

Green Micro-Grid Operation Constrained to Reliability and Flexibility Indices in the Presence of Distributed Generations and Energy Storage Systems

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A This paper presents microgrid (MG) operation constrained to the reliability, flexibility, and environment indices in the
B presence of distributed generations (DGs) and energy storage systems (ESSs). The proposed scheme minimizes the total
S expected operating cost of MGs and DGs. It is also subject to alternating current (AC) power flow equations of MGs,
T constraints of operation, reliability, and flexibility of MGs, and operation model of power sources and storage devices.
R Stochastic programming is incorporated to model uncertainties of load, energy price, the active power of renewable energy
A generation, availability of MG equipment, sources, and storage devices. Following on, a hybrid solver formed by combining
C an artificial bee colony (ABC) and a sine-cosine algorithm (SCA) is adopted to achieve the optimal solution with approximate
T conditions of the unique ultimate response. Eventually, the suggested scheme is implemented on a 69-bus radial MG, where
the numerical results confirm the capability of the scheme in improving the operation, reliability, flexibility, and environment
status of the MG.

Article Info

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Nomenclature

Indices and sets

h, n, s	Indices of operation hour, bus, scenario
l	Auxiliary index denoting a bus
ref	Slack bus
$\Omega_H, \Omega_B,$	The set of operation hour, the set of MG buses,
Ω_S	and the set of scenarios
Ω_R	The set of buses including renewable DGs

Variables

C	The sum of the expected operating cost of the MG and DGs (\$)
$EENS$	Expected energy not-supplied in per-unit (p.u.)
P^{DG}, Q^{DG}	Active and reactive power of the DG (p.u.)
P^{DL}, Q^{DL}	Active and reactive power flowing through the distribution line (p.u.)
P^{DS}, Q^{DS}	Active and reactive power flowing through the distribution substation (p.u.)
$P^{E,D}, P^{E,C},$	Discharge and charge active power of the ESS
Q^E	and reactive power of the ESS (p.u.)
P^{NS}	Load not-supplied (p.u.)
V, β	Voltage magnitude (p.u.) and angle (rad)
y	A binary variable denoting the operation status of the ESS in the charge and discharge mode

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Constants

$a^{DL}, a^{DS}, a^{DG}, a^E$	Availability of the distribution line, distribution substation, DG, and ESS
CR, DR	Charge and discharge rate of the ESS (p.u.)
$EENS^{max}$	Maximum value of expected energy not-supplied (p.u.)
EM^{max}	Maximum environmental pollution (kg)
E^{min}, E^{max}	Minimum and maximum storable energy in the ESS (p.u.)
G^{DL}, B^{DL}	Conductance and susceptance of the distribution line (p.u.)
IM	Incidence matrix of buses and the distribution line
PF^{min}	Minimum power factor
$P^{DG,m}$	Maximum active power generation by the renewable DG (p.u.)
P^L, Q^L	Active and reactive power of consumers (p.u.)
$S^{DG,m}$	Maximum capacity (size) of the DG (p.u.)
$S^{DL,m}$	Capacity of the distribution line (p.u.)
$S^{DS,m}$	Capacity of the distribution substation (p.u.)
$S^{E,m}$	Capacity of the ESS charger (p.u.)
V^{min}, V^{max}	Minimum and maximum permissible values of voltage magnitude (p.u.)
V_{ref}	The voltage of the slack bus
γ^{DS}, γ^{DG}	Coefficient of the total pollution of NO _x , CO ₂ , and SO ₂ for supplying energy from the upstream network and DGs (kg/MWh)
η^C, η^D	Charge and discharge efficiency of the ESS
κ, χ, ν	Coefficients of the fuel cost function of the non-renewable DG respectively in \$, \$/MWh, and \$/MWh ²
π	The probability of occurrence of the scenario
ρ	Energy price (\$/MWh)
ΔF	Flexibility tolerance (p.u.)

I. INTRODUCTION

To reduce the environmental pollution caused by fossil fuel consumption, the utilization of distributed generations (DGs) at the consumption site has gained attention [1]. Renewable DGs produce negligible pollution and impose low operating costs. Thus, their application at consumption sites, such as distribution networks and microgrids (MGs), has been considered [2]. However, since the active power of these sources is uncontrollable and their active power generation relies on climatic conditions, it is expected that the results of day-ahead and real-time operations of a network in the presence of these sources differ due to the weather forecast error [3]. Therefore, the balance of generation and consumption in the network is possibly not established in exchange for real-time operation, which is considered as low flexibility status of the network [3, 4]. To address this issue, it is recommended to use non-renewable DGs and energy storage systems (ESSs) that are controllable along with renewable

DGs [4]. Pollution coefficients of these sources and ESSs are smaller than the power supply from the upstream network [1]. Also, DGs and ESSs are generally distributed at different points across the network, so operating (reliability) indices such as voltage profiles (expected energy not supplied) are expected to be more favorable than those of power flow studies (power supply only via the upstream network) [3, 4]. Finally, to achieve the mentioned goals, it is necessary to implement an appropriate management system in the network. Therefore, it is predicted that the status of several network technical indices is improved by establishing a power management system (PMS) in a network, such as MG, and by optimal operation management of DGs and ESSs [5].

Various researches have been carried out in the field of operation of distribution networks and MGs. In [6], the effect of active and reactive power management of electric vehicles (EVs) in the parking lot on operation indices of distribution networks, such as energy loss and voltage profile, is investigated. It is formulated in a nonlinear optimization problem form and the linear approximation model (LAM) is used to achieve the optimal solution. Next, based on the results obtained in [6], a significant computational error is obtained for the design variables per linearization of the problem so that it is about 3% for active and reactive power. Also, due to the simultaneous management of active and reactive power of EVs in the network, a large number of EVs can be supplied by a distribution network in addition to minimizing energy loss and obtaining a smooth voltage profile. To improve the operation indices of the distribution network in the presence of a large number of photovoltaics (PVs), planning (sitting and sizing) of batteries in the distribution network is presented in [7]. The results indicate the ability of battery energy management in enhancing the status of distribution network operation indices. Note that batteries in [7] have been used as a source of flexibility improvement for a distribution network with PVs, but a mathematical model for evaluation of the flexibility level and status is not presented. This issue is also present in [8], where the authors incorporate demand response (DR) and battery as a source of flexibility in a wind system, while it does not provide a numerical index for flexibility. In [9], the simultaneous operation of several MGs is formulated by minimizing their operating cost as an objective function and the optimal power flow (OPF) equations as constraints of the problem. Similar to [7], robust optimization is incorporated in [9] to model uncertainties of load and renewable power. In [10], MG energy management is studied in two islanded and grid-connected modes to minimize energy costs and environmental pollution in the presence of responsive loads. In [11], the OPF model of several MGs connected to the grid is constrained by the voltage stability in the presence of DGs and DR. Based on the results presented in [11], simultaneous energy management of sources and responsive loads in the MG can create a safe margin for the bus voltages. Ref. [12] introduces the optimal

operation model of MGs in the presence of sources, ESSs, and DR, which incorporates grey wolf optimization (GWO) to achieve the optimal solution. In [13], a non-hybrid evolutionary algorithm (NHEA), named Porcellio Scaber algorithm (PSA), is employed to achieve the optimal solution of the MG energy management problem. Energy management of a multi-carrier MG connected to a network is described in [14]. This MG has electrical and thermal networks, so it is OPF with electrical and thermal power flow. Optimal operation of the distribution network with DGs and thermal blocks including boilers and combined heat and power (CHP) system is discussed in [15]. This design is in the form of multi-objective optimization and minimizes environmental pollution, energy loss, and the function of voltage deviations subject to OPF equations, the operation model of DGs, and the mentioned thermal block. It then uses the firefly algorithm to find the optimal solution. In [15], non-renewable DGs are exploited as a source of flexibility of a network with renewable sources, but similar to [7, 8], the mathematical model of flexibility is not presented. Finally, a summary of the recent research works is listed in Table I.

TABLE I
TAXONOMY OF RECENT RESEARCH WORKS

Ref.	Indices					Mathematical model of flexibility	Solver
	Economic	Operation	Reliability	Pollution	Flexibility		
[6-7]	Yes	Yes	No	No	No	No	LAM
[8]	Yes	Yes	No	No	No	No	MA
[9]	Yes	Yes	No	No	No	No	MA
[10]	No	Yes	No	Yes	No	No	MA
[11]	No	Yes	No	No	No	No	MA
[12-14]	No	Yes	No	No	No	No	NHEA
[15]	No	Yes	No	Yes	No	No	NHEA
Proposed scheme	Yes	Yes	Yes	Yes	Yes	Yes	HEA

MA: Mathematical approach, HEA: Hybrid evolutionary algorithm

Based on the literature presented and Table I, the following main research gaps related to the MG operation problem can be mentioned:

- In most researches, one or two indices, such as operational and economic indices, are generally considered in the problem of energy/power management of distribution networks and MGs. Nonetheless, this does not guarantee that other indices will be improved. For instance, to minimize the cost of power purchase from the upstream network imposed on the MG, high amounts of energy injected by DGs and ESSs are required, although it causes overvoltage in the network.
- Most research also mentions the use of flexibility sources such as ESS along with renewable DGs to enhance system flexibility, but a numerical index for it is rarely available in the literature. Yet, its magnitude is required to evaluate the status

of an index in a system, and this is obtained by mathematical modeling of the problem.

- The MG energy management problem has generally a nonlinear framework for which some studies such as [1-3] adopt the LAM. This case leads to a significant computational error. Some other researches utilize NHEAs or suitable mathematical solutions for nonlinear problems. Nevertheless, such solvers do not provide a unique optimal solution.

To compensate for these research gaps, this paper presents MG's operation subject to reliability and flexibility indices in the presence of DGs and ESSs to provide clean energy. The scheme is based on an optimization problem whose objective function aims to minimize the total expected cost of power purchase by the MG from the upstream network and the expected cost of DGs. Constraints include AC power flow (AC-PF) equations; operation, reliability, flexibility, and environmental constraints of the MG; and formulation of DGs and ESSs operation. This scheme is subject to uncertainties of load, active power generation of renewable DGs, energy cost, and availability of network equipment, DGs, and ESSs. Therefore, the paper incorporates stochastic programming based on a combination of Monte Carlo simulation (MCS) and simultaneous backward method (SBM) to model the mentioned uncertainties. Then, a combination of an artificial bee colony (ABC) and a sine-cosine algorithm (SCA) is used to explore the optimal solution. Since decision variables are updated in two different processes by the algorithm, it is expected to reach approximate conditions of the unique final response. Eventually, the contributions of the proposed scheme are summarized as follows:

- Achieving a mathematical model for evaluating MG's flexibility;
- Simultaneous modeling of operation, reliability, economics, flexibility, and environmental indices of the MG; and
- Achieving the optimal solution with approximate conditions of the unique response by the hybrid ABC-SCA algorithm.

In the following, Section 2 presents the mathematical model of MG power management. Section 3 describes the problem-solving process based on the hybrid ABC-SCA algorithm. Numerical results and conclusions are expressed in Sections 4 and 5, respectively.

II. PROBLEM FORMULATION

In this section, the mathematical operation model of the MG subject to technical and environmental constraints is presented in the presence of DGs and ESSs. This scheme minimizes the total expected operating cost of MGs and DGs. It is also bound by AC-PF equations, operation, reliability, flexibility, and environmental constraints of the MG, and operation models of

DGs and ESSs. Details of this problem are provided below.

A) Objective function: Equation (1) indicates the objective function of the proposed problem, which has two parts. The first part represents the minimization of the expected cost of energy purchase by the MG from the upstream network [16], which is equal to the product of energy price and power received by the MG from the upstream network at any given time. In the second part of Eq. (1), the minimization of the expected cost of fuel or operation of DGs is considered, which follows the parabolic fuel cost-power curve of a DG [16].

min $C =$

$$\sum_{s \in \Omega_s} \pi_s \sum_{h \in \Omega_H} \left(\rho_{h,s} P_{ref,h,s}^{DS} + \sum_{b \in \Omega_B} \left(\kappa_b + \chi_b P_{b,h,s}^{DG} + \nu_b (P_{b,h,s}^{DG})^2 \right) \right) \quad (1)$$

B) *MG model*: The MG model is based on the AC-PF equations as given in (2)-(7) [1-2]. The active and reactive power balance in different MG buses is presented in (2) and (3). Also, active power and reactive power flowing through distribution lines are calculated by (4) and (5), respectively. Finally, (6) and (7) refer to voltage angle and magnitude of the slack bus, respectively. Note that, in this case, the MG is assumed to be connected to the upstream network via a distribution substation located on the slack bus. Therefore, variables P^{DS} and Q^{DS} are not zero only for the slack bus and are zero for other buses.

$$P_{b,h,s}^{DS} + P_{b,h,s}^{DG} + (P_{b,h,s}^{E,D} - P_{b,h,s}^{E,C}) + \sum_{l \in \Omega_B} IM_{b,l} P_{b,l,h,s}^{DL} = P_{b,h,s}^L - P_{b,h,s}^{NS} \quad \forall b, h, s \quad (2)$$

$$Q_{b,h,s}^{DS} + Q_{b,h,s}^{DG} + Q_{b,h,s}^E + \sum_{l \in \Omega_B} IM_{b,l} Q_{b,l,h,s}^{DL} = Q_{b,h,s}^L \quad \forall b, h, s \quad (3)$$

$$P_{b,l,h,s}^{DL} = \begin{cases} G_{b,l}^{DL} (V_{b,h,s})^2 - V_{b,h,s} V_{l,h,s} \\ G_{b,l}^{DL} \cos(\beta_{b,h,s} - \beta_{l,h,s}) + B_{b,l}^{DL} \sin(\beta_{b,h,s} - \beta_{l,h,s}) \end{cases} a_{b,l,s}^{DL} \quad \forall b, l, h, s \quad (4)$$

$$Q_{b,l,h,s}^{DL} = \begin{cases} -B_{b,l}^{DL} (V_{b,h,s})^2 + V_{b,h,s} V_{l,h,s} \\ B_{b,l}^{DL} \cos(\beta_{b,h,s} - \beta_{l,h,s}) - G_{b,l}^{DL} \sin(\beta_{b,h,s} - \beta_{l,h,s}) \end{cases} a_{b,l,s}^{DL} \quad \forall b, l, h, s \quad (5)$$

$$\beta_{ref,h,s} = 0 \quad \forall h, s \quad (6)$$

$$V_{ref,h,s} = V_{ref} \quad \forall h, s \quad (7)$$

C) *Technical and environmental constraints of the MG*: This part presents technical constraints of the network including operation (8)-(11) [5-7], flexibility (12), and reliability (13)-(14) constraints [17]. Operation constraint consists of limits of distribution lines and distribution substations (8) and (9), distribution substation power factor (10), and voltage

magnitudes of buses (11). The MG flexibility limit is expressed in (12). Note that, according to [3], the results of day-ahead and real-time operation of a system with renewable sources differ due to their power generation forecast error. This will cause an imbalance of generation and consumption in that system under real-time operating conditions, which is taken into account as the system's poor flexibility. To overcome this challenge and improve system's flexibility, small time-constant flexibility sources such as battery-type ESSs are used [4]. However, to ensure the desired optimal flexibility of the network, this index needs to be modeled in the proposed scheme. The limitation of changes in the active power received by MG from the upstream network for different scenarios is considered as (12) in this paper. The reason is that the unbalance between day-ahead and real-time operations will be minimal if the changes in active power are very low for different scenarios [3]. Hence, if the flexibility tolerance (ΔF) is zero, flexibility of 100% is accessible for the MG. Besides, reliability limitations of the MG are listed in (13) and (14). The constraint on the interrupted load due to the occurrence of an $N - 1$ event caused by the outage of a distribution line, distribution substation, DG, or ESS is presented in (13) [17]. Moreover, the expected energy not-supplied (EENS) of the MG is formulated in (14) for all of the above possible events [17]. In the end, the environmental constraint of the MG is modeled in (15), which has two parts. The first part refers to total NO_x , CO_2 , and SO_2 emissions caused by the upstream power supply. Furthermore, the pollutants produced by DGs are calculated in the second part of this equation, where coefficient γ is the sum of NO_x , CO_2 , and SO_2 pollution coefficients [18]. Noted that the proposed scheme has no limitation on being implemented on different networks such as an active distribution network or a MG. Another point is that parameter a^{DS} (Eq. (9)) in the proposed scheme refers to the accessibility of the MG connection to the upstream network. If it is 1, it means that the grid-connected mode is considered for the MG, and it is 0, it is operating in the islanded mode. This means the paper assumes that the MG is disconnected from the upstream network during critical conditions such as the occurrence of an $N - 1$ event. The reason is that an MG requires a strong backup source so that it could provide desired stable situation against the changes in the generation of renewable DGs and consumption load and this is accessible through connection to the upstream network. Also, assuming that the MG participates in the energy and ancillary services market, the grid-connected operation mode is needed. Thus, this operation mode is essential for MGs and this paper mainly focuses on this type of operation mode for MGs.

$$\sqrt{(P_{b,l,h,s}^{DL})^2 + (Q_{b,l,h,s}^{DL})^2} \leq S_{b,l}^{DL,m} \quad \forall b, l \quad (8)$$

$$\sqrt{(P_{ref,h,s}^{DS})^2 + (Q_{ref,h,s}^{DS})^2} \leq S_{ref}^{DS,m} a_{ref,s}^{DS} \quad \forall h, s \quad (9)$$

$$\frac{|P_{ref,h,s}^{DS}|}{\sqrt{(P_{ref,h,s}^{DS})^2 + (Q_{ref,h,s}^{DS})^2}} \geq PF^{\min} \quad \forall h, s \quad (10)$$

$$V_b^{\min} \leq V_{b,h,s} \leq V_b^{\max} \quad \forall b, h, s \quad (11)$$

$$|P_{ref,h,s}^{DS} - P_{ref,h,s'}^{DS}| \leq \Delta F \quad \forall h, s \neq s' \quad (12)$$

$$0 \leq P_{b,h,s}^{ND} \leq P_{b,h,s}^L \quad \forall b, h, s \quad (13)$$

$$\sum_{s \in \Xi_s} \pi_s \sum_{h \in \Omega_H} \sum_{b \in \Omega_B} P_{b,h,s}^{NS} \leq EENS^{\max} \quad (14)$$

$$\sum_{s \in \Xi_s} \pi_s \sum_{h \in \Omega_H} \left(\gamma_{ref} |P_{ref,h,s}^{DS}| + \sum_{b \in \Omega_B} \gamma_b P_{b,h,s}^{DG} \right) \leq EM^{\max} \quad (15)$$

D) *DG operation model*: In this part of the paper, the DG capacity constraint or the limit of simultaneous control of active and reactive power of DG is given by (16) [5]. Note that two renewable and non-renewable types of DGs are considered in this paper. In renewable DGs such as wind and PV systems, active power is always equal to the maximum active power generated by these sources in proportion to weather conditions [5]. This is modeled in (17). The active power of these sources is not generally considered to be controllable for minimizing energy cost and pollution, but its reactive power control capability has been used in this study [5]. Hence, these DGs follow two constraints (16) and (17). However, non-renewable DGs can control active and reactive power, so they only comply with constraint (16).

$$\sqrt{(P_{b,h,s}^{DG})^2 + (Q_{b,h,s}^{DG})^2} \leq S_b^{DG,m} a_{b,s}^{DG} \quad \forall b, h, s \quad (16)$$

$$P_{b,h,s}^{DG} = P_{b,h,s}^{DG,m} a_{b,s}^{DG} \quad \forall b \in \Omega_R, h, s \quad (17)$$

E) *ESS operation model*: The ESS operation model is formulated in (18)-(21) [2, 7]. Constraints (18) and (19) consider the ESS discharge and charge rate limits, respectively. Also, in these constraints, a binary variable y is used to observe the asynchronous operation of the ESS charge and discharge modes. Hence, if y is equal to unity (zero), the ESS is in the discharge (charge) mode and injects (receives) active power into (from) the MG. The limit of energy stored in the ESS is given by (20). Finally, the limit of size of the ESS charger in simultaneous control of active and reactive power is presented in (21).

$$0 \leq P_{b,h,s}^{E,D} \leq DR_b y_{b,h} a_{b,s}^E \quad \forall b, h, s \quad (18)$$

$$0 \leq P_{b,h,s}^{E,C} \leq CR_b (1 - y_{b,h}) a_{b,s}^E \quad \forall b, h, s \quad (19)$$

$$E_b^{\min} \leq E_b^{(0)} + \sum_{t=1}^h \left(\eta_b^C P_{b,h,s}^{E,C} - \frac{1}{\eta_b^{E,D}} P_{b,h,s}^{E,D} \right) \leq E_b^{\max} \quad \forall b, h, s \quad (20)$$

$$\sqrt{(P_{b,h,s}^{E,D} - P_{b,h,s}^{E,C})^2 + (Q_{b,h,s}^E)^2} \leq S_b^{E,m} a_{b,s}^E \quad \forall b, h, s \quad (21)$$

F) *Stochastic programming*: In the proposed scheme, parameters such as active and reactive load, P^L and Q^L , energy price, ρ , the maximum active power output of the renewable DG, $P^{DG,m}$, availabilities of the distribution line and distribution substation, DG and ESS, a^{DL} , a^{DS} , a^{DG} and a^E are uncertain. Therefore, in this paper, the stochastic programming method based on a combination of the MCS and the SBM [19] is utilized to model uncertainties of the problem (1)-(21). Following this method, the MCS first generates a large number of scenarios. In each scenario, uncertainties of P^L , Q^L , ρ , and $P^{DG,m}$ are determined according to their mean and standard deviation values [19]. Other uncertainties are also specified based on their forced outage rate (FOR) [17]. Next, for each scenario, the probability value of the first three uncertainty parameters is calculated based on the normal probability distribution function (PDF) [1]. To calculate the probability value of the parameter $P^{DG,m}$, beta/Weibull PDF is employed for PV/wind system [1]. For other uncertainty parameters, Bernoulli PDF is used to determine the probability of these uncertainties in each scenario [17]. The probability of each scenario is equal to the product of the probability of the uncertainty parameters mentioned in this scenario. Eventually, the SBM method used as a scenario reduction technique selects a certain number of scenarios with short distance from each other generated by the MCS. Details of this method are provided in [19].

III. METHODOLOGY

The problem presented in the previous section, (1)-(21), has a mixed integer non-linear programming (MINLP) framework. Therefore, the hybrid ABC [20] and SCA [21] algorithm is incorporated to cover the last research gap and achieve the optimal solution. This algorithm determines the values of decision variables including P^{NS} and P^{DG} for non-renewable DG, Q^{DG} , $P^{E,C}$, $P^{E,D}$, Q^E , and y based on the (22)-(28), respectively. Then, the values of dependent variables such as P^{DG} for renewable DG, P^{DS} , P^{DL} , Q^{DS} , Q^{DL} , V , and β are calculated according to the values of decision variables and constraints (2)-(7) and (17). In this section, the value of the first dependent variable is determined based on (17), then the

values of other dependent variables of AC-PF constraints, (2)-(7), are calculated based on the backward-forward method [22]. To estimate the technical and environmental limitations of MG, (8)-(12) and (14)-(15), DG size limit, (16), energy limit stored in the ESS and its charger capacity, (20)-(21), the penalty function technique is used [23]. This function for a constraint $a \leq b$ is in the form of $\mu \cdot \max(0, a - b)$ which is added to the objective function of the proposed problem, (1). In this equation, $\mu \geq 0$ represents Lagrangian multipliers, the value of which is determined similarly to a decision variable by the ABC-SCA algorithm. Next, the fitness function is equal to the sum of the objective function (1) and all the penalty functions resulting from constraints (8)-(12), (14)-(16), and (20)-(21).

$$P_{b,h,s}^{NS} \in \text{Eq. (13)} \quad \forall b, h, s \quad (22)$$

$$P_{b,h,s}^{DG} \in [0, S_b^{DG,m}] \quad \forall b \in \Omega_B - \Omega_R, h, s \quad (23)$$

$$Q_{b,h,s}^{DG} \in [0, S_b^{DG,m}] \quad \forall b, h, s \quad (24)$$

$$P_{b,h,s}^{E,D} \in \text{Eq. (18)} \quad \forall b, h, s \quad (25)$$

$$P_{b,h,s}^{E,C} \in \text{Eq. (19)} \quad \forall b, h, s \quad (26)$$

$$Q_{b,h,s}^E \in [0, S_b^{E,m}] \quad \forall b, h, s \quad (27)$$

$$y_{b,h} \in \{0,1\} \quad \forall b, h \quad (28)$$

Algorithm 1 ABC-SCA process

Initialization step

A- Generate random values for decision variables and Lagrangian multipliers according to constraints (22)-(28) and $\mu \geq 0$

B- Calculate the values of the dependent variables based on AC-PF constraints (2)-(7) and Eq. (17), where AC-PF equations are solved by the forward-backward power flow method

C- Calculate the fitness function that minimizes the sum of the objective function (1) and all penalty functions for constraints (8)-(12), (14)-(16), and (20)-(21)

Update decision variables and Lagrangian multipliers

for $i = 1: I_{max}$

1- Apply the ABC algorithm to calculate new values of decision variables and Lagrangian multipliers

2- Calculate dependent variables and fitness function according to steps B and C

3- Repeat steps 1 and 2 based on the SCA algorithm

end

Algorithm 1. Process of the ABC-SCA algorithm to solve the proposed formulation

The execution process of this solver is provided in Algorithm (1) and flowchart of Fig. 1. Accordingly, the solver initially generates a random value for decision-making variables and Lagrange multipliers proportional to constraints (22)-(28) and $\mu \geq 0$ for a certain number of populations such as N . Then, the values of dependent variables and the fitness function are calculated for N values of decision variables and Lagrange multipliers. Next, the updating process of the

decision variables and Lagrange multipliers is performed based on the optimal value (minimum value for the proposed scheme based on (1)) of the fit function. In this section, first, the ABC process is executed, then the SCA operation is responsible for the update process. Finally, this operation continues until the convergence point for the proposed scheme is estimated. In this paper, it is assumed that the convergence point is available after a maximum number of iterations I_{max} .

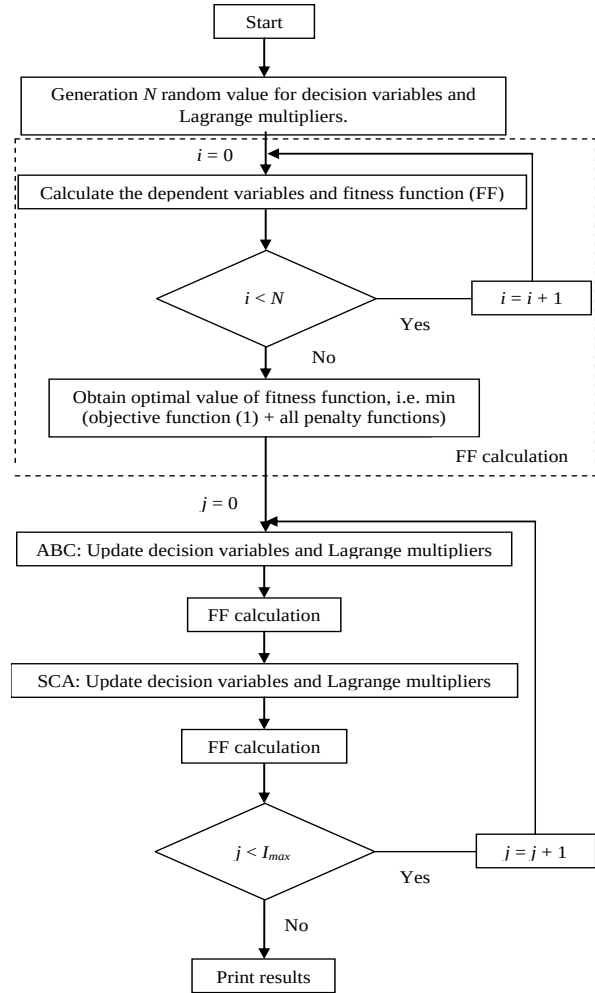


Fig. 1 Flowchart of the methodology for the proposed scheme

IV. NUMERICAL RESULTS

A. Case studies

In this section, the proposed problem is applied to the 69-bus radial MG [24-25]. This network has base power and base voltage of 1 MVA and 12.66 kV, respectively, and minimum power factor of the distribution substation is 0.9. Its permissible voltage range is between 0.9 p.u. and 1.1 p.u. Information of the distribution line and data of the peak load are provided in [24]. The daily load is equal to the product of the peak load and the daily load factor, as given in Fig. 2(a)

[26-27]. Load factor per hour is defined as the ration between the consumption power and the peak load, the value of which is between 0 and 1. Energy prices for three time periods, i.e. off-peak, 1:00-7: 00, middle-peak, 8:00-16:00, and 23:00-00:00, and peak, 17:00-22:00, are 16 \$/MWh, 24 \$/MWh, and 30 \$/MWh, respectively [5]. The network consists of DGs of wind system (WS), photovoltaic (PV), and fuel cell (FC) types with sizes of 0.7 MVA, 0.7 MVA, and 1.2 MVA, respectively. The FCs are placed on buses 21 and 53, WSs are on buses 40 and 51, and PVs are located on buses 32 and 47. The daily active power profile of WS and PV is equal to the product of their size and the daily power rate, as presented in Fig. 2(b) [28, 29]. The coefficients κ , χ , and ν for renewable DGs such as WS and PV are zero, and for FC are equal to \$ 100, 20 \$/MWh, and 0.002 \$/MWh², respectively. Also, the pollution coefficient for WS and PV is zero, is 2323.4523 kg/MWh for FC, and is 927.128 kg/MWh for power supply from the upstream network [18]. The network has battery-type (B) ESSs located on buses 32, 40, 47, and 51. The battery size is 5 MWh and has a charge/discharge efficiency of 0.95. Charge/discharge rate and charger sizes are 1.5 MW and 1.5 MVA, respectively. Minimum energy (initial energy) of 0.5 MWh is set for this ESS. FORs of distribution lines and substations are 1% and 0.1%, respectively, and FORs of DG and ESS are 1%. To achieve favorable flexibility, reliability, and environmental conditions, the terms ΔF , $EENS^{max}$, and EM^{max} are equal to 0.02 p.u., 2 MWh, and 25 tons, respectively. Finally, 1000 scenarios are generated by MCS for the uncertainties presented in Section 2, and then 40 of these scenarios are selected by the SBM.

B. Results

The proposed problem along with the mentioned solver is coded in MATLAB software environment, and the obtained numerical results are analyzed as follows.

A) *Analysis of the mentioned solver capability*: Table II reports the expected operating cost of MGs and DGs based on (1) calculated by ABC-SCA, ABC, SCA solvers, particle swarm optimization (PSO) [23], and Genetic Algorithm (GA) [23]. In this section, the population size (N) and the maximum number of convergence iterations (I_{max}) for the mentioned solvers are set 50 and 2000, respectively, and the rest of their adjustment parameters are selected according to [20-21, 23]. Also, to calculate the standard deviation of the final response of each algorithm, the problem solving is repeated 20 times by each solver. Finally, according to Table II, it is observed that the hybrid ABC-SCA algorithm obtains the lowest value for the operating cost of the proposed scheme, i.e. \$1184.4, compared to other non-hybrid algorithms. This point is obtained at 628 convergence iterations and a computational time of 112.3 s for the ABC-SCA algorithm, while the

optimum point in other algorithms is obtained for convergence iterations greater than 760 and computational time longer than 122 s. Another advantage of the hybrid ABC-SCA algorithm over other non-hybrid algorithms is that it has a low standard deviation. Hence, this solver has the approximate conditions of the final unique response compared to the other mentioned algorithms. Finally, the capability of the ABC-SCA solver presented in this section is a confirmation of the last research gap and the last contribution presented in Section 1.

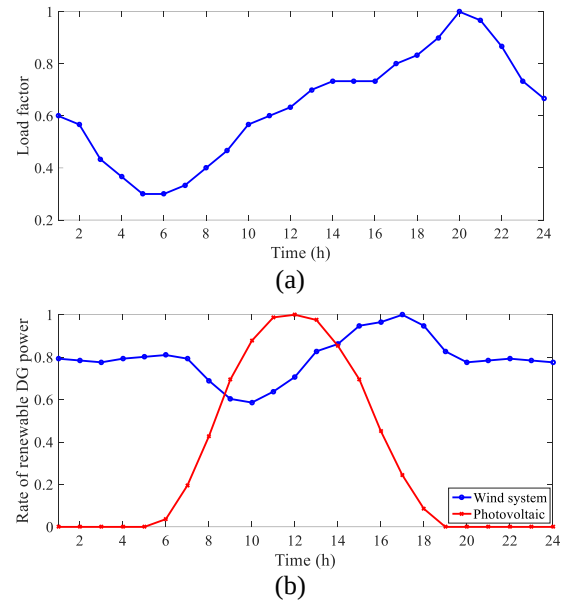


Fig. 2. The daily curve of the, (a) load factor [26-27], (b) rate of renewable DGs power [28, 29]

Table II
EXPECTED OPERATION COST CALCULATED BY
DIFFERENT ALGORITHMS

Solver	Expected operation cost (\$)	Convergence iteration	Calculation time (sec)	Standard deviation (%)
GA	1355.7	1511	154.8	2.95
PSO	1303.5	1346	141.2	2.13
SCA	1262.2	801	127.5	1.87
ABC	1249.1	761	122.4	1.55
ABC-SCA	1184.4	628	112.3	0.97

B) *Evaluation of the operation of sources and storage devices in the MG*: Figs. 3 and 4 show the daily active and reactive power curves of sources and storage devices, respectively. Comparing the results of Fig. 3 and the data of subsection 4.1 and Fig. 2, renewable sources such as WSs and PVs inject active power equal to their maximum capacity into the MG following the weather conditions during all operating hours because these sources have zero pollution coefficients and fuel costs according to subsection 4.1; thus, it is appropriate for these sources to inject high active power into the network to minimize the operating costs of the proposed

scheme and environmental pollution. In the case, FCs inject low active power into the network during off-peak hours 1:00-7:00 as shown in Fig. 3, but they inject active power equal to their maximum capacity into the MG at other operation hours. Note that the fuel price of FCs (coefficient χ) during 1:00-7:00 is higher than the energy price (reported in subsection 4.1); hence, consumers are supplied by the upstream network in accordance with the objective function (1). Nonetheless, since an FC is a source that can control its active power and is located at consumption points, it can improve flexibility, reliability, and the environmental conditions of the MG. Therefore, it is not switched off between 1:00-7:00. From 8:00 to 00:00, the energy price is higher than the FC fuel price. Consequently, to improve the operation, flexibility, reliability, and environmental conditions of the network, they inject high active power into the MG. In the following, according to Fig. 3, the batteries operate in the charge mode during off-peak hours due to low energy prices and receive active power from the network. At other times, they operate in discharge mode due to high energy prices, but a high percentage of their stored energy during 1:00-7:00 is injected into MG during peak hours, 17:00-22:00, to minimize the operating costs of the proposed scheme. Between 8:00-16:00 and 23:00-00:00, the batteries are not switched off and low active power is injected into the MG as shown in Fig. 3. As the battery can control its active power and is located at consumption points, its presence in the network can improve the reliability, environmental, and flexibility indices of the MG.

Based on the results reported in Fig. 4 and the data of Fig. 2, the daily reactive power curve of batteries, WSs, and PVs has the same format of changes as does the daily load profile. As a result, they feed a certain percentage of the MG reactive load every hour. The trend of changes of reactive power curve is as given in Fig. 2(a). Now, consumption reactive power of the network needs to be supplied by local sources distributed within the distribution network so that the voltage profile is improved in accordance with constraint (11) and power factor of the network is enhanced as per constraint (10). As a result, the curve of the mentioned elements will be almost similar to the load factor curve. Note that PVs can inject low reactive power into the network during 11:00-13:00, so that they cannot inject reactive power into the network at 12:00. This is because PVs inject active power close to S^{DG} to the network at these hours according to Fig. 3; hence, according to (16), they cannot inject high reactive power into the MG during these hours. This situation occurs for WSs between 16:00-17:00. Finally, it is observed from Fig. 4 that FCs are only able to inject reactive power into the network between 1:00 and 7:00, and their reactive power is zero at other times. During 1:00-7:00, FCs inject low active power into the network according to Fig. 3; thus, as per (16), they can inject reactive power into the network during these hours. Nevertheless, this is not the case for other hours. Moreover, according to Fig. 3, the amount of

energy demanded by batteries and passive loads of the MG is high during 1:00-7:00. As a result, FCs inject high reactive power into the MG to prevent a large voltage drop in these conditions. Noted that Batteries are connected to the network generally via power electronics converters called chargers. In case a proper topology is used for the converter. i.e. the IGBT bridge, active power of the battery and reactive power of the charger can be controlled simultaneously [30]. Hence, in this case, the charger and battery together can play a role in active and reactive power management of the network. Moreover, active power of batteries, as given in Fig. 3, is between -3 MW and 3 MW (or p.u.) during operation hours, while the charging size of batteries as stated in subsection 4.1 is 6 MVA. Thus, the batteries' chargers can inject high reactive power into the network during the operation horizon. Consequently, based on the network demand and considering the voltage limitation, chargers inject reactive power into the network as illustrated in Fig. 4.

C) *Analysis of the economic and technical indices of the MG:* Fig. 5 presents the changes of the expected operating cost of the MG and DGs in accordance with the changes in the values of $EENS^{max}$, EM^{max} , and ΔF . As per Fig. 5(a), with increasing $EENS^{max}$ for $EM^{max} = 25$ tons and $\Delta F = 0.02$ p.u., the operating cost decreases until it is a fixed value for $EENS^{max} \geq 10$ MWh. Furthermore, according to Fig. 5(b), for $EENS^{max} = 2$ MWh and $\Delta F = 0.02$ p.u., the operating cost decreases up to 37 tons with increasing EM^{max} , but it is a fixed value for $EM^{max} \geq 37$ tons. Based on Fig. 5(c), for $EENS^{max} = 2$ MWh and $EM^{max} = 25$ tons, the operating cost decreases with increasing the flexibility tolerance (ΔF) up to 0.12 p.u. Yet, for $\Delta F \geq 0.12$ p.u., the operating cost is always constant. It is worth noting that increasing the parameters $EENS^{max}$, EM^{max} , and ΔF means less importance of reliability, environmental conditions, and flexibility of the MG compared to the operating cost of the proposed scheme. Thus, under such conditions, sources and batteries will operate in a way that the operating cost is lower than that of a case with minimum values of $EENS^{max}$, EM^{max} , and ΔF .

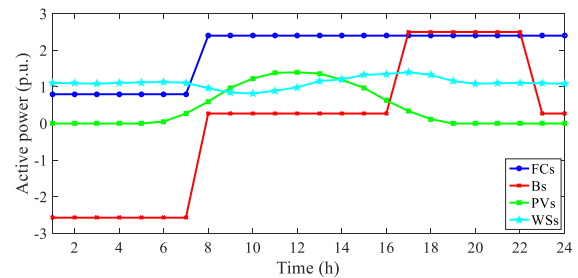


Fig. 3. Daily active power curve of sources and storages

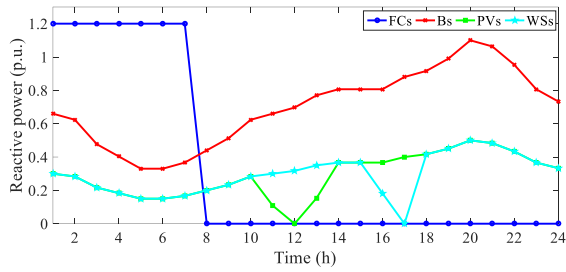
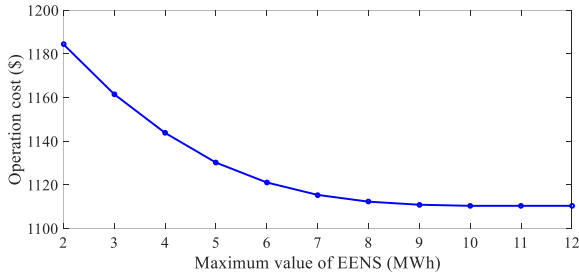
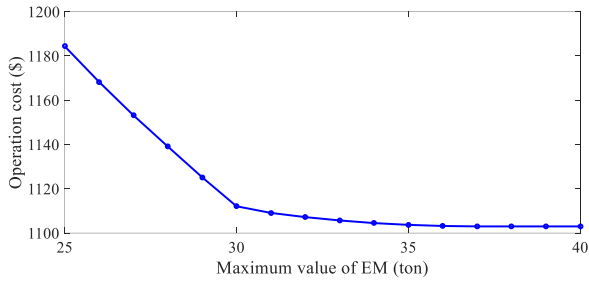


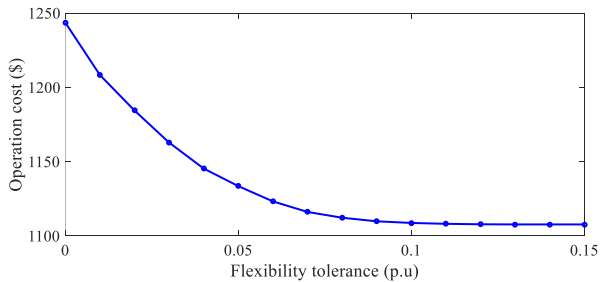
Fig. 4. Daily reactive power curve of sources and storages



(a)



(b)



(c)

Fig. 5. Operating cost curve for (a) $EENS^{max}$ ($EM^{max} = 25$ tons, $\Delta F = 0.02$ p.u.), (b) EM^{max} ($EENS^{max} = 2$ MWh, $\Delta F = 0.02$ p.u.), (c) ΔF ($EM^{max} = 25$ tons, $EENS^{max} = 2$ MWh)

Table III tabulates the values of different technical indices for two case studies: power flow analysis (Case I) and the proposed scheme (Case II). Referring to this table, the pollution level, reliability, operating cost, energy loss, and maximum voltage drop in Case I have higher values than Case II. However, considering the flexibility of 100% for MG ($\Delta F = 0$), the proposed scheme succeeds to reduce the aforementioned parameter values up to 51.2% ((51.1-25)/51.2), 95.9%, 34.2%, 33.7%, and 43.3% compared to Case I, while enhancing the technical and economic status of the network in comparison to Case I. Nonetheless, it should be noted that the

percentage of improvement in operating cost, energy loss, and the maximum voltage drop is higher with increasing ΔF as per Table III but the values of reliability and environmental status of the MG are always constant for various values of ΔF . Additionally, the maximum overvoltage occurring in the MG in Case II, compared to Case I, is between 0.012 p.u. to 0.013 p.u. for different values of ΔF , although its value is always smaller than the permissible value of 0.1 (1.1– 1) p.u. It is noteworthy that, according to Table III, the maximum voltage drop occurs at bus 65 (the weakest bus in the 69-bus networks [24]) at hour 20:00 (the peak load hours based on Fig. 2(a)). Also, it is possible that the maximum over-voltage occurs at hours 17:00 (based on Fig. 3, the maximum active power of sources and batteries is injected to the network at this hour) at bus 2 (close to the reference bus).

Table III:

VALUE OF TECHNICAL INDICES FOR DIFFERENT CASES

Parameter	Case I	Case II		
		$\Delta F = 0$ p.u.	$\Delta F = 0.01$ p.u.	$\Delta F = 0.02$ p.u.
Pollution (left side of Eq. (15)) in ton	51.2	25	25	25
EENS (MWh)	48.6	2	2	2
Operation cost (\$)	1891.3	1243.6	1208.3	1184.4
Energy loss (MWh)	5.19	3.44	3.39	3.35
Maximum voltage drop (p.u.) (occurred in hour (.) and bus (.))	0.092 (20:00 - 65)	0.0522 (20:00 - 65)	0.0527 (20:00 - 65)	0.053 (20:00 - 65)
Maximum over-voltage (p.u.) (occurred in hour (.) and bus (.))	0 (-)	0.0129 (17:00 - 2)	0.0124 (17:00 - 2)	0.012 (17:00 - 2)

V. CONCLUSION

This paper presents the operation of MGs in the presence of DGs and ESSs considering the limitations on reliability, pollution status, and network flexibility. This scheme minimizes the total expected operating cost of MGs and DGs as the objective function. Its constraints also include MG's AC power flow equations; operation, reliability, flexibility, and environmental constraints of the MG; and operation model of sources and storage devices. Stochastic planning was adopted to model the uncertainties of renewable power, energy price, load, and availability of MG equipment, sources, and storage devices. Moreover, the hybrid ABC-SCA algorithm was exploited to solve the proposed problem. Eventually, based on the obtained numerical results, it was observed that the mentioned algorithm obtains a more optimal point than non-hybrid algorithms in a lower number of convergence iterations and shorter computational time. The least standard deviation, that is 0.97%, in the final response is also achieved by the suggested algorithm. Besides, the proposed scheme with

proper management of active and reactive power of sources and storage devices reduces the environmental status, reliability, operating cost, energy loss, and maximum voltage drop in MG by about 51.2%, 95.9%, 34.2%, 33.7%, and 43.3% compared to power flow studies by adopting flexibility of 100%.

It is possible that load change in the MG after islanding, or the transfer power changes in two modes of grid-connected mode and islanded one, or energy prices in these two modes changes, where these limits are considered in the future works.

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