Multi-objective design method for construction of multi-microgrid systems in active distribution networks

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Abstract: One of the important issues in the planning stage of active distribution networks (ADNs) is the optimal design of microgrids (MGs). The design, as a multi-MG system, is comprehensively investigated in this study. In this way, the allocation of energy storage systems (ESSs) and partitioning of ADN are simultaneously performed in order to minimise the cost and maximise the self-adequacy and the reliability considering the uncertainty of load and renewable energy resources. In this study, two approaches are considered. In approach I, the cost, reliability and self-adequacy objectives are taken into account whereas, in approach II, a new probabilistic index representing the ratio of load to storage capacity is also added to mentioned objectives. The proposed multi-objective problem is solved with non-dominated sorting genetic algorithm-II (NSGA-II) as a well-known algorithm based on a probabilistic approach using the Monte-Carlo simulation method (MCSM) and in each approach, several Pareto optimal solutions are evaluated. To simulate and validate the effectiveness of the proposed method, two benchmark distribution networks (the 33-bus and the 119-bus) are used.

Nomenclature

Indices

| Symbol | Description |
|--------|-------------|
| l | index of lines ($l = 1, 2, \ldots, N_{l}$) |
| d | index of DGs ($d = 1, 2, \ldots, N_{DG}$) |
| e | index of ESSs ($e = 1, 2, \ldots, N_{ESS}$) |
| lp | index of load points ($lp = 1, 2, \ldots, N_{lp}$) |
| i, j | index of busses ($i, j = 1, 2, \ldots, N_{b}$) |
| m | index of months ($m = 1, 2, \ldots, N_{m}$) |
| h | index of hours ($h = 1, 2, \ldots, N_{h}$) |
| MCS | index of Monte-carlo scenarios ($MCS = 1, 2, \ldots, N_{MCS}$) |
| r | index of reliability indices ($r = 1, 2, \ldots, N_{index}$) |

Parameters and constants

- $P_{STC}$: active power of PV module at standard conditions
- $S$: solar irradiance
- $S_{STC}$: solar irradiance at standard conditions
- $T_{c}, T_{a}$: cell and ambient temperature, respectively
- $P_{t}$: wind turbine rated active power
- $v$: wind speed
- $v_{ci}, v_{co}$: cut-in and cut-out speeds of the wind turbine, respectively
- $v_{r}$: wind turbine rated speed
- $W_{ESS, min}$, $W_{ESS, max}$: upper and lower bounds on energy stored in ESS, respectively
- $W_{ESS, initial}$: state of charge of the ESS before hour 1
- $V_{max}, V_{min}$: maximum and minimum bus voltage ranges, respectively
- $Y_{ij}$: admittance from bus $i$ to $j$
- $l_{lp}$: annual failure rate of each load point
- $U_{lp}$: annual outage duration of each load point
- $\mu, \sigma$: mean value and standard deviation, respectively
- $k_{MPT}$: maximum power temperature coefficient
- $c$: scale parameter of Weibull distribution function
- $P_{total}$: total active power in ESS
- $P_{loss_{Total_{in, MCS}}}$: power loss total at month $m$ and hour $h$ in scenario MCS
- $W_{ESS_{in, MCS}}$: energy stored in ESS at hour $h$ in scenario MCS
- $P_{ij}$: line power flow from bus $i$ to $j$

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- $\mu, \sigma$: mean value and standard deviation, respectively
- $k_{MPT}$: maximum power temperature coefficient
- $c$: scale parameter of Weibull distribution function
- $P_{charge, max}$, $P_{discharge, max}$: maximum rate of charge and discharge during a period of time $\Delta h$, respectively
- $\eta_{charge}$, $\eta_{discharge}$: charge and discharge efficiencies of battery, respectively
- $P_{loss}$: cost of active power received from the upstream network at month $m$ and hour $h$ in scenario MCS
- $N_{ cust}$: number of customer in each MG/segment
- $N_{ MG}$: number of customers connected to each load point
- $N_{ DG}$: number of active power of PV module
- $P_{total}$: active power of wind turbine permitted rate of charge and discharge of each ESS during a period of time $\Delta h$ in scenario MCS
- $\theta_{ij}$: phase angle of bus $i$ voltage at hour $h$ in scenario MCS
- $\delta_{ij}$: phase angle between bus $i$ and bus $j$
- $P_{DG_{in, MCS}}$, $P_{ESS_{in, MCS}}$, $P_{loss_{Total_{in, MCS}}}$: active power of $\Delta h$ DG at hour $h$ in scenario MCS, respectively
- $P_{loss_{Total_{in, MCS}}}$: power loss total at month $m$ and hour $h$ in scenario MCS
- $W_{ESS_{in, MCS}}$, $W_{ESS_{in, MCS} - 1}$: energy stored in ESS at hour $h$ and $h - 1$, respectively
- $P_{ij}$: line power flow from bus $i$ to $j$
transferred power between MGs at month \( m \) and hour \( h \) in scenario MCS active power received from the upstream network at month \( m \) and hour \( h \) in scenario MCS probability parameter that indicates generation is greater than load in each MG reliability index in each MG reliability index of whole system optimum value for each reliability index cost objective function reliability objective function self-adequacy objective function ratio of load to storage capacity objective function

1 Introduction

1.1 Motivation and aim

Liberalisation of electricity markets, the advancement of small size generators, a decrease of technology costs and the emergence of environmental issues, are among the reasons for the recent deployment of large amounts of distributed generation (DG). Despite having economic benefits, increasing amounts of DG brings serious challenges for the planning and operation of distribution networks. Nowadays, intermittent DGs, represented by photovoltaic (PV) and wind turbine (WT) generators, are developing rapidly [1, 2].

With the integration of DGs, the nature of the conventional distribution networks with unidirectional power flow has changed from passive to active distribution networks (ADNs). Conventional distribution networks are passive since the loads are supplied by the national grid system but in an ADN, loads may be supplied locally by DGs. ADNs should employ network technologies for the integration of distributed energy resources as microgrid (MG) networks. In other words, some parts of the ADN can be considered as multiple interconnected distribution networks, so-called MGs, which can operate in grid-connected or in islanded modes with many DGs. An MG is a small-scale power grid in the low or medium voltage that must be able to connect a group of consumers to a number of DGs and energy storage systems (ESSs) [3, 4].

As mentioned above, a drawback to DGs is the stochastic nature of renewable energy sources (RESs) and supply of demand under different weather conditions. In addition, the variations of these resources may not be consistent with the time distribution of demand. These drawbacks cause drastic reliability concerns in the design and operation of RESS [5]. Generally, it is common to use ESSs in order to decrease the reliability challenges posed by RESs. That is why the issue of optimal ESS allocation is raised. In [6], the impact of ESSs is examined on the reliability of the distribution network.

MGs with high penetration of DGs, play a vital role in the transformation of the existing power grid to the smart grid. However, there are several concerns about the design and operation of MGs to make them beneficial for utilities and customers [7]. Optimal design and operation of MGs are facing challenges due to uncertainties in DGs, load demand and electricity price. By combining a set of MGs to form a multi-MG (MMG) system, these uncertainties can be handled. A typical MMG system is shown in Fig. 1.

In recent years, various researches have been conducted regarding the MMG systems [8]. Reliability has always been an important issue for the design and operation of distribution networks or specifically for the design of MGs [9]. Actually, the main goal for designing MGs is the reliable supply of the load, under varying weather situations, with the maximum reliability and minimum cost. It is clear that to achieve higher reliability, further costs are subsequently required. Thus, considering the importance of both reliability and cost aspects in MG design is inevitable.

Self-adequacy is another important issue in the design of MGs. By minimisation of the generation-load imbalance within MGs, they become more self-sufficient. Hence, in the islanded-mode operation of MGs, more loads can be supplied. Therefore, one of the important factors in the construction of MGs in an ADN is minimising transferred energy between MGs [10].

1.2 Literature review and contributions

The reviewed researches in this subsection are divided into two aspects. First, the siting and sizing of ESSs in ADNs are considered and then, the design and operation of MMG in ADNs are investigated.

1.2.1 Siting and sizing of ESSs in ADNs: Nowadays the penetration of renewable DG is greatly increased in ADNs. However, the intermittent nature of these sources raises the risks of the secure and economical operation of ADN. To solve this problem, ESSs can be placed in the ADN.

From the viewpoint of ESS allocation, in [11], in order to minimise the total net present value, an optimisation model is presented to the optimal allocation of ESSs in the ADN. In [12], aiming at minimising the cost function, the optimal location and capacity of the ESSs and DGs are determined in an ADN. Authors in [13], considering security constraints of the network, propose an approach to the planning of ESSs and DGs simultaneously in ADNs for maximising the distribution company profit. Integration of ESSs in ADN considering minimising power losses, minimising the operational costs and maximising the reliability is presented in [14]. The optimal siting and sizing of ESSs aiming at load minimisation, voltage support and cost of the received power from the upstream network to ADN are addressed in [15]. In [16] with the purpose of allocating ESSs into ADNs, a multi-objective problem is defined in order to find a trade-off between different technical and economic objectives. Optimal sizing and siting of ESSs taking into account technical and economic aspects are presented in [17]. In [18] concerning voltage quality and peak shaving, a multi-objective model for optimal allocation of ESSs is defined in the ADN is presented.

1.2.2 Design and operation of MMG in ADNs: Partitioning an ADN to the MGs may have many benefits for consumers as well as many applications such as functioning as a local control strategy to have minimum interaction between different MGs, reducing power losses and finally, improving the reliability of the system. Among the published researches on MMG aspects, in [7], based on multi-agent system (MAS), a hierarchical energy management system is proposed for optimal operation of MMGs. Authors in [18] applied cooperative game theory to achieve a coordinated operation of MMGs in the ADN. In [19], a MAS coordination approach is developed for the resilient self-healing operation of MMGs. Authors in [20] presented an optimal operation of MMGs taking into account network reliability. An economic dispatch model for an ADN with multiple MGs is presented in [21].
Table 1  Comparison of this paper and the related research in the area of constructing MMG

| Classification                  | Features                  | [3]  | [4]  | [6]  | [9]  | [33] | [34] | [35] | [36] | [37] | [38] | This paper |
|---------------------------------|---------------------------|------|------|------|------|------|------|------|------|------|------|------------|
| considering component modelling | DG                         | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
| objective function for MG construction | ESS             | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | stochastic              | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | operation cost           | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | losses                   | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | efficiency               | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | adequacy                 | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | reliability              | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | voltage controllability  | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
| construction of MG and allocation of ESS | load-storage ratio | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
| optimisation method                | simultaneous            | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | single-objective         | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |
|                                   | multi-objective          | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓          |

In [22], by considering the power exchange between MMGs and the main grid, a distributed approach is proposed to solve the energy management problem of energy internet. Energy management of MMG using leader–follower and coordinated strategies is presented in [23, 24]. A control strategy for coordinated energy management of MMG is proposed in [25]. Another study presented the interactive energy management of MMG [26]. To optimise energy transactions in an MMG system, a MAS-based market framework is proposed in [27]. In this study, the participation of market players is possible through the MAS-based hierarchical structure.

Authors in [28] have proposed an outage management scheme to enhance the resilience of MMG systems against sudden natural hazards. The reliability evaluation of MMGs is discussed in [29]. In [30], the impact of the outage management strategy is shown on the reliability performance of MMG distribution networks.

An energy integrated approach based on mixed-integer linear programming for residential MMG planning is proposed in [31]. Moreover, an MMG system is designed in [32] considering multiple objectives and non-dispatchable RESs. A number of researches are developed on partitioning the distribution power network into MMG [3, 4, 6, 9, 33–38]. A comparison between this paper and the related researches in the area of constructing MMG is presented in Table 1.

1.3 Contributions

Connecting MGs to construct an MMG system enhances the system against disturbances and extreme weather conditions and improves overall network performance while maintaining the flexibility of the operating in isolated mode. Up to now, relatively little attention has been paid to the MMG design based on a multi-objective approach.

In most studies, objectives are combined with each other as a single objective function and conflicts between them are not considered. However, there has been little discussion about the simultaneously optimal allocation of ESSs and MMG design. The purpose of this paper is defining a new probabilistic index to propose two approaches for the construction of an MMG system considering the importance of reliability, self-adequacy and operation cost. All cost including losses and received power from the upstream network costs. For this reason, first, in approach I, in an ADN, that the location of DGs is predetermined, optimum allocation of ESSs and partitioning of the network are simultaneously performed in order to cost minimisation of losses and received power from the upstream network and improvement of reliability and self-adequacy. Second, in approach II, in order to obtain a better network performance, considering the energy storage capacity and uncertain nature of loads, we define a new probabilistic index which is named the load-storage index. In fact, we define this index so as to the ESSs have the most contribution in supply the loads. This index has not been addressed in previous researches. Actually, in approach II, the optimal construction of MGs is performed based on minimisation of operation cost and the impact of load uncertainty, also improvement of reliability and self-adequacy.

Finally, the results of the two approaches are compared. The main contributions of this paper are related to the optimum design of MMG-based ADNs that will benefit utilities, electricity consumers and DG owners. Such contributions can be pointed as follows:

- Simultaneously modelling the uncertainty of RESs, loads and energy prices.
- Proposing a systematic strategy for the design of MMG systems considering reliability, self-adequacy, losses and operation cost in different approaches and comparing the results of these approaches. Considering these objectives together, as a multi-objective function, is one of the main differences between this paper and the other papers such as [3, 4, 6, 9, 33–37].
- Proposing a new probabilistic index for simultaneously optimum allocating ESSs and optimal construction of MGs in ADN. In fact, we propose a new index called the load-storage ratio, by locating the ESSs and sectionising switches to increase the probability of supply of mean load. Defining this index is the main difference between this paper, [6], and the other related papers.
- From problem solving viewpoint, using multi-objective optimisation to determine the location of the ESSs and the MGs boundary and applying the Pareto optimality concept that provides more realistic and reasonable outputs (the analysis of Prato’s solutions has not been performed in any of the references in Table 1).

1.4 Paper organisation

The study is organised as follows: Section 2 explicates the modelling of the system components. Section 3 expresses the design of the MMG system, the ESSs allocation and objective functions. The optimisation problem solution is described in Section 4. Simulation results are presented in Section 5. Finally, the paper conclusion is explained in Section 6.

2  Modelling of ADN components

The proposed design is implemented in the context of an ADN. The DGs in this network are WTs and PV modules and their location is predetermined. In this paper, the stochastic nature of RESs and load demand are modelled based on probability density functions (PDFs). Modelling of these components and ESSs are described in this section.

2.1 PV modules

Power generation of PVS is a function of environmental conditions, solar irradiation and its orientation. The output power of each PV module is described using
\[ P_{pp} = \frac{S}{\text{STC}} \times [1 + k_{\text{MPT}}(T_c - T_s)] \]  
(1)

where \( S \) and \( T_s \) are modelled with the beta PDF in accordance with [2] [4]

\[ f(x) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \times \Gamma(\beta)} \times (x)^{\alpha - 1} \times (1 - x)^{\beta - 1}; \quad x = \{S, T_s\} \]  
(2)

where

\[ \beta = (1 - \mu) \times \left( \frac{\mu(1 + \mu)}{\sigma^2} - 1 \right) \]  
(3)

\[ \alpha = \frac{\mu \times \beta}{(1 - \mu)} \]  
(4)

### 2.2 Wind turbine

The output power of WTs is a function of wind speed and characteristics of the turbine. The Weibull PDF is usually used to model the wind speed as

\[ f_w(v) = \left( \frac{2}{\beta} \right)^v \times \exp \left( -\frac{v^2}{\beta} \right) \]  
(5)

The relation between wind speed and WT power is given by [6] [37]

\[ P_w = \begin{cases} 0 & v \leq \nu_i \\ k_i v + k_i & \nu_i \leq v \leq \nu_f \\ P_c & \nu_f \leq v \leq \nu_{co} \\ 0 & v \geq \nu_{co} \end{cases} \]  
(6)

where

\[ k_i = \frac{P_c}{\nu_f - \nu_i}, \quad k_i = - k_i \times \nu_i \]

### 2.3 Load and energy price

Although there are various PDFs for load modelling, here the intermittent nature of the loads and energy prices, which varies for each hour, is modelled using a normal PDF as [37]. The mean value and standard deviation are obtained from the historical data [35]

\[ f_{\text{sd}}(x) = \frac{1}{2\sqrt{2\pi} \sigma} \exp \left( -\frac{(x - \mu)^2}{2\sigma^2} \right); \quad x = \{P_c, C\} \]  
(7)

### 2.4 ESSs

In the modelling of ESSs, the restrictions which may exist on the charge and discharge rate should be considered. Therefore, in each time interval, (8) should be satisfied [39]. According to (8), the amount of available energy in the ESS at the time \( h \) is obtained by the amount of energy stored in the last hour \( (h-1) \) in addition to the amount of energy which is charged or discharged at time \( h \).

\[ W_{\text{ESS}_h} = W_{\text{ESS}_{h-1}} + \eta_{\text{charge}} P_{\text{charge}} \Delta h - \frac{1}{\eta_{\text{discharge}}} P_{\text{discharge}} \Delta h \]  
(8)

### 3 Proposed MMG design and ESSs allocation in ADN

Partitioning a distribution network helps operators maintaining the network stable with respect to severe conditions. MGs can operate in grid-connected or islanded modes. The generation capacity is required to be adequate for an MG operation in the islanded mode. Therefore, it is necessary to consider the optimum allocation of ESSs and the design of MGs simultaneously. The purpose of this paper is to optimally design an ADN based on cost, reliability, and self-adequacy. For this purpose, two approaches are considered as below:

- **Approach I:** simultaneously allocation of ESSs and design of MGs in order to improve reliability and self-adequacy as well as to minimise annual cost.
- **Approach II:** simultaneously allocation of ESSs and design of MGs in order to improve reliability and self-adequacy as well as to minimise the impact of load uncertainty and annual cost.

In this section, the objective functions and the constraints of each approach are explained in detail.

#### 3.1 Approach I

Clearly, ESSs can give a set of benefits such as minimising power losses, minimising the operational costs and minimising the reliability challenges from RESs. Therefore, a quantitative assessment of the exact amount of the required ESS is essential to achieve a reliable target.

#### 3.1.1 Objective function: One of the important goals in the design of MGs is, supplying the load at the lowest cost and maximum reliability in both grid-connected and islanded modes. Therefore in approach I, the optimum allocation of ESSs and partitioning the ADN are simultaneously performed by taking into account the importance of reliability, self-adequacy as well as the cost of power losses and received power from the upstream network. Hence, in this approach, a multi-objective optimisation problem is used. In this problem, the cost function is formulated as

\[ F_C = \sum_{m=1}^{N_m} \left( \sum_{lp=1}^{N_{\text{lp}}} \frac{1}{N_{\text{MCS}}} \left( P_{\text{Loss}, \text{Total}m,h,\text{MCS}} + P_{\text{UN}m,h,\text{MCS}} \right) \right) \times N_D \]  
(9)

The first term in (9) indicates the total losses and the second term shows the received power from the upstream network to the ADN.

From the reliability viewpoint, MGs are modelled as the segment in a distribution network. Therefore, the whole system is modelled as several segments. During normal conditions, each segment is interconnected to a distribution network while during faults or disturbances it is able to autonomously operate as an island. Since the number of segments, as well as the number of elements inside each segment, affects the reliability indices, therefore, optimal MG design should be determined by solving the optimisation problem.

As, in most references, system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI) and customer average interruption duration index (CAIDI) are the basic reliability indices in distribution networks, we have also used these indices in this paper. For each load point, these indices are defined by

\[ \text{SAIFI} = \frac{\sum_{lp=1}^{N_{\text{lp}}} N_{\text{cbf}} \times I_{\text{lp}}}{\sum_{lp=1}^{N_{\text{lp}}} N_{\text{cbf}}} \]  
(10)

\[ \text{SAIDI} = \frac{\sum_{lp=1}^{N_{\text{lp}}} N_{\text{cbf}} \times U_{\text{lp}}}{\sum_{lp=1}^{N_{\text{lp}}} N_{\text{cbf}}} \]  
(11)

\[ \text{CAIDI} = \frac{\sum_{lp=1}^{N_{\text{lp}}} N_{\text{cbf}} \times U_{\text{lp}}}{\sum_{lp=1}^{N_{\text{lp}}} N_{\text{cbf}}} = \frac{\text{SAIDI}}{\text{SAIFI}} \]  
(12)

For a distribution network without any DG, the reliability indices can be calculated using these equations. For an MMG system with DGs, in case of faults in an MG, it will be disconnected from the rest of the system. If there is enough DG in the downstream MGs to supply the loads for the duration of the interruption, this fault...
will not cause service interruption for the downstream MGs. Therefore, for an MG, the SAIFI, SAIDI, and CAIDI can be calculated as

\[
\text{SAIFI}_{\text{MG}} = \text{SAIFI}_{\text{MG,all}} + (1 - \rho_{\text{MG}}) \times \sum \text{SAIFI}_{\text{MG,upstream}} \\
\text{SAIDI}_{\text{MG}} = \text{SAIDI}_{\text{MG,all}} + (1 - \rho_{\text{MG}}) \times \sum \text{SAIDI}_{\text{MG,upstream}} \\
\text{CAIDI}_{\text{MG}} = \text{CAIDI}_{\text{MG,all}} + (1 - \rho_{\text{MG}}) \times \sum \text{CAIDI}_{\text{MG,upstream}}
\]  

(13)\hspace{1cm}(14)\hspace{1cm}(15)

Here, the subscript ‘self’ indicates the reliability index for the MG without considering other parts of the system and the subscript ‘Upstream’ shows the reliability index for upstream MGs. After calculating the above indices for each MG, the reliability indices for the whole system can be calculated as the weighted summation of the indices as

\[
R_{\text{index}} = \frac{\sum_{\text{MG}} N_{\text{MG}} \times R_{\text{index, MG}}}{\sum_{\text{MG}} N_{\text{MG}}}
\]  

(16)

In order to minimise all the three indices simultaneously, the weighted summation of the indices should be normalised. Therefore, the reliability function is formulated according to (17). Here, \( K_i \) coefficients are set as one

\[
F_R = \sum_{i=1}^{N_{\text{index}}} K_i \left( \frac{R_{\text{index}} - R_{\text{index, opt}}}{R_{\text{index, opt}}} \right)
\]  

(17)

The self-adequacy issue is considered for the MG operation in the islanded mode. Hence, by minimising the transferred power on lines connecting the MGs, more self-sufficient MGs will be created and more loads can be supplied. Here, the self-adequacy function is formulated as

\[
F_s = \sum_{m=1}^{N_{\text{MG}}} \left( \sum_{n=1}^{N_{\text{MG}}} \frac{1}{N_{\text{MG}}} \times \left| P_{\text{trans}, n, h, \text{MG}} \right| \right) \times N_{\text{D}}
\]  

(18)

Equation (19) shows the objective functions of Approach I.

\[
\min \text{ OF}_I = \{ F_C, F_R, F_s \}
\]  

(19)

3.1.2 Constraints: For the design problem, the following constraints are considered:

- Power flow equation:

\[
P_{\text{UN, h, MCS}} = \sum_{i=1}^{N_{\text{MG}}} P_{\text{load}, i, h, \text{MCS}} + \sum_{i=1}^{N_{\text{MG}}} P_{\text{e, h, MCT}} - \sum_{d=1}^{N_{\text{MG}}} P_{\text{DG}, d, h, \text{MCS}} + \sum_{\epsilon=1}^{N_{\text{ES}}} P_{\text{ESS}, \epsilon, h, \text{MCS}}
\]

\[
P_{\text{load}} = \left| V_{\text{h, MCS}} \right| \left| V_{\text{j, h, MCS}} \right| \left| Y_{\text{j}} \cos(\theta_{\text{j}}) - \delta_{\text{h, MCS}} - \delta_{\text{j, h, M}} \right|
\]

\[
P_{\text{Loss, Total}} = \sum_{i=1}^{N_{\text{MG}}} P_{\text{Loss}, i, h, \text{MCS}}
\]

- Voltage limit:

\[
V_{\text{min}} \leq V_{\text{i, h, MCS}} \leq V_{\text{max}}, i \neq 1, V_{\text{i, h, MCS}} = 1 < 0
\]

- Active power ramp rate:

\[
P_{\text{charge, h, MCS}} \leq P_{\text{charge, max}}, P_{\text{discharge, h, MCS}} \leq P_{\text{discharge, max}}
\]

- Stored energy limits:

\[
W_{\text{ESS, min}} \leq W_{\text{ESS}, h, \text{MCS}} \leq W_{\text{ESS, max}}
\]

Based on the life span of the ESSs, the minimum state of charge is considered 0.2 \( \times W_{\text{ESS, max}} \).

- Initial state of charge:

\[
W_{\text{ESS, init}} = W_{\text{ESS, 24}}
\]

(24)

- The necessity of changing the stored energy in ESSs:

\[
\sum_{h \in N_{\text{MG}} \neq 1} \left| W_{\text{ESS}, h} - W_{\text{ESS}, h} \right| > 0
\]

(25)

- The necessity of the existence of both DG and ESS with at least two load points in the constructed MGs [35].

3.2 Approach II

Increasing the share of RESs in a distribution network poses a challenge in terms of increased load variability. In order to consider the issue of the stochastic nature of load and try to supply more load demand, we define a new probabilistic index, namely the load-storage index \( F_{\text{LS, I}} \), which is the ratio of load to storage capacity in each MG. In this work, the number of ESSs, as well as the total rated capacity of the ESSs, installed in the network is supposed constant (for instance, according to [35] we have seven ESS with the total capacity equal to 380 kW for the 33-bus network). The goal is that this number of ESSs with this capacity is shared into the network. In fact, we define this index so as to the ESSs have the most contribution in supply the loads. Therefore, in the islanded mode, more loads can be supplied. By minimising this index, the impact of load uncertainty is reduced and this will be beneficial for both customers and the network operator. Therefore, the aim of approach II is simultaneously optimum allocating ESSs, partitioning the ADN through improving reliability and self-adequacy also, minimising the load-storage index and annual cost of power losses and received power from the upstream network. The load-storage index is formulated as (26). According to this equation, the ratio of total consumption loads to total ESS capacity in all MGs is averaged and then minimised. This index is integrated with the objective functions of approach I as (29)

\[
F_{\text{LS, I}} = \frac{1}{N_{\text{MG}}} \sum_{m=1}^{N_{\text{MG}}} \left( \sum_{n=1}^{N_{\text{MG}}} P_{\text{L, n}} \right)
\]

(26)

where

\[
P_{\text{L, n}} = \sum_{m=1}^{N_{\text{MG}}} \sum_{N_{\text{MG}}}^{1} \left( \sum_{\epsilon=1}^{N_{\text{ES}}} P_{\text{ESS}, \epsilon, h, \text{MCS}} \right)
\]

(27)

\[
P_{\text{ESS, n}} = \sum_{m=1}^{N_{\text{MG}}} \sum_{N_{\text{MG}}}^{1} \left( \sum_{\epsilon=1}^{N_{\text{ES}}} P_{\text{ESS}, \epsilon, h, \text{MCS}} \right)
\]

(28)

\[
\min \text{ OF}_I = \{ F_C, F_R, F_s, F_{\text{LS, I}} \}
\]

(29)

It should be noted that the constraints of this approach are the same as the constraints of approach I.

4 Solution algorithm

Many real-world applications involve simultaneous optimisation of multiple objectives, which may be conflicting with each other. The multi-objective optimisation problem gives a set of optimal solutions, instead of one optimal solution. Optimal solutions for these problems are generally achieved by Pareto optimality. The Pareto optimal method is the best way to obtain a trade-off among the objectives and, according to the preferences of decision makers, gives the capability of making the decision by selecting appropriate solutions. In order to the evaluation of these solutions, the concept of Pareto dominance is used. This concept is defined as follows.

For a multi-objective optimisation problem, a vector \( \mathbf{m} = [m_1, m_2, \ldots, m_l]^T \) is said to dominate a vector \( \mathbf{n} = [n_1, n_2, \ldots, n_l]^T \) (denoted by \( m < n \)), if and only if

\[
m_i \leq n_i, \text{for all } i \in \{1, 2, \ldots, l\}, \text{and there exists at least one } j \in \{1, 2, \ldots, l\} \text{ such that } m_j < n_j.
\]
∀i ∈ {1, . . . , k}, m_i ≤ n_i ∧ ∃i ∈ {1, . . . , k}: m_i < n_i (30)

where k is the dimension of the objective space.

A solution m is said to be Pareto optimal if and only if, there exists no other solution n, such that m is dominated by n. Such solutions are called Pareto set non-dominated solutions. Here the multi-objective optimisation is resolved using non-dominated sorting genetic algorithm-II (NSGA-II). This algorithm was first proposed by Deb et al. [40]. Each of the approaches presented here included multiple objective functions, constraints and decision variables. In this research, the sites and sizes of ESSs and the location of sectionalising switches in the ADN are the decision variables. However, the number and the total rated capacity of ESSs are fixed for each network. Therefore, the decision variables for both scenarios are considered as

\[ V = [ES_1, ES_2, \ldots, ES_n, SW_1, SW_2, \ldots, SW_n] \] (31)

where each ES_i is a vector of binary variables that represents the location and sizes of the i-th ESS. For example, for a 33-bus test system, this vector contains six binary variables with the first four variables being the number of buses in which the ESS is located and the last two variables determining the size of the ESS. Each SW_i is also a binary variable that represents the location of switches. The length of SW_i is equal to the number of network lines.

After proposing the location and size of the ESSs as well as the location of sectionalising switches with the optimisation algorithm, to calculate the objective function, due to considering the probabilistic model for generation and load, the forward/backward (F/B) load flow should be run using an hour by hour Monte-Carlo simulation method (MCSM) over the planning period. This process is repeated for each hour of the day and at each load-generation state. Actually, due to consideration of the probabilistic model for generation and load, it has resulted in excessive growth of possible states for the load flow execution and making the problem to become impractical. Therefore, MCSM is applied to resolve this issue. The flowchart of the proposed method is shown in Fig. 2. The blue blocks are related to the approach II.

5 Simulation results

In order to demonstrate the effectiveness of the proposed approaches, two benchmark cases have been employed: the 33-bus and the 119-bus distribution networks. For simplicity and without loss of generality, an average day in each month is considered as the representative for each month of the year. In fact, we set the planning horizon to be one year. The proposed method is tested via the MATLAB software and all the simulation programs are executed on a desktop PC with an Intel Core i7-6700 3.4-GHz processor and 16 GB of RAM.

5.1 Case 1: 33-bus distribution network

First, the proposed method is tested on the benchmark 33-bus distribution network as a small scale radial distribution network. The nominal voltage of this system is 12.66 kV and its peak load is 3715 kW [41]. It is assumed that the location of DGs is predetermined. The ESSs power can be 20, 40, 60 and 80 kW. The number and total rated capacity of ESSs are equal to 7 and 380 kW, respectively. It is assumed that the charging and discharging time of the ESSs is 8 h [35]. The load and price data are given in [42] and the RESs data can be seen in [43]. Moreover, the reliability data is taken from [44]. The load curves for all months are depicted in Fig. 3. These values are in per unit that we assign them to the 33-bus and the 119-bus distribution networks.

5.1.1 Results of approach I: Simulation results of approach I are depicted in Table 2. As mentioned above, the multi-objective optimisation results led to several Pareto optimal solutions; however, none of the solutions yielded an absolute global optimal solution. In fact, one can choose the desired solution from the viewpoint of each objective function or trade-off between all the
Table 2  Simulation results, case 1: approach I

| Pareto optimal solutions | Objective function OFI | $F_{C}(10^5)$ | $F_{R}$ | $F_{S}$, MWh | $P_{UN}$, MWh | $P_{Loss, Total}$, MWh | Number of constructed MGs |
|--------------------------|-------------------------|---------------|---------|--------------|---------------|------------------------|--------------------------|
| 1                        | 7.23                    | 0.5403        | 99.76   | 0.1092       | 50.69         | 3.48                   | 5                        |
| 2                        | 7.22                    | 0.6713        | 92.77   | 0.1682       | 49.68         | 3.56                   | 4                        |
| 3                        | 6.87                    | 0.6713        | 101.34  | 0.1287       | 48.64         | 3.57                   | 4                        |

The bold values separate the number of buses on which the battery should be installed, from the other buses.

Table 3  Optimum ESSs location, case 1: approach I

| Pareto optimal solutions | Optimal ESSs location (bus) | Optimum ESSs size, kW |
|--------------------------|-----------------------------|-----------------------|
| 1                        | 3, 5, 8, 11, 20, 30, 31     | 40, 60, 80, 40        |
| 2                        | 2, 5, 11, 12, 26, 28, 31    | 40, 60, 80, 20, 60    |
| 3                        | 3, 5, 8, 11, 20, 28, 31     | 20, 60, 80, 60, 60    |

Fig. 4  Profile of energy charge/discharge of ESSs for a typical day for solution 1, case 1: approach I

Fig. 5  Partitioning of ADN for solution 1, case 1: approach I

Table 4  Reliability indices for solution 1, case 1: approach I

| MG No. | SAIFI | SAIDI | CAIDI |
|--------|-------|-------|-------|
| 1      | 0.1331| 3.0531| 22.9386|
| 2      | 0.6579| 15.6395| 23.7706|
| 3      | 0.8797| 20.8245| 23.6723|
| 4      | 0.2825| 6.5774| 23.2348|
| 5      | 0.4570| 10.6875| 23.3883|

objectives. Hence, from the optimal reliability point of view, we have selected three solutions among all of the solutions that are given in Table 2.

The minimum and maximum of $F_{C}$ in Pareto solutions are $5.84 \times 10^9$ and $7.60 \times 10^9$, respectively. For $F_{R}$, this range varies from 0.5403 to 5.7481, respectively and for $F_{S}$ the minimum and maximum values in Pareto solutions are equal to 73.24 and 189.36 MWh, respectively. Based on the priority of the decision maker, one of the solutions can be selected. As an example, from the reliability viewpoint, a middle self-adequacy, solution 1 would be the best choice. Other quantities in this simulation are also listed in Table 2. These quantities are the load-storage index, the annual power received from the upstream network, the annual losses and, the number of constructed MGs for each solution. As can be seen, five MGs are proposed for solution 1, whereas four MGs are obtained for solutions 2 and 3. The optimum locations and rated capacities of ESSs are presented in Table 3.

It is observed that in all the three solutions, several similar buses are proposed as the optimum location of ESSs. These buses are the critical buses, meaning that in the proposed design, the ESSs should be installed on these buses. These buses are shown in bold.

The profiles of energy charge/discharge of the ESSs, for one of the 12 days, for solution 1 are shown in Fig. 4. It can be seen that depending on the environmental conditions such as wind and solar radiation which affect the power output of WT and PV modules, as well as the network load, the ESSs charge or discharge in the network.

In fact, when there is no intensity of solar radiation (in this paper, the intensity of the sun's radiation is taken into account from 7 AM to 19 PM), if the power generation is less than the load consumption, the ESSs are not charged and are discharged if they are charged earlier than in the 20–24 h. Therefore, with the power generation by the PV modules from 7 AM, the power output of the network is increased and the ESSs can be charged. The upward/downward curve shows the charge/discharge of ESSs, respectively. The charging/discharging profiles of the ESSs installed on buses 3 and 11 are the same so their profiles are aligned. The number of buses on which the ESS is installed is shown on the legend.

Reliability indices for solution 1 are given in Table 4. Constructed MGs for this solution is shown in Fig. 5. The network is divided into MG1 to MG5. Fig. 6 shows the monthly losses and exchanged power in this approach. It can be seen that the amount of power received from the upstream network varies from month to month. Actually, at peak load times (June) this power increases. At these times, the batteries are discharged and the rest of the power needed to supply loads is purchased from the upstream network.

5.1.2 Results of approach II: The results of executing approach II are shown in Table 5. From the optimal reliability viewpoint, three solutions are demonstrated in the table.

According to these results and by comparing them with the results of Table 2, it is seen that after adding the new index to the objective functions, with some decrease in self-adequacy, the cost and the reliability values are improved. For instance, by comparing the first solution in both approaches, with a 26.46% decrease in self-adequacy, the cost, the reliability and the load-storage ratio by 12.09, 23.83 and 10.30% can be improved, respectively.

For different objectives, the minimum and maximum values are different. These values for annual cost are $5.79 \times 10^9$ and $8.16 \times 10^9$, respectively. The reliability function is changed from 0.3771 to 5.8631. This range varies from 81.64 to 168.26 MWh for self-adequacy objective and varies from 0.0143 to 0.2247 for load-
storage ratio objective. Depending on the decision maker’s priority each solution in Table 5 can be selected. The comparison of these results shows that solution 2 has better conditions because it has obtained the best trade-off from all objectives viewpoint. Other results of the operation of ADN in this approach are also shown in this table. According to this table, five MGs are proposed for solution 1 and the number of constructed MGs is the same for solutions 2 and 3.

The results of ESSs allocation for all solutions of Table 5 are shown in Table 6. It is necessary to mention that after adding this index, the number and total rated capacity of the storages are constant in different solutions. However, the location and capacity of ESSs are changed in different solutions.

As seen from the second column of this table, buses 3, 5 and 31 are identical in all the ESSs allocation solutions. These buses are critical buses. Fig. 7 shows the changes in energy stored in the ESSs, for solution 2, for a typical day representing the number of days chosen per year.

Reliability indices for the best trade-off solution are given in Table 7. The MGs design for solution 2 is shown in Fig. 8. In this partitioning, the MGs are named as MG1–MG6. Moreover, the monthly losses and exchanged power in approach II are shown in Fig. 9.

5.2 Case 2: 119-bus distribution network

The proposed method is then implemented on a large scale distribution network. This is a 119-bus and 11 kV radial distribution network with a peak load of 22,7097 MW [45]. This network has no DGs, so here the location of DGs is done in a stochastic manner, according to [46]. The total DG capacity is 14.559 MW, which includes 10 WT units and 22 PV units. The ESSs power can be 100, 150, 200 and 250 kW. The reliability data of this network is modelled using [47].

![Fig. 6 Monthly power, case 1: approach I](http://example.com/fig6)

(a) Exchanged power, (b) Losses

| Table 5 | Simulation results, case 1: approach II |
| --- | --- |
| Pareto optimal solutions | Objective function $OF_i$, $P_{UN}$, MWh, $P_{Loss_{,Total}}$, MWh | Number of constructed MGs |
| | $F_C (10^9)$ | $F_R$, MWh | $F_{S, E}$ | |
| 1 | 6.45 | 0.4963 | 126.16 | 0.0990 | 46.82 | 3.62 | 5 |
| 2 | 6.67 | 0.3993 | 134.91 | 0.0957 | 48.59 | 3.56 | 6 |
| 3 | 6.87 | 0.3771 | 144.27 | 0.0296 | 50.35 | 3.64 | 6 |

| Table 6 | Optimum ESSs location, case 1: approach II |
| --- | --- |
| Pareto optimal solutions | Optimal ESSs location (bus) | Optimum ESSs size, kW |
| 1 | 3, 5, 7, 11, 20, 30, 31 | 60, 60, 20, 60, 80, 60, 40 |
| 2 | 3, 5, 12, 20, 28, 30, 31 | 20, 60, 60, 60, 40, 80, 60 |
| 3 | 3, 5, 7, 12, 20, 28, 31 | 20, 60, 60, 60, 80, 40, 60 |

The bold values separate the number of buses on which the battery should be installed, from the other buses.

![Fig. 7 Profile of energy charge/discharge of ESSs for a typical day for solution 2, case 1: approach II](http://example.com/fig7)

| Table 7 | Reliability indices for solution 2, case 1: approach II |
| --- | --- |
| MG No. | SAIFI | SAIDI | CAIDI |
| 1 | 0.1348 | 3.2333 | 22.9859 |
| 2 | 0.5315 | 12.5774 | 23.6631 |
| 3 | 0.5104 | 12.0090 | 23.5289 |
| 4 | 0.9666 | 22.8613 | 23.6515 |
| 5 | 0.3078 | 7.1490 | 23.2257 |
| 6 | 0.4950 | 11.5449 | 23.3254 |

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5.2.1 Results of approach I:

The values of the objective function, the received power from the network, the losses and the number of constructed MGs in the ADN for three Pareto optimal solutions are given in Table 8. It should be noted that the criterion for selecting the solution for case 2 is the same as case 1. Similar to case 1, from the viewpoint of reliability, solution 2 is the best solution. The partitioned ADN and the location of ESSs resulting from solution 2 are shown in Fig. 10.

5.2.2 Results of approach II:

The values of the objective function and other quantities resulting from this approach are given in Table 9. These results show that with some decrease in self-adequacy, cost and reliability values have improved compared to Approach I and this result confirms the results obtained from case 1. For example, by comparing the first solution in both approaches, with a 140 MWh annual decrease in self-adequacy value can improve the cost, the reliability and the load-storage ratio by 3 × 10^11 $, 1.4506 and 0.1065, respectively. Regardless of cost, solution 2 can be chosen as the best trade-off for approach II.

5.3 Comparison between approach I and approach II

The issue of constructing MGs involves multiple objectives. As the objectives increase in number, the decision making becomes more complicated. However, here the fourth goal has improved most of the objectives. By comparing approaches I and II, we can see that in approach II, in spite of the relative reduction of MGs self-adequacy, the cost and the reliability values are improved, and the load uncertainty impact is decreased. This improvement is also reflected in the amount of received power from the upstream network. By using this new index, the need to buy power from the main grid also decreases. This is seen in both cases 1 and 2. That is the reason for the superiority of approach II to approach I. On the other hand in approach II, the boundary of the MGs is smaller. This will improve the control of each MG in the event of disturbances that is more evident in the large scale network. This is another reason for the superiority of this approach. It should be noted that as the number of objectives increases, the computational burden also increases.

6 Conclusion

In this paper, considering the importance of operation cost, reliability, self-adequacy and the impact of load uncertainty aspects for the optimal design of MGs in an ADN, two approaches are proposed based on probabilistic simulation using the MCSM. In approach I, the allocation of ESSs and the ADN partitioning to the construction of MGs are simultaneously performed in order to improve reliability and self-adequacy as well as to minimise the annual cost of losses and received power from the upstream network in which reliability indices are SAIFI, SAIDI and CAIDI.
In approach II, in order to reduce the impact of load uncertainty, a new probabilistic index, namely the load-storage ratio is also added to the objectives in approach I. Multi-objective optimisation is solved by NSGA-II and yielded multiple Pareto optimal solutions in one single simulation run.

In each approach, some of the Pareto optimal solutions are evaluated. According to the results, in each approach, several buses are identical in all the Pareto optimal solutions to install the ESSs. Despite a slight decrease in self-adequacy in approach II, the advantages of this approach can be summarised as follows:

- Reduction of the cost of losses and purchasing power from the upstream network.
- Enhancing reliability.
- Enhancing of the load-storage ratio.

The results show that the addition of the fourth index improves the other objectives relatively. In general, a better decision can be made using Pareto's optimal solutions compared to when we consider all objectives as a weighted summation single objective function.

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