Multi-microgrids approach for design and operation of future distribution networks based on novel technical indices

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HIGHLIGHTS
- Proposing the MMGs-based approach for optimal operation of ADNs.
- Comparing the results with conventional method in different scenarios.
- Considering novel technical indices for quality evaluation of ADNs operation modes.
- Using a powerful multi-objective optimization method known as NSGA-II.
- Modeling the intermittent nature of RESs, loads, and energy prices by considering their PDFs.

ABSTRACT
Clustering the large scale active distribution networks (ADNs) into a set of smaller microgrids (MGs) or multi-microgrids (MMGs)-based operation of ADNs can have several benefits for the utility, electric power consumers, and distributed generation (DG) owners such as easier control strategy, distributed control among MGs, load routing and transfer among MGs and reliability enhancement. This research proposes a novel program for optimal operation of ADNs based on the MMGs approach. Initially, the operation of ADNs was carried out by integrated management of all distributed energy resources (DERs) using probabilistic forward-backward load flow using Monte Carlo simulation (MCS) algorithm. In this stage, energy storage devices (ESDs) as one of the significant components of MG are sized and sited in ADN. In the second stage, the operation quality is scrutinized accurately by testing the possibility of MG construction in the modified ADN based on various technical criteria such as adequacy, efficiency, voltage profile, and reliability. This issue has not been addressed in the previous researches. Finally, the results of the proposed model are compared with conventional operation method in different scenarios by implementation on IEEE 33-bus ADN and an actual Portuguese distribution network using a powerful multi-objective optimization tool known as non-dominated genetic algorithm-II (NSGA-II).

1. Introduction
Distributed generations (DGs) are not taken into consideration in the design of existing distribution systems, hence exploitation of these resources (which their penetration level continually increases) can result in the appearance of unwanted conditions in some parameters such as power quality, reliability, efficiency, safety, among others. As a result, novel efficient management in the operation of the active distribution networks (ADNs) will be required. In the final report of Electric Power Research Institute (EPRI) about technical and economic aspects of microgrid (MG) compared with traditional power system from cost, efficiency, reliability, and ancillary services viewpoints, it has been recommended over the superiority of MG in several aspects [1]. In this manner, using the MG concept for taking the advantages of renewable-based DGs and efficient utilization of ADNs would be a suitable approach which is the scope of this research. A typical MG is presented in Fig. 1. In this model, elastic or responsive loads and energy storage devices (ESDs) play a significant role. In fact, two main advantages are provided in MG for flexible management of load and system operation. The first refers to the passing of the load from its passive state to an active one and increasing its capability to participate in demand side management (DSM) programs. The second advantage is the fast development of ESDs for load and generation balancing [2]. This research takes the effect of ESDs into consideration.

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## Nomenclature

### Acronyms

- **ADN**: active distribution network
- **CHP**: combined heat and power
- **DER**: distributed energy resource
- **DG**: distributed generation
- **DNO**: distribution network operator
- **ESD**: energy storage device
- **EMM**: energy management module
- **GA**: genetic algorithm
- **GSEMS**: global smart energy management system
- **LSEMS**: local smart energy management system
- **NSGA II**: non-dominated sorting GA II
- **MCS**: Monte-Carlo simulation
- **MG**: microgrid
- **MGCC**: microgrid central controller
- **MMG**: multi-microgrid
- **NSGA**: non-dominated genetic algorithm
- **RES**: renewable energy resource
- **PCM**: protection management module
- **PDF**: probability density function
- **PV**: photovoltaic generator
- **SOC**: state of the charge
- **WT**: wind turbine

### Indices and sets

- \( i, j, k \): index and set for total number of time ranges in the simulation
- \( c \): index and set for total number of MCS algorithm execution
- \( i, j, n \): index and set for total number of busses and customers
- \( n, m, N \): index and set for total number of constructed MGs
- \( r, N \): index and set for total number of RESs
- \( e, N \): index and set for total number of ESDs
- \( N \): total number of network lines

### Parameters

- \( E_{ES, min} \): minimum storable energy in ESD
- \( E_{ES, max} \): maximum storable energy in ESD
- \( V_{min} \): minimum bus voltage amplitude
- \( V_{max} \): maximum bus voltage amplitude
- \( Y_{ij} \): line admittance
- \( T_{c} \): PV cell temperature
- \( \lambda \): annual failure rate
- \( Q_{L} \): reactive power of load
- \( E_{ES} \): stored energy in ESD
- \( U \): annual interruption duration
- \( P_{r} \): rated active power of wind turbine
- \( P_{STC} \): active power of PV module at standard test conditions
- \( S_{STC} \): solar irradiance at standard test conditions
- \( P_{Ch/dis, max} \): maximum charge/discharge power rate of ESD
- \( v_{c} \): cut-in speed of wind turbine
- \( v_{t} \): rated speed of wind turbine
- \( c \): scale index
- \( S \): solar irradiance
- \( h_{t} \): time segment (here two hours)
- \( k_{MPT} \): maximum power temperature coefficient

### Variables

- \( B_{DG} \): price of active power received from upstream network
- \( P_{DG} \): active power received from upstream network
- \( Q_{DG} \): reactive power received from upstream network
- \( P_{RES} \): active power of RES
- \( Q_{RES} \): reactive power of RES
- \( P_{loss} \): active power losses
- \( T_{j} \): average value of load demand
- \( \rho_{mg} \): power matching percent of load and generation in MG
- \( P_{pv} \): active power of PV module
- \( T_{a} \): ambient temperature
- \( SAIFI \): system average interruption failure index
- \( CAIDI \): customer average interruption duration index
- \( R_{index, opt} \): optimum predefined amount for reliability index
- \( R_{index,self} \): reliability index for each MG without consideration of upstream MGs
- \( R_{index, upstream} \): reliability index of upstream MGs

## 2. Literature review

Up to now, only a few studies have been proposed about the operation methods of ADNs, and most of the studies have focused on the operation of MGs in which the properties of all distributed energy resources (DERs) (i.e. DGs and ESDs) such as location, type, and capacity are given as input data. For instance, Ref. [3] proposes a stochastic model for optimal MG operation considering uncertainties related to load, generation and market prices based on multi-objective optimization framework. Also, in [4] the model predictive control is developed for reducing the running costs of an experimental MG. Optimal MG scheduling has been done by Jarrollo and Weidlich [5] aiming at the reduction of peak power received from the upstream network. In this work, more focus has been given to hydrogen storage system which is made up of an alkaline electrolyzer, hydrogen cylinder bundles and a fuel cell for energy storage. The subject of energy management in MG has been observed by Kuznetsova et al. [6] where they have developed an integrated framework for agent-based modeling. The given approach demands an increase in system performance in terms of reliability indices. In [7], optimal energy management regimes in a practical MG are determined. Meanwhile, the sensitivity analyses of storage capacity and energy demand are carried out. Optimal planning and operation of aggregated DERs considering their interaction with market prices in presence of aggregators has been proposed in [8]. Morvaj et al. [9] have combined the distribution grid constraints and building energy use with the optimal design and operation of DERs as an optimization framework. Finally, an approach for optimal operation of DERs containing RESs and ESDs for diesel-free remote communities has been presented in [10].

Among the published researches on operation methods of ADNs, Ref. [11] has proceeded to the operation of future distribution networks under MMGs concept and has considered the economic management of this MGs with probabilistic modeling of load and generation by probability density functions (PDFs). The subject of ESDs and their mode of operation have not been treated in this research. In [12], the authors have carried out similar research considering environmental costs and comparing certain heuristic methods of simulation. In [13], the coordinated energy management in subsidiary MGs connected to the main ADN has been followed with the calculation of generation cost (particularly...
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