A novel self-adaptive polar stochastic energy management approach for hybrid microgrids with high penetration of renewable energy sources

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Abstract
This article develops a probabilistic scheme for the efficient controlling of hybrid microgrids seeing renewable sources and power storages. Owing to the increasing popularity of DC loads (such as laptops, phones, etc) and distributed generation, hybrid AC–DC microgrids can provide more advantages than AC microgrids by direct power supply to AC and DC loads individually. In order to incorporate the randomness of forecast values’ impacts, a new load flow approach constructed based on unscented transform is engaged to handle the uncertainties of electrical demand, bidding pricing, tidal turbine output power and photovoltaic output. As the planned problem is a hard non-linear optimization, an influential polar crow search optimization algorithm is created to explore the problem domain. The polar version helps to search the optimal solution in a smoother and symmetrical space. Also, a new self-adaptive three platform correction system is used to reinforce the search aptitude of crow search optimization algorithm when evading early convergence. The total energy losses has improved from the initial condition of 4,065.363 $ to 3,216.129, 3,147.086 and 3,276.394 $ in the 1st, 2nd and 3rd scenarios, respectively. Moreover, the second scenario could get into the best voltage profile with deviation of 0.077428 pu.

1 INTRODUCTION

1.1 Motivation
The microgrid idea has attracted the attention of many researchers by bringing out lots of welfares for instance lower loss, higher power quality, reliability enrichment, advanced efficiency and cleaner technology [1–3]. In the investment part, the development of microgrid can help to charge the far-distance loads once the Transmission and Distributions (T&D) organization do not exist in the area. On account of the islanding proficiency of microgrids, they can recharge consumers when faulty which the straight consequence would be the sophisticated reliability and power quality [4]. Technically, microgrids are divided into unlike clusters based on their sort (site, armed, housing, marketable, and manufacturing), size (minor, average, and big scales), request (best power, resilience-oriented and loss decrease), and connectivity (far-off and grid-connected) [5]. According to the voltage phasor, microgrids are defined in three key collections of: AC microgrids, DC microgrids and hybrid microgrids.

1.2 Literature review
In AC microgrids, the consumers and producers are coupled at the AC point. In such microgrids, DC consumers are in the loop by means of AC-to-DC inventers and the DC DGs are in service using DC-to-AC convertors. On the opposite side, DC microgrids exist which use DC buses and take rectifiers and inverters to couple with AC DGs and DC demands, correspondingly. The hybrid microgrid is a grid, which has the features of both AC and DC microgrids in a united structure. In the hybrid microgrids, the elements of varied technology are joint with the buses with identical machinery (DC or AC) so it results in a good saving in the microgrid capital cost by eluding...
needless invertors/rectifiers. In [6], a novel genetic procedure is employed to inspect the ideal plan of AC microgrids using three modules of forecasting, battery, and optimizing. In [7], a linear programming approach is proposed to minimize the charge of a solar-wind AC microgrid incorporating the ecological restraints. In [8], an optimization method is suggested to find the best oil ingesting pattern in a microgrid when supporting the electrical/thermal energy strains with least reserve power. Four dissimilar arrangements are measured among the units in the microgrid to crack the problem. In [9], the communicating power exchange between an AC microgrid and the main company are judged using a master controller. Similar work is done in [10] to schedule a microgrid with a wind turbine (WT) and DG for minimalizing the microgrid costs. A good review on the operation and management challenges of AC microgrids can be found in [11]. Conversely, DC microgrids can put forward numerous welfares in association with AC microgrids: 1) advanced efficacy and lower losses by overlooking a number of converters utilized in AC microgrids for supplying DC loads, 2) comfort use for DC units for instance photovoltaic and battery, 3) allowing bus ties to function deprived of the necessity to synchronize buses and 4) providing DC loads for example electric vehicles with higher efficacy [12]. The swelling size of DC appliances like PCs, laptops, LED lights, TVs and radios to support the idea of DC microgrids especially in the areas with no access to the AC electric grid. The last group goes to the hybrid microgrids, which utilizes the profits in AC and DC microgrids. The main idea of the hybrid AC–DC microgrids is to charge the AC and DC loads directly from the AC and DC generating, respectively. The number of study works on the DC microgrid is lower than the number of works on the AC microgrids. In [13], a linear model is proposed to provide consensus between the power and demand sides seeing the interconnection of AC and DC areas in the hybrid microgrid. The problem formulation aims at minimalizing the functioning cost of the system using a controller for managing the power transfer between the AC and DC parts of the microgrid. In [14], a multi-structure based on evolutionary algorithm is established for preparation of DC microgrid to yield the cost of electricity and energy flow of storage batteries as objective functions. In [15], authors recommend a preparation method bearing in mind load/generation variations and time of use (TOU) pricelist for a low voltage DC microgrid plus energy storage battery, fuel cell and photovoltaic generations to advance energy efficacy, diminish ecological impressions and increase grid dependability. In [16], a hybrid AC–DC microgrid is planned for better coupling of DGs to upstream grid, and abusing the protuberant structures of AC and DC microgrids. In order to connect these microgrids, an interlacing AC/DC converter (IC) with a correct power organization and control policy is working here.

1.3 Contributions

Although each of the above studies have highlighted some aspects of the microgrid operation, still there are much more efforts are needed to inspect different aspects of this new technology. In order to get to this goal, a probabilistic structure based on unscented transform [17] is utilized which can not only optimally dispatch the units, but can also capture the high randomness of the uncertainty effects. The microgrid total AC and DC costs are integrated in the form of a unit cost function regarding the total power purchasing costs. The concept of hybrid grid can let the AC and DC areas exchange power at some hours and minimize their dependency on the main grid. The probabilistic model takes out some estimating point from the density function of the randomness and they solves the problem using several equivalent deterministic frames. A new optimization method based on crow search optimization algorithm (CSOA) is also proposed which is inspired form the natural hiding habit of crows [18]. In order to increase the convergence of the algorithm, the polar version of CSOA is introduced in this work. Moreover, a novel self-adaptive three-step correction approach based on crossing and mutating operators along with advanced math based method are suggested. This can enhance the optimization performance and avoid using repetitive modification methods in the optimization process. Therefore, the main paper contributions can be summarized as follows:

(i) Investigating the effect of new technical renewable energy sources of tidal units and PV units on the optimal energy management of hybrid AC-DC microgrids.
(ii) Developing a stochastic framework based on unscented transform and modified SOA to capture the uncertainty effects in the model.
(iii) Developing a new self adaptive modification method based on polar CSOA (called MCSOA) to solve the problem.
(iv) Assessing the effect of optimal scheduling on the voltage profile and cost of the hybrid microgrids.

The performance and high reliability of the proposed structure is inspected through some scenarios on the IEEE test system.

In the following: Section 2 yield a comprehensive model for the hybrid microgrids. Section 3 studies the probabilistic model of capturing the uncertainty. Section 4 clarifies the new algorithm (called MCSOA) as the optimization means. The comprehensive comparison and simulation scenarios are provided in Section 5. Section 6 elucidates the focal outcomes of the study. To finish, the core impressions and assumptions are given in Section 7.

2 HYBRID TECHNOLOGY FOR MICROGRIDS

2.1 Hybrid microgrid knowledge

Hybrid microgrid reveals a groundbreaking way of intelligence about enterprise and expansion of ecological grids, which the final purpose is to get access towards smart grids. Hybrid microgrids have a faster implementation and have the capability of constructing an electric grid with redundancy, DG and
storage, cogeneration, heat and power combined power generation, higher reliability and better consumer control (so-called demand response). Technically, supporting DC loads with AC power sources as well as the AC loads with DC power sources requires the use of many conversion (either inverter or rectifier) devices which not only increase the investment cost but also increase the power losses in the system. Therefore, in its place of taking individual AC or individual DC microgrids, hybrid microgrids which integrate both AC and DC microgrids are the best solution to boost the efficiency and quality of the electric power grid. Hybrid AC–DC microgrids have separate feeders and decrease the total losses of the system by omitting many unnecessary conversion devices. Figure 1 displays the theoretical design of hybrid AC–DC microgrids wherein countless AC and DC elements are coupled to the consistent DC and AC grid. The AC and DC relations are coupled through some transformers to make the idea of hybrid microgrids. With the intention of delivering power to the microgrid, the AC bus of the hybrid microgrid is coupled with the main utility.

2.2 Problem formulation

2.2.1 The cost function combines the cost of power production by DGs, storages, renewable units and the upstream company in the hybrid microgrid as

\[
\text{Min } E(f(X)) = \sum_{i=1}^{N_{\text{DG}}} \left( \sum_{j=1}^{N_{j}} [u_j(E(p'_{\text{DG}}))B'_{\text{Gi}} + \gamma_{\text{Gi}} \max(0, u_j^{f,1} - u_j^{f-1})] + \gamma_{\text{Gi}} \max(0, u_j^{f-1} - u_j^{f}) \right)
\]

\[
+ \sum_{j=1}^{N_{j}} [u_j^{f} E(p'_{i,j})B'_{i,j} + \gamma_{i,j} \max(0, u_j^{f} - u_j^{f-1})] + \gamma_{i,j} \max(0, u_j^{f-1} - u_j^{f}) + E(p_{\text{Grid}}^{f})B_{\text{Grid}}^{f} \right)
\]

In this equation, \( E(f(X)) \) is the aggregated cost of microgrid. The main limitations are explained in the rest.

2.2.2 Power–load balance at DC part of hybrid microgrid

Total generation in the DC area meets the total demand if:

\[
\sum_{i=1}^{N_{\text{DG}}} E(p'_{\text{DG}}) + \sum_{j=1}^{N_{j}} E(p'_{i,j}) + E(p'_{\text{Grid}}) = \sum_{k=1}^{N_{\text{Load}}} E(P'_{\text{Load},k})
\]

2.2.3 Power generation limit

Each DG can work in its capacity range:

\[
\eta^{f}p_{\text{Gi},\text{min}}^{f} \leq E(p_{\text{Gi}}^{f}) \leq \eta^{f}p_{\text{Gi},\text{max}}^{f}
\]

\[
\eta^{f}p_{i,j,\text{min}}^{f} \leq E(p_{i,j}^{f}) \leq \eta^{f}p_{i,j,\text{max}}^{f}
\]

\[
p_{\text{Grid},\text{min}}^{f} \leq E(p_{\text{Grid}}^{f}) \leq p_{\text{Grid},\text{max}}^{f}
\]

2.2.4 Charge/discharge boundary

The total energy size as well as the charge/discharge rate of battery are limited as follows:

\[
E(W_{\text{ess}}^{f}) = E(W_{\text{ess}}^{f-1}) + \eta_{\text{charge}}E(P_{\text{charge}}^{f})\Delta t
\]

\[
- \frac{1}{\eta_{\text{discharge}}} E(P_{\text{discharge}}^{f})\Delta t
\]

\[
\times \left\{ \begin{array}{l}
W_{\text{ess},\text{min}}^{f} \leq E(W_{\text{ess}}^{f}) \leq W_{\text{ess},\text{max}}^{f}E(P_{\text{charge}}^{f}) \\
\leq P_{\text{charge},\text{max}}^{f}E(P_{\text{discharge}}^{f}) \leq P_{\text{discharge},\text{max}}^{f}
\end{array} \right\}
\]

2.2.5 Spinning reserve

\[
\sum_{i=1}^{N_{\text{DG}}} u^{f} p_{\text{Gi},\text{max}}^{f} + \sum_{j=1}^{N_{j}} u^{f} p_{i,j,\text{max}}^{f} + E(P_{\text{Grid},\text{max}}^{f})
\]

\[
\geq \sum_{k=1}^{N_{\text{Load}}} E(P'_{\text{Load},k}) + E(p_{\text{loss}}^{f}) + \text{Res}^{f}
\]

2.2.6 Maximum power flow

\[
|E(p'_{\text{Line}}^{f})| < p_{\text{Line}}^{f,\text{max}}
\]
2.2.7 | Maximum and minimum voltage level

\[ V_{\text{min}}^m \leq E(V_m) \leq V_{\text{max}}^m \]  \hspace{1cm} (11)

3 | STOCHASTIC SCHEME BASED ON UNSCENTED TRANSFORM

The hybrid microgrid operation requires the appropriate modelling of several uncertainties. This is not limited to the renewable sources like tidal and PV but includes the total load demand and market price as well. This paper makes use of a correlated estimation scheme to get into this goal. The superiority of the proposed approach over the most well-known methods is validated in [17]. Let's assume \( v \) as number of uncertain parameters, then unscented transform creates \( 2v+1 \) deterministic frameworks to handle the uncertainty effects. For the sake of simplicity, let's show the nonlinear relation by \( S = f(Z) \) wherein \( Z \) and \( S \) represent the input and output vectors. Having \( \mu \) as the expected value, the standard deviation of the uncertainties are included in matrix \( P_{zz} \). By means of \( Z \) and \( P_{zz} \), the next steps are obligatory to catch the expected \( \mu_s \) and standard deviation \( P_{ss} \):  

Step 1: Assess \( 2v+1 \) attentiveness points \( s \) through the input:

\[ s^0 = \mu \]  \hspace{1cm} (12)

\[ s^k = \mu + \left( \sqrt{\frac{v}{1 - W^0 P_{zz}}}ight) k; k = 1, 2, ..., v \]  \hspace{1cm} (13)

\[ s^k = \mu - \left( \sqrt{\frac{v}{1 - W^0 P_{zz}}}ight) k; k = 1, 2, ..., v \]  \hspace{1cm} (14)

Step 2: Assess the weighting feature of any sample point by means of the underneath equations:

\[ W^0 = W^0 \]  \hspace{1cm} (15)

\[ W^k = \frac{1 - W^0}{2^v}; k = 1, 2, ..., v \]  \hspace{1cm} (16)

\[ W^{k+v} = \frac{1 - W^0}{2^v}; k + v = v + 1, ..., 2v \]  \hspace{1cm} (17)

Note it that the sum of weighting factors must become one:

\[ \sum_{k=0}^{2v} W^k = 1 \]  \hspace{1cm} (18)

Step 3: Attain the cost function \( 2v+1 \) times using \( 2v+1 \) points:

\[ S^k = f(Z^k) \]  \hspace{1cm} (19)

Step 4: By the use of (19), the \( \mu_s \) and \( P_{ss} \) are attained:

\[ \mu_s = \sum_{k=0}^{2v} W^k s^k \]  \hspace{1cm} (20)

\[ P_{ss} = \sum_{k=0}^{2v} W^k (S^k - \mu_s)(S^k - \mu_s)^T \]  \hspace{1cm} (21)

In Equation (21), the symbol \( S \) represents the nonlinear function existing between the input and output variables of the prob-
lem. In this problem, the nonlinear function \( f(Z) \) in Equation (19) is the load flow equations.

## 4 | OPTIMIZATION ALGORITHM

In comparison with PSO and GA, the CSOA has fewer setting parameters. CSOA is prepared with both local and global search mechanisms which make it applicable for handling nonlinear mixed integer programming. Also, the concept behind the CSOA is simple and this algorithm is easy to get implemented on any problem. In the CSOA, the chasing and following process of crows are simulated such that it can create a powerful optimization algorithm. In contrast to most of the optimization methods, CSOA does not require any derivative means and can model the binary and discrete variables in the same way. In CSOA, each crow is a possible solution for scheduling of the hybrid microgrid. In this paper and based on the problem, \( X \) vector (each crow) demonstrates the power dispatch status of DGs, storages, grid and their ON/OFF position as follows:

\[
X = [P_G, U_P]^T, \forall t \in N_T
\]

\[
P^t_G = [P^t_{G1}, P^t_{G2}, \ldots, P^t_{G_N}],
\]

\[
P^t_{Grid} = [P^t_{G1}, P^t_{G2}, \ldots, P^t_{G_N}],
\]

\[
U^t = [u^t_1, u^t_2, \ldots, u^t_N], u^t_k \in \{0, 1\}
\]

This means that each crow is a unique vector, with a length equal to the number of problem variables. As mentioned in the introduction section, a polar version of the CSOA is introduced here to accelerate the convergence of the algorithm. The hidden concept for polar CSOA is to replace the Cartesian framework by the polar framework. Consequently, the velocity and position of crows are updated in polar framework. Therefore, each crow \( X \) is replaced by \( \theta \). After generating a random original population \( U_0 \), crows are updated with the following strategy:

\[
\theta_i^{iter+1} = \theta_i^{iter} + r \times \theta_i^{iter} \times (M_i^{iter} - \theta_i^{iter}), \quad i = 1, \ldots, N
\]

Here \( \beta \) plays the role of pitch adjusting, i.e. it can let the algorithm make either a local or a global search. In CSOA, a crow needs to hide her nest from other birds. This process happens with a specific probability value which can be simulated as follows:

\[
\theta_i^{iter+1} = \begin{cases} 
\theta_i^{iter} + r_i \times \theta_i^{iter} \times (M_i^{iter} - \theta_i^{iter}), & \text{if } \sigma_j \geq p_m^{iter} \\
\theta_i^{iter} + r_i \times \theta_i^{iter} \times \theta_i^{iter} \times (M_i^{iter} - \theta_i^{iter}), & \text{if } \sigma_j < p_m^{iter}
\end{cases}
\]

The parameter \( p_m \) determines how much a crow would be successful or not.

In such a polar formulation, \( \theta \in (-\frac{\pi}{2}, \frac{\pi}{2}) \). With the intention of computing the problem objective functions, crows should be return into the Cartesian framework as below:

\[
X_j = \frac{X_{\max} - X_{\min}}{2} \sin \theta_j + \frac{X_{\max} + X_{\min}}{2}
\]

About the equality and inequality constraints and how they are satisfied, note it that CSOA follows the same way as other heuristic algorithms such as GA, PSO, etc. to meet the constraints. For equality constraints, the crow vector (solution vector \( X \)) is corrected such that if it is higher than the maximum value of the variable, it is fixed on the maximum value and if it lower than the minimum value of the variable, it is fixed on the minimum value. For equality constraints, an error vector in a “while loop” is defined which should get to zero. It means, as long as the two sides of the equality constraints are not equal, the elements of the corresponding solution are updated randomly.

This paper proposes a new self adaptive correction approach to make sure that it will not fall in the local optimal of the microgrid operation. The main reason for the choice of adaptive modification is that it makes it possible to get use of the best modification methods when avoiding to use them repeatedly when the optimization performance is accepted. In other words, the proposed self adaptive modification mechanism helps to pick only one of the modification methods in each iteration based on the algorithm needs and preferences.

In the first modification method, the most optimal solution in the crow population is saved \( G_{best} \) to guide the crow flocks. Bearing in mind the velocity \( V_j \) for crow \( \theta \), each crow moves toward \( G_{best} \) as follows:

\[
\theta_j^{iter+1} = \theta_j^{iter} + \beta_1(G_{best} - \theta_j^{iter})
\]

In the second correction approach, three dissimilar crows are picked up from the crow population randomly to construct new varied crows. Therefore, crows \( \theta_m1, \theta_m2 \) and \( \theta_m3 \) are picked up such that \( m1 \neq m2 \neq m3 \) and a new mutated crow is produced:

\[
\theta_{mut} = \theta_m1 + \beta_2 \times (\theta_m2 - \theta_m3)
\]

Now some test solutions are created by the crossover operator:

\[
\theta_{Test1} = \begin{cases} 
\theta_{mut} & \beta_2 \leq \beta_3 \\
\theta_{G_{best}} & \text{else}
\end{cases}
\]

\[
\theta_{Test2} = \begin{cases} 
\theta_{mut} & \beta_3 \leq \beta_4 \\
\theta_j & \text{else}
\end{cases}
\]

\[
\theta_{Test3} = \beta_4 \times G_{best} + \beta_4 \times (G_{best} - \theta_j)
\]
The fittest solution in the above will replace $X_i$ in the iteration.

In the third correction, it is tried to update the value of $f_l$ and $\text{pro}$ such that it helps the algorithm to converge more successfully. Since at the beginning of the algorithm we need more global search, third values should be large enough. As time passes, their values decreases to make local search:

$$
\text{pro}_{\theta}^{\text{iter}+1} = 1 - \text{pro}_{\theta}^{\text{iter}}[1 - e^{-\rho_1 \times \text{iter}}]
$$

$$
\theta_{l}^{\text{iter}+1} = 1 - \theta_{l}^{\text{iter}}[1 - e^{-\rho_2 \times \text{iter}}]
$$

where $\text{pro}_{\theta}^{0}$ and $\theta^{0}$ are the initial values.

The way of making a self-adaptive mechanism is to let each solution pick up the modification method which helps it the most to improve its situation. First, a probability stack, called $\text{Prb}_{\theta}$ is defined for the three modification methods, here $\theta = 1, 2, 3$. Moreover, an accumulator is considered to each modification which is originally zero ($Aum_{\theta}$). In each iteration, by sorting the crows based on objective function and in a descending order, a weighting value is assigned to them as below:

$$
W_{\text{fit}} = \frac{\text{Log}(N - j + 1)}{\sum_{i=1}^{N} \text{Log}(i)}
$$

Now the accumulator and stack can be updated for modifications as follows:

$$
Aum_{\theta} = Aum_{\theta} + \frac{W_{\text{fit}}}{n_{\text{Mod}_{\theta}}}, \theta = 1, 2, 3
$$

$$
\text{Prb}_{\theta} = (1 - \varepsilon) \times \text{Prb}_{\theta} + \varepsilon \times \frac{Aum_{\theta}}{\text{iter}}, \theta = 1, 2, 3
$$

Finally the probability of each modification is normalized as below:

$$
\text{Prb}_{\theta} = \frac{\text{Prb}_{\theta}}{\sum_{\theta=1}^{3} \text{Prb}_{\theta}}
$$

Each solution can pick the suitable modification based on roulette wheel mechanism (RWM), randomly.

5.1 DC microgrid

In this part the optimal scheduling of the DC microgrid is done. This is dedicated to demonstrate the performance of MCSOA as the optimization means. The DC microgrid includes several types of DGs including one photovoltaic source, one fuel cell, one tidal unit, one micro turbine and one battery as the storage device. The microgrid supplies a residential area, an industrial area and a light commercial area. The problem is solved for 24 h. Figure 3 displays the hourly forecast load demand, utility energy price, tidal unit output power and photovoltaic output power. Other information regarding the DG capacities and prices are provided in Table 1 [20]. With the aim of seeing the place of each power unit in the supply of the load, three diverse scenarios are demarcated. In scenario one, DGs are forced to stay ON and battery is assumed fully charged. In the second scenario, DGs can switch ON/OFF but the battery is the same as scenario 1. In the third scenario, the DGs can turn On or OFF but the battery is out of charge. Please note it that tidal unit is not considered as a dispatchable unit here. In Table 1, the tidal turbine value is showing the power generation capacity only. The output power generation pattern is shown in Figure 3 as non-dispatchable unit.

Table 2 expresses the results for all scenarios. Please note it that here we have considered wind turbine instead of tidal unit to have the situation required for the comparison. So as to have deep analysis, simulations are continued for 20 trials and the best result, worst result, average of results, standard deviation of result along with the CPU time are provided in the table. Also, the simulation results of some of the most well-known methods in the area have been provided to have better comparison. Bestowing to the results of Table 2 [21], the proposed MCSOA has superior performance than the other optimization algorithms in all scenarios. Based on these results, the high robustness of MCSOA from the low standard deviation value and the high global search ability from the other criteria are deduced. Also, it is seen that the least cost belongs to the second scenario. On the opposite side, the last scenario takes the uppermost cost value in consequence of the zero preliminary charge of the battery.

The power generation values by other units are given in Figures 4–6 for the three scenarios. In Figure 4 (first scenario), due to its low flexibility, the expensive units are in service so the total cost has increased. In the case of battery, it is charged at the first hours and is get in use in the later loading hours.

5 RESULTS AND DISCUSSIONS

The test system is a hybrid microgrid with the AC part borrowed from IEEE 33-bus and the DC part is connected to it through bus 18 (shown in Figure 3). According to Figure 2, the DC and AC areas are coupled to each other by a converter. The nominal operation voltage value is 12.66 kV. Complete data for the AC area exist in [19] and the complete data of the DC area are taken from [20]. With the purpose of having better analysis about the performance of the proposed stochastic method, the simulations are done in two different parts. In the first part, only the DC microgrid is simulated and the AC part is neglected. The main perseverance of this part is to compare the search ability of modified CSOA (MCSOA) over the other recognized algorithms in the area. The second part of the simulations is devoted to simulate the hybrid AC-DC microgrid. In both cases, three unlike scenarios are developed to reach better indulgent of the problem.
when peak. In Figure 5 which belongs to the second scenario, the units can turn ON/OFF, thus giving more freedom to the operator to manage the units such that the total cost is minimized. Such a strategy can help to turn off expensive units and let the microgrid to purchase power from the main grid when it is more economical. Finally, in Figure 6, the simulation results for the 3rd scenario show that the battery has to get charged in the first hours, otherwise can not attend the economic power

![Structure of the test microgrid](image)

**FIGURE 2** Structure of the test microgrid [17]

**TABLE 1** Characteristics and bidding offer of the power sources and utility

| Type            | Low capacity [kW] | High capacity [kW] | Cost [€/kWh] | Start-up/shut-down cost [€] |
|-----------------|-------------------|--------------------|--------------|-----------------------------|
| Micro turbine   | 6                 | 30                 | 0.457        | 0.96                        |
| Fuel cell       | 3                 | 30                 | 0.294        | 1.65                        |
| Photovoltaic    | 0                 | 25                 | 2.584        | 0                           |
| Tidal turbine   | –                 | –                  | 1.073        | 0                           |
| Battery         | –30               | 30                 | 0.38         | 0                           |
| Main utility    | –30               | 30                 | –            | –                           |
At the beginning, the ability and steadfastness of the proposed optimization structure based on MCSOA was calculated. From now on, the wind turbine is replaced by the tidal unit. With this notion, the second part of the simulations is devoted to the optimal operation of the hybrid AC–DC microgrid. As mentioned before, the hybrid microgrid consists of an AC part which is the IEEE 33-bus test system and a DC part the same as the DC microgrid in the last part. In the AC network, micro turbines 2

5.2 hybrid AC–DC microgrid

dispatch problem, later. This indeed has increases the microgrid total cost.
TABLE 2  Inspecting the performance of the proposed MCSOA over 20× of run

| Method         | Best solution [€ct] | Worst solution [€ct] | Average [€ct] | Standard deviation [€ct] | Mean simulation time [s] |
|----------------|---------------------|----------------------|---------------|--------------------------|-------------------------|
| First Scenario |                     |                      |               |                          |                         |
| GA [20]        | 277.7444            | 304.5889             | 290.4321      | 13.4421                  | –                       |
| PSO [20]       | 277.3237            | 303.3791             | 288.8761      | 10.1821                  | –                       |
| FSAPSO [20]    | 276.7867            | 291.7562             | 280.6844      | 8.3301                   | –                       |
| CPSO-T [20]    | 275.0455            | 286.5409             | 277.4045      | 6.2341                   | –                       |
| CPSO-L [20]    | 274.7438            | 281.1187             | 276.3327      | 5.9697                   | –                       |
| AMPSO-T [20]   | 274.5507            | 275.0905             | 274.9821      | 0.3210                   | –                       |
| AMPSO-L [20]   | 274.4317            | 274.7318             | 274.5643      | 0.0921                   | –                       |
| GSA [21]       | 275.5369            | 282.1743             | 277.8021      | 2.9283                   | 0.78                    |
| SGSA [21]      | 269.7600            | 269.7600             | 269.7600      | 0                        | 0.36                    |
| CSOA           | 270.8852            | 275.3951             | 272.2205      | 3.1149                   | 0.026                   |
| MCSOA          | 264.7600            | 264.7600             | 264.7600      | 0                        | 0.019                   |
| Second Scenario|                     |                      |               |                          |                         |
| GA [20]        | 277.7444            | 304.5889             | 290.4321      | 13.4421                  | –                       |
| PSO [20]       | 277.3237            | 303.3791             | 288.8761      | 10.1821                  | –                       |
| FSAPSO [20]    | 276.7867            | 291.7562             | 280.6844      | 8.3301                   | –                       |
| CSOA           | 271.8933            | 273.4739             | 272.8592      | 0.6753                   | 0.027                   |
| MCSOA          | 261.2340            | 261.2340             | 261.2340      | 0                        | 0.019                   |
| Third Scenario |                     |                      |               |                          |                         |
| GA [21]        | 334.8694            | 345.0211             | 336.2912      | 17.6310                  | 36                      |
| PSO [21]       | 327.7211            | 340.3123             | 331.2102      | 13.1244                  | 36                      |
| FSAPSO [21]    | 326.4291            | 335.4931             | 331.4301      | 10.6621                  | 36                      |
| GSA [21]       | 319.6284            | 331.8401             | 323.1782      | 5.0257                   | 0.066                   |
| SGSA [21]      | 304.1147            | 304.1873             | 304.1492      | 0.0108                   | 0.026                   |
| CSOA           | 314.6639            | 334.5825             | 322.6720      | 5.8844                   | 0.028                   |
| MCSOA          | 299.4124            | 299.4124             | 299.4124      | 0                        | 0.020                   |

TABLE 3  Capacity and bids of the RESs and the utility

| Type            | MinpPower [kW] | Max power [kW] | Bid [€ct/kWh] | Start-up/shut-down cost [€ct] |
|-----------------|----------------|----------------|--------------|-------------------------------|
| Fuel cell       | 9              | 30             | 0.294        | 1.65                          |
| Photovoltaics   | 0              | 55             | 2.584        | 0                             |
| Tidal unit 1    | 0              | 45             | 1.073        | 0                             |
| Battery         | −80            | 80             | 0.38         | 0                             |
| AC–DC converter | −80            | 80             | –            | –                             |
| Micro-turbine 2 | 50             | 250            | 0.215        | 1.65                          |
| Micro turbine 3 | 65             | 250            | 0.275        | 1.65                          |
| Tidal unit 2    | 0              | 250            | 2.584        | 0                             |

and 3 are working on buses 12 and 25. In addition, tidal unit 2 is installed on bus 30. To better perceive the exchange power capability of the hybrid microgrid, the capacities of DGs are updated and shown in Table 3.

Similar to the first part of the simulation results, the three scenarios are employed here to provide deep analysis over the performance of different parts. Since the search ability of MCSOA was verified in the last part, here the simulation results are implemented only by MCSOA to avoid repetition. Table 4 shows the simulation results in all cases including energy lost, voltage deviation and utility costs. According to these results, the proposed technique is talented to advance the system from different aspects counting the operation cost, power losses and grid voltage level. By comparing different scenarios, it is seen that the second scenario could reach to lower cost function value than the other scenarios. This is because of the higher flexibility of
TABLE 4  Comparing different objectives of the operation in the test system

| Case            | Energy losses [kWh] | Voltage deviation [pu] | Cost value [€ct] |
|-----------------|---------------------|------------------------|-----------------|
| Initial status  | 4,063.363           | 0.086909               | 105,826.12      |
| First scenario  | 3,216.129           | 0.080079               | 89,710.154      |
| Second scenario | 3,147.086           | 0.077428               | 89,695.966      |
| Third scenario  | 3,276.394           | 0.080564               | 89,789.100      |

this scenario for DGs. Similar improvement can be seen in the amount of total energy losses and voltage deviation. One significant point about that can be found from these results is the positive effect of power units on the system. In fact, the system initial status shows the situation in which the hybrid microgrid is only supported by the main grid and does not include any DG, battery or renewable energy sources. However, after considering the hybrid microgrid, in all three scenarios, the system performance is enhanced in judgement with the early case. With the purpose of well observing the change between these three scenarios, Figures 7–9 display the generation of dissimilar units for the 1st, 2nd and 3rd scenario, correspondingly. As said by these outcomes, fuel cell as an inexpensive DG is at work at its supreme capacity practically at most of the scheduling hours. Then again, micro turbines due to their expensive nature are favoured to produce power only through the heavy loading hours. Checking the power exchange pattern between the DC and AC areas, one can deduce that the DC microgrid needs energy from the AC area at the first hours of the day. But the middle of the day, the power flow direction gets reverse and DC area supports part of the energy in the AC area.

To have a good idea about the system voltage profile through the different scenarios, Figure 10 displays the voltage deviation of the system during 24 h. According to this figure, the...
TABLE 5 Results of modelling uncertainty effects in the analysis

| Case [€/ct] | Scenario one | Scenario two | Scenario three |
|-------------|--------------|--------------|---------------|
| Deterministic framework | 89,710.154 | 89,695.966 | 89,789.100 |
| Stochastic framework | 89,823.730 | 89,784.229 | 89,901.492 |

second scenario is showing a more smooth voltage pattern and thus a better voltage profile. The significant point is that the system voltage profile has overall enhanced in all scenarios in comparison with the initial case. In order to inspect the uncertainty effect on the cost function, Table 5 shows the simulation results for both the deterministic and stochastic structures. As it is seen here, uncertainty incorporation has resulted in higher cost values in all scenarios. This cost is paid to have a reliable and safe operation considering low probability but possible scenarios in the analysis due to the tidal turbine, PV, load demand and market price forecasting errors.

6 | CONCLUSION

Hybrid microgrids can progress the electrical quality using straight charging of DC and AC consumers. Also, by omitting the unnecessary converters in the AC and DC areas of the microgrid, the total microgrid costs are reduced. This paper proposes a probabilistic framework for optimal energy running in the hybrid microgrids to get to better mismatch between the demand and generation in the smart grids. The main topographies of the proposed energy management method can be shortened as follows:

(i) Hybrid structure: The proposed hybrid microgrid incorporates two different parts of AC and DC which are coupled to each other through the power electronic converters.

(ii) Stochastic framework: The planned probabilistic scheme based on unscented transform is talented for handling the uncertainties associated with renewables such as PV and WT as well the market price and load demand. The structure of this method is such that can model the correlated uncertainty efficiently.

(iii) Optimization method: On the word of the high complexity and nonlinearity of hybrid microgrids, an intelligent optimization algorithm called CSOA along with a new two-phase modification method is established to solve the problem optimally.

(iv) Customer convenience: According to the appearances of the hybrid microgrid, DC loads are supplied by the DC part of the microgrid and AC loads are supplied by the AC part. As the result, the possible small changes in the balance between the demand and generation is avoided greatly.

(v) Technical Progress: From the technical point of view, the simulation results show the high role of optimal switch-

ing in the real applications in power grids by reducing the power losses and costs. Also, it is seen that the grid automation can help to improve the voltage profile in the system, effectively.

(vi) Stability Issues: Hybrid ac/dc microgrids, like other types of microgrids, are subjected to dynamic instability when operated in islanding mode. In fact, as the microgrid gets disconnected from the main grid, it is always possible that the system experiences some instability issues in the first moments due to the unbalance issues between the generation and demand. Still, since the DG units are small and fast in response, the system can restore the stable situation in the very short time. It is clear that it is quite expected that if load demands exceeds the total power generation, some load shedding happens in the microgrid in the islanding mode.

Owing to the main focus of this paper on the steady state analysis of the hybrid microgrids, the concept of stability and dynamic analyses are beyond the scope of this paper. Moreover, the proposed model in this paper is only applicable to the centralized systems. In order to solve the problem in a distributed framework, the hybrid microgrid needs to be divided into its agents. The proposed method in this paper does not consider the electric vehicles, a topic which can be discussed in the future works.

NOMENCLATURE

| Aumg          | Accumulator for each modification method |
|---------------|-----------------------------------------|
| (A)k          | kth row/column in A                      |
| BGi,t & Bj,t  | Bidding offer of ith DG and jth storage at t |
| Bi,Grid       | Power selling offer of the main company at t |
| d             | Number of optimizing variables           |
| f             | Cost function                            |
| βiter         | Fighting parameter                       |
| Iter          | Algorithm iterations                      |
| Mj            | the nest of crow j covering her food     |
| N             | Size of CSOA population                   |
| Nr            | Operation horizon                         |
| Ns            | Quantity of storages                      |
| Ns, DG        | Quantity of DGs                           |
| NLoad         | Number of loading level                   |
| n, Mij        | Number of solutions chosen                |
| θmodification |                                      |
| n             | Aggregated number of power units          |
| PsGrid        | Main utility power generation at time t   |
| pGi,t & pGj,t | Amount of power produced by ith generator and jth storage |
| PLoad, k    | load value in kth level of ith hour |
| Pm, Lmit/t & Qm, Lmit/t | Active/reactive power produced on bus m at t |
| pGimin & pGimax | Lower & upper capacity of ith DG at t     |
\[ \rho \] Significance of the deterministic framework \[ \mu \] Energy stored in the battery energy at \( t \) \[ \xi_{ij} \] \( i \)-th element of the \( j \)-th control vector \[ \gamma \] Magnitude/phase of \( Y \) admittance \[ \delta \] Any nonlinear function \[ \mathbf{Z} \] Vector representing the uncertain parameters \[ \beta_1, \ldots, \beta_6 \] Random values \[ \eta_{\text{charge}} (\eta_{\text{discharge}}) \] Battery charging (discharging) efficiency

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