.55	51.14	8.69	59.19	7.69
	Without Loss	490.69	92.45	62.76	10.67	79.27	10.31
MG3	With Loss	529.03	54.24	125.32	20.05	154.67	18.56
	Without Loss	494.90	49.50	170.54	27.29	165.74	19.89

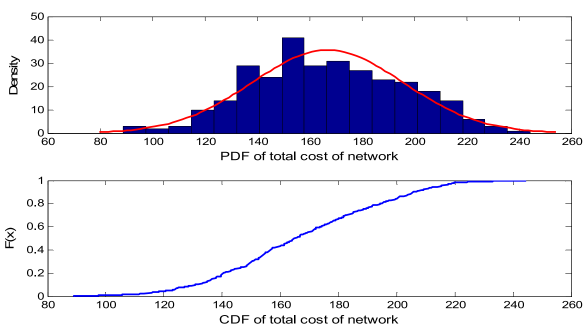

Fig. 8. PDF and CDF of total cost of network.

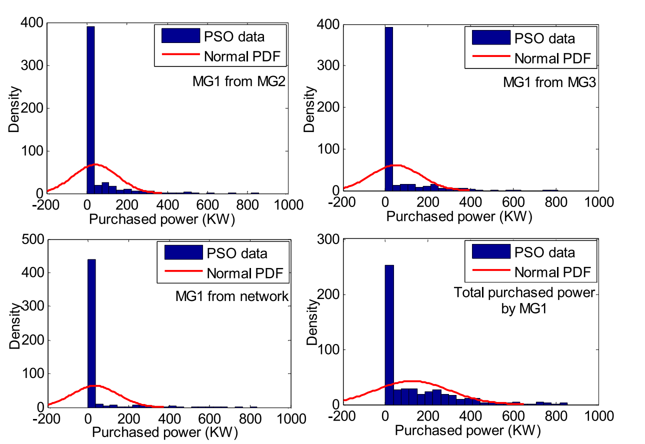

Fig. 9. PDF of purchased power in different states of MG1 in interconnected MMG mode.

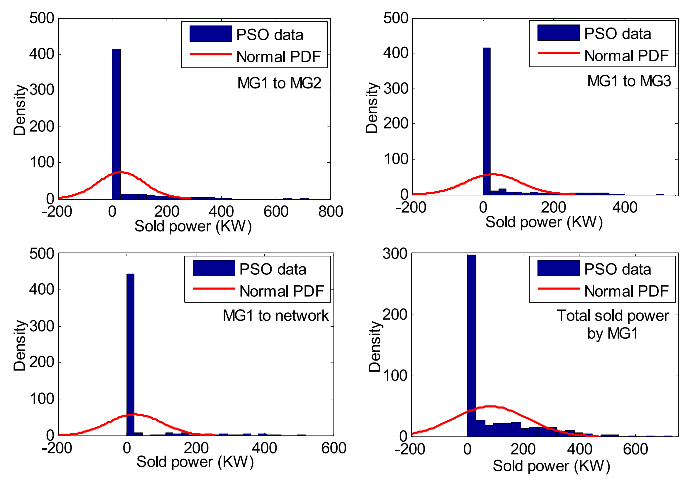

Fig. 10. PDF of sold power in different states of MG1 in interconnected MMG mode.

Because of the small size of the load and power generation the effect of network loss can be considered in this paper. The network loss is also small because of the small size of the network. To evaluate the effects of network losses in the proposed method, in Table VII the statistical analysis of power transaction and costs in multimicrogrids (MMGs) mode considering network loss is given. In this table, the network main parameters are compared. Based on Table VII, the cost of power generation within each MG is increased because of the loss modeling, while the cost of purchased power is decreased. The PDF of the network loss is shown in Fig. 11. According to the figure while the input parameters have the random behavior, hence the network output parameters such as network loss is also a random parameter. The histogram of the network loss is indicated in this figure. This figure show that the network loss can be modeled as a normal distribution function.

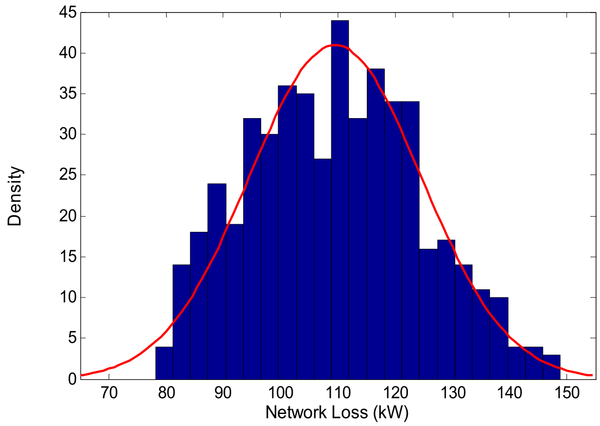

Fig. 11. PDF of network loss.

VIII. Conclusion

In this paper, future distribution networks operation is discussed in the presence of MMGs is discussed. The economic operation of MMGs is formulated as an optimization problem. A stochastically and probabilistic modeling of both SSERs and load is performed to determine the optimal operation of each MGs with minimum cost based on economic analysis of the power transaction between the MGs and main grid. The balance between the total power generation in each MGs and the load demand is determined regarding the sold or purchase power of the main grid. Based on the results, the mean, standard deviation, and PDF of each generated power with SSERs is determined considering optimization constraints. Statistical analysis for generated power and costs are given. The PSO is applied to minimize the cost function as an optimization algorithm. Results show that it is possible to regulate the power demand and transaction between each MG and the neighbors MG and between each MG and the main grid. Moreover, it is indicated that the power sharing between MGs with main grid can reduce the total operation cost of the future distribution network. One of the main results of this paper by probabilistic modeling of the input variables, the output variables can be represented as random variables. This leads to a better and comprehensive vision for network experts to manage the marginal operation of the network under uncertainties. This can guarantee the robust operation of smart distribution grids in the presence of network uncertainties.

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