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***Abstract*— Due to the reappearance of DC loads in electrical systems and advanced improvement in energy storage systems (batteries) and environment-friendly properties of photovoltaics as a green energy supply, DC architecture is considered as a new solution for next-generation power distribution systems. Hybrid AC-DC microgrids (MG) can take advantage of DC and AC flows in a smart distribution system. The best strategy for the optimal operation of hybrid MGs is to minimize the converting energy between AC and DC sides such that DC loads are provided by photovoltaics, fuel cells, and the stored energy in batteries and AC loads are satisfied by AC-based sources including wind turbines (WTs) and diesel generators (DEs). Accordingly, this paper aims to scrutinize an optimal green power management strategy for hybrid AC-DC MGs from an economic viewpoint while considering photovoltaics as a prior source for the DC side and wind turbines for the AC side. Moreover, the uncertainties of renewable energy sources (RESs), DC and AC loads, and the correlation among them are investigated using the unscented transformation method.**

Keywords—Hybrid AC-DC Microgrids, Optimal Operation, Power Management, Uncertainties, Unscented Transformation

I. INTRODUCTION

The combination of distributed generators (DGs) to integrate renewable energy sources (RESs) into local distribution systems besides the advantages of DC power including decreasing the power loss in transmission lines and better controlling of power flow led to the reappearance of DC power [1, 2].

AC systems have some benefits due to the innate characteristics of AC appliances and the presence of transformers to transmit power over far areas to afford AC loads, however, gradual and permanent changes in the type of loads and DGs in AC distribution systems led to the combination of DC networks to the current AC networks [1, 2]. Even though most grids function in AC mode, the large penetration of distributed DC generations, energy storage units, and loads, along with other features, has necessitated the creation of DC distribution networks [3].

The main advantage of these networks is high efficiency due to lower power electronic interfaces, which leads to no flow of reactive power. In addition, it is not required to synchronize the DGs [3]. This configuration needs a lot of modifications to the current power grid and thus raises costs [1-3]. Although DC microgrids (MGs) have many advantages over AC MGs, this technology has not yet been fully adapted to seriously change existing systems. Since AC systems are more dominant, it is more likely to combine AC and DC MGs to solve existing problems efficiently [1-3].

Hybrid MGs which benefit from both AC and DC MGs ease the combination of DC technologies to the current AC systems. By using hybrid AC-DC MGs, DC power supplies are connected to DC loads while AC power sources supply AC loads and the bidirectional converter (BDC) shares power between these two sides [1]. A supervisory controller is needed for dividing the power among different sources. This led researchers to create power management systems [2, 3]. Accordingly, meeting the required power while maximizing the use of RESs, minimizing the use of fuel-based generators, increasing battery life, and limiting the use of the main power converter between AC and DC MGs are considered the main aspects [2]. The hybrid AC-DC MG configuration attracted much attention due to the simultaneous integration of the advantages of AC and DC structures. The main characteristic of this configuration is the integration of both AC and DC networks into the same distribution network, which helps the straight combination of AC and DC distributed loads, storage units, and generating units. This feature provides a convenient way to incorporate future renewable sources or electric vehicles with minimal modifications to the current distribution network and cost reduction [5].

Hybrid MGs consist of AC and DC networks and the BDC between these two networks, which helps the power flow between these two networks and the power grid. These arrangements have many benefits because AC and DC-powered appliances can easily be linked to the grid with fewer power electronic interfaces [2].

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The concept of hybrid MG as an efficient, economic, and environmentally friendly distribution network for the future has been investigated from several viewpoints [6-16]. In [42], a study on hybrid MG was done. This paper formulated a multi-objective optimization problem for AC-DC hybrid MG operation that minimized energy costs and pollutants.

In [6, 7], an algorithm was utilized for power transmission between AC and DC sides. It was shown that a lack of a proper control strategy in the system can lead to the shutdown of the entire system.

The dynamic evaluation of the AC-DC hybrid system was done in [8]. Authors in [9] implemented a droop-based controller to satisfy the constraints of the DC bus voltage. The studied system included a WT and several controllable loads without controllable generators, such as diesel generator (DE) units, fuel cells (FC), etc. In addition, reference [9] did not investigate the operation of off-grid MGs in different contingencies.

Authors in [13] studied the optimal utilization of hybrid MGs assuming a 24-hour time-dependent effects of the network. This article investigated two different structures (AC MG and hybrid MG) with the same production and local consumption. In [14, 15], issues related to power sharing in a hybrid MG were studied. These papers did not consider the day-ahead planning under different connection states (connected to or disconnected from the network) or the interface converter problem. In [16] the effects of connection inefficiencies in day-ahead scheduling for a hybrid MG were investigated.

The major goal of our current paper is to study the performance of a hybrid MG in the presence of uncertainties in load, and the output power of RESs. Main contributions of the paper can be mentioned as:

1. Optimal power management of hybrid MGs while taking into account the uncertainties of AC and DC loads and output power of RESs.
2. Solving the probabilistic optimal power management problem using a hybrid method.

II. PROBLEM FORMULATION

A hybrid MG is illustrated in Fig.1. As is observed, the hybrid MG consists of an AC side that includes DE units, wind turbines (WT), and AC loads. The DC side includes FC, photovoltaic (PV) panels, battery storage devices (Batt), and DC loads. The DC and AC sides are connected via a bidirectional converter (BDC) which deals with the power-sharing between DC and AC sides.

A. Objective Functions

The objective is to demonstrate a daily schedule of units in the hybrid MG while considering the related constraints. It is considered that the studied AC-DC MG consists of one DE unit, one FC unit, PV and WT units, a battery, and a BDC. Moreover, the AC-DC MG can exchange power between AC and DC sides. The objective function is to minimize the total cost as follows:

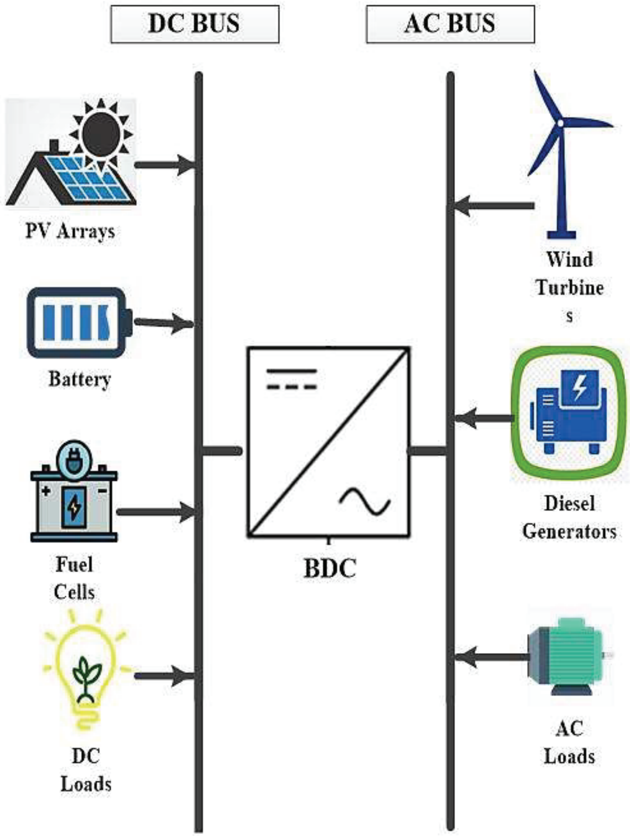

Fig. 1. Hybrid microgrid configuration.

$$min\left\{\sum_{t=1}^{T}(DE\_cos\,t_t + FC\_cos\,t_t)\right\} \quad (1)$$

$$DE\_cos\,t_t = a_{DE}(P_{DE,t})^2 + b_{DE}P_{DE,t} + c_{DE} + SUC_{DE} \times V_{DE,t} \times (1 - V_{DE,t-1}) \quad (2)$$

$$FC\_cos\,t_t = (C_{NG}P_{FC,t}/Q_{LHV}\eta_{FC}) + SUC_{FC} \times V_{FC,t} \times (1 - V_{FC,t-1}) \quad (3)$$

where *t* and *T* represent a time slot and the perspective of study, respectively. $DE\_cos\,t_t$ and $FC\_cos\,t_t$ are respectively the operational and start-up costs of DE and FC. a_{DE}, b_{DE} and c_{DE} are the coefficient of the cost function of DE. $P_{DE,t}$ is the output power of DE unit in time interval *t*. SUC_{DE} is the start-up cost of DE in time interval *t*. $V_{DE,t}$ is 0 or 1 to show the state of DE being on or off in time *t*. C_{NG} is the consumption cost of each meter cube of natural gas, $P_{FC,t}$ is the output power of FC in each time interval *t*, Q_{LHV} is the low heating value of natural gas in kW/m^3. SUC_{FC} is the start-up cost of FC in time interval *t* and $V_{FC,t}$ is 0 or 1 to show the on or off state of FC in time *t*.

B. Technical Constraints

1. The constraint of the rate of production changes

The following equations represent the change rate of output powers of DE and FC and the change of power of the BDC.

$$P_{DE,t+1} - P_{DE,t} \le R_{DE}^{up} \quad (4)$$

$$P_{DE,t} - P_{DE,t+1} \le R_{DE}^{down} \quad (5)$$

$$P_{FC,t+1} - P_{FC,t} \le R_{FC}^{up} \quad (6)$$

$$P_{FC,t} - P_{FC,t+1} \le R_{FC}^{down} \quad (7)$$

$$P_{BDC,t+1} - P_{BDC,t} \le R_{BDC}^{up} \quad (8)$$

$$P_{BDC,t} - P_{BDC,t+1} \le R_{BDC}^{down} \quad (9)$$

where $P_{BDC,t}$ represents the exchanged power of bidirectional converter in time interval t. R_{DE}^{up}, R_{DE}^{down}, R_{FC}^{up}, R_{FC}^{down}, R_{BDC}^{up} and R_{BDC}^{down} are respectively the upper and lower band of the changes of power of DE and FC units and bidirectional converter.

2. The constraint of the minimum on/off time of units

The minimum time that each unit should maintain its on/off status to be able to change its status can be demonstrated as the following (each unit that changes its status from off to on/ on to off, should continuously remain in the circuit for a minimum time for technical considerations. Moreover, whenever a unit turns off it should continuously remain off for a certain minimum time.)

$$V_{DE,t} - V_{DE,t-1} \le V_{DE,\tau}$$

$$\forall \tau \in [t+1, min(t + MUT_{DE}, T)] \; \forall t \in [2, T] \quad (10)$$

$$V_{DE,t-1} - V_{DE,t} \le 1 - V_{DE,\tau}$$

$$\forall \tau \in [t+1, min(t + MDT_{DE}, T)] \; \forall t \in [2, T] \quad (11)$$

$$V_{FC,t} - V_{FC,t-1} \le V_{FC,\tau}$$

$$\forall \tau \in [t+1, min(t + MUT_{FC}, T)] \; \forall t \in [2, T] \quad (12)$$

$$V_{FC,t-1} - V_{FC,t} \le 1 - V_{FC,\tau}$$

$$\forall \tau \in [t+1, min(t + MDT_{FC}, T)] \forall t \in [2, T] \quad (13)$$

where MUT_{DE}, MDT_{DE}, MUT_{FC} and MDT_{FC} are respectively the minimum up and down time of DE and FC units.

3. Battery limits

The constraints of the battery charging/ discharging process include charging/discharging limits and up and down rates of the stored energy in the battery as follows [17]:

$$P_{Batt,Min}^{Ch} \le P_{Batt,t}^{Ch} \le P_{Batt,Max}^{Ch} \quad (14)$$

$$P_{Batt,Min}^{Dch} \le P_{Batt,t}^{Dch} \le P_{Batt,Max}^{Dch} \quad (15)$$

$$E_{Batt,Min} \le E_{Batt,t} \le E_{Batt,Max} \quad (16)$$

$$E_{Batt,t} = E_{Batt,t-1} + P_{Batt,t}^{Ch} \eta_{Batt}^{Ch} - \left(P_{Batt,t}^{Dch} / \eta_{Batt}^{Dch}\right) \quad (17)$$

where $P_{Batt,t}^{Dch}$ and $P_{Batt,t}^{Ch}$ represent the discharging and charging rates of the battery in *t*, $P_{Batt,Min}^{Ch}$ and $P_{Batt,Max}^{Ch}$ are the upper and lower bounds of battery charging rate and $P_{Batt,Min}^{Dch}$ and $P_{Batt,Max}^{Dch}$ are the upper and lower bounds of battery discharging rate in *t*. $E_{Batt,t}$ is the stored energy in the battery, $E_{Batt,Min}$ and $E_{Batt,Max}$ are the lower and upper bounds of the stored energy in the battery. η_{Batt}^{Dch} and η_{Batt}^{Ch} are respectively the battery discharging and charging efficiencies.

4. Power balance constraints in each AC and DC side

This constraint implies that the overall power of AC units should satisfy the demanded AC load while the overall the DC power satisfies the demanded DC load.

$$P_{DE,t} + P_{WT,t} + P_{BDC,t} = Load_{AC,t} \quad (18)$$

$$P_{FC,t} + P_{Batt,t} + P_{PV,t} + P_{BDC,t} = Load_{DC,t}$$

$$t = 1,2,\ldots,T \quad (19)$$

where $P_{WT,t}$ and $P_{PV,t}$ are the output powers of WT and PV units, $Load_{AC,t}$ and $Load_{DC,t}$ are the demanded electrical load of each DC and AC sides of the hybrid MG in time intervals *t*.

Moreover, the output power of DE and FC and the exchanged power of the bidirectional converter should fulfill the following:

$$P_{DE,Min} \le P_{DE,t} \le P_{DE,Max} \quad (20)$$

$$P_{FC,Min} \le P_{FC,t} \le P_{FC,Max} \quad (21)$$

$$-P_{BDC,Max} \le P_{BDC,t} \le P_{BDC,Max} \quad (22)$$

$P_{DE,Min}$, $P_{DE,Max}$, $P_{FC,Min}$, and $P_{FC,Max}$ are the lower and upper bounds of the output powers of DE and FC units. $P_{BDC,Max}$ represents the maximum exchangeable power between AC and DC sides of the hybrid MG.

III. PSO-UT Algorithm

To deal with the considered problem particle swarm optimization (PSO) algorithm is implemented. The efficiency of the PSO algorithm in solving optimization problems from stability, and accuracy viewpoints as well as its simple application and formulation are justified in the literature [18, 19].

In this paper, the uncertainties of demanded load and the inherent uncertainties of renewable energies are also considered. Consequently, the unscented transformation (UT) method as an efficient approach is applied in this paper to deal with the probabilistic nature of the considered optimal operation of hybrid MGs. UT is a suggested and widely used approach which is proved to be faster than while it is approximately as accurate as Monte-Carlo [20]. The detailed formulation of UT was studied in [19].

The probabilistic problem of optimal power management of AC-DC hybrid MGs is solved using the proposed PSO-UT approach. The uncertain variables including demanded loads, wind speed and solar irradiation are modeled by the UT. Afterward, the PSO algorithm is used for minimizing the cost while the constraints are satisfied.

IV. Simulation Results

The results of the optimal day-ahead power management of hybrid MGs in deterministic and probabilistic scenarios are presented and the planning of units is done such that the considered cost objective function is minimized. In the deterministic analysis, the solar irradiation, wind speed, and the demanded load in the DC and AC sides of the hybrid MG are considered without uncertainty and the problem is solved using

PSO with a population size of 50 and the number of maximum iterations equal to 200 in MATLAB. Afterward, to consider the uncertainties of the power management of hybrid MGs, UT is integrated with the PSO algorithm, and the probabilistic problem is solved.

Tables I to IV, respectively show the parameters of the DE, FC, battery, and bidirectional converter. The initial charge of batteries, the rated power of PV units, and the rated power of WTs are respectively 150 kWh, 200 kW and 150 kW.

A. Optimal Day-ahead Power Management of AC-DC Hybrid MGs (deterministic scenario)

It is considered that the demanded load in the AC and DC sides and the output power of PVs and WTs are deterministic. PSO is used to solve the problem and the scheduling of units in AC and DC sides in the studied horizon are shown in Figs. 2 and 3.

In Figs. 2 and 3, in each hour the power of units that are consumer or load is shown by negative values and the power of generative units is shown by positive values. The sum of the consumed and generated powers in each hour are equal. In Figs. 2 and 3, the negative values related to the battery are representative of battery charging which shows the battery is a consumer while positive values show that the battery is discharging, and acts as a power supplier.

B. Optimal Day-ahead Power Management of Hybrid MGs while Considering Uncertainties

The stochastic optimal power management of hybrid MGs is studied in this section. UT approach is used to deal with the uncertainties of DC and AC demanded loads and the output power of PV and WT. Assuming that the demanded load of the hybrid MG and the available output powers of WT and PV units are based on a normal distribution function and if the considered values of the deterministic scenario are the mean value (MV) of these variables, and the standard deviation (SD) equal to 5%, as well as a positive linear correlation among loads of the AC and DC sides of the MG, 8 scenarios according to equations of UT approach are originated. Afterward, the considered power management for each scenario is solved and the optimal planning of each unit is presented.

The optimal planning of the hybrid MG which is the result of the average of the eight considered scenarios based on the UT method is shown in Figs. 4 and 5. By comparing the results of Figs. 2 and 3 with Figs. 4 and 5, it is observed that the optimal power management of units in hybrid MG when considering uncertainties is different from those of the deterministic scenario.

The operational cost of the hybrid MG in different considered scenarios, the MV, and the SD of the total scenarios are tabulated in Table V.

According to Table V, in scenarios I and III where output powers of WT and PV units are increased the operation cost is decreased and vice versa. According to scenarios V-VIII, the effect of load changes has a considerable effect on the expected cost of hybrid MG.

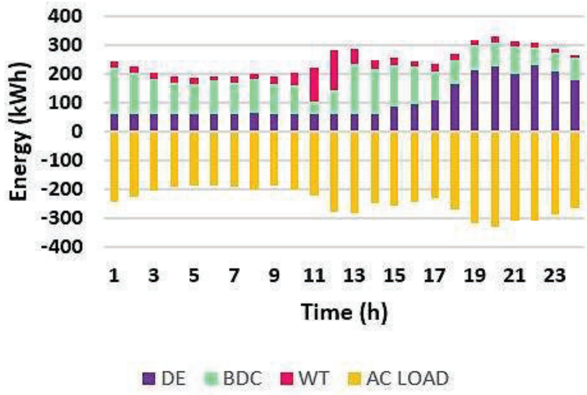

Fig. 2. Planning of units in the AC side of the hybrid microgrid without considering uncertainties.

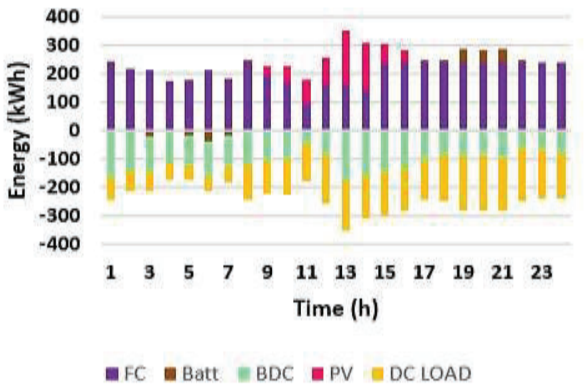

Fig. 3. Planning of units in the DC side of the hybrid microgrid without considering uncertainties.

TABLE I. PARAMETERS OF DE UNITS.

	P_{Min} (kW)	P_{Max} (kW)	a ($\$/kWh^2$)	b ($\$/kWh$)	c ($\$$)	SUC ($\$$)	R^{up}/R^{down} (kW)	MUT/MDT (h)
DE	60	360	0.007	0.03	2.9	0.68	120	2

TABLE II. PARAMETERS OF FC UNITS.

	P_{Min} (kW)	P_{Max} (kW)	C_{NG} ($\$/m^3$)	Q_{LHV} (kWh/m^3)	η (%)	SUC ($\$$)	R^{up}/R^{down} (kW)	MUT/MDT (h)
FC	40	240	0.35	9.7	58	0.86	150	2

TABLE III. PARAMETERS OF BATTERY.

Unit	$P_{Batt,Max}^{Ch/Dch}$ (kW)	$P_{Batt,Min}^{Ch/Dch}$ (kW)	$E_{Batt,Min}$ (kWh)	$E_{Batt,Max}$ (kWh)	η_{Batt} (%)
Battery	45	0	60	240	90

TABLE IV. PARAMETERS OF BDC.

Unit	$P_{BDC Max}(kW)$	$R^{up}/R^{down}(kW)$
BDC	250	150

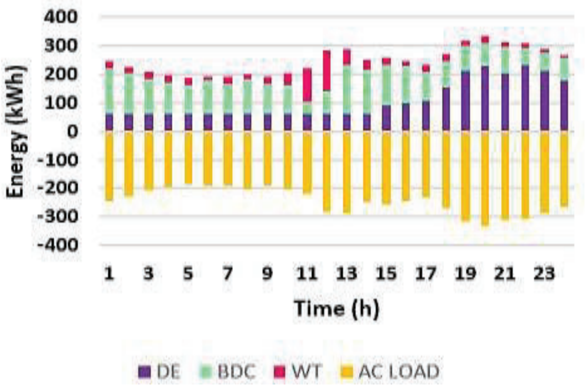

Fig. 4. Planning of units in the AC side for optimal power management of hybrid microgrid resulting from averaging of the eight generated scenarios by UT method.

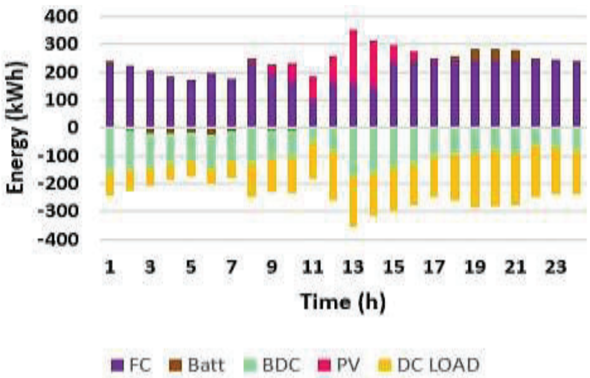

Fig. 5. Planning of units in the DC side for optimal power management of hybrid microgrid resulting from averaging of the eight generated scenarios by UT method.

TABLE V. OPERATIONAL COST IN DIFFERENT CONSIDERED SCENARIOS.

Scenario	Operational cost ($)
The base case (deterministic)	965
Scenario I: increasing the output power of PV unit	949
Scenario II: decreasing the output power of PV unit	978
Scenario III: increasing the output power of WT unit	941
Scenario IV: decreasing the output power of WT unit	990
Scenario V: increasing the AC demanded load	1308
Scenario VI: decreasing the AC demanded load	704
Scenario VII: increasing the DC demanded load	1152
Scenario VIII: decreasing the DC demanded load	800
The mean value and standard deviation	974 ±144.7

By comparing the base case (deterministic scenario) with the probabilistic scenario it is observed that the mean value of the expected operation cost increases with 15% tolerance while the tolerance of uncertain variables is considered equal to 10% of their mean values.

V. Conclusions

Recently, power management of hybrid MGs attracts attention due to the daily increase of DC loads including electric vehicles as well as the tendency to apply the maximum potential capacity of RESs and energy storage devices. The probabilistic problem of scheduling a hybrid MG is investigated in this paper using the PSO-UT algorithm. The problem is assessed from the economic point of view with RESs, AC, and DC load uncertainties, and the correlation among the random variables. It is concluded that the closer the MG parameters are to real conditions and the more accurate the modeling of uncertain variables, the more valid the solutions obtained from clarifying the MG power management problem. When the way of considering uncertain variables is far from the existing reality, the solution obtained as the optimal solution for MG power management and units' planning may not be the optimal solution.

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