Optimal construction of microgrids in a radial distribution system considering system reliability via proposing dominated group search optimization algorithm

Daryani, Narges; Zare, Kazem; Tohidi, Sajjad ; Guerrero, Josep M.; Bazmohammadi, Najmeh

Published in:
Sustainable Energy Technologies and Assessments

DOI (link to publication from Publisher):
10.1016/j.seta.2024.103622

Publication date:
2024

Citation for published version (APA):
Daryani, N., Zare, K., Tohidi, S., Guerrero, J. M., & Bazmohammadi, N. (2024). Optimal construction of microgrids in a radial distribution system considering system reliability via proposing dominated group search optimization algorithm. *Sustainable Energy Technologies and Assessments*, *63*, 103622. Article 103622. https://doi.org/10.1016/j.seta.2024.103622

Optimal Construction of Microgrids in a Radial Distribution System Considering System Reliability via Proposing Dominated Group Search Optimization Algorithm

Narges Daryani[1], Kazem Zare[2], Sajjad Tohidi[3], Josep M. Guerrero[4], Najmeh Bazmohammadi[5]

[1, 2, 3] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran.
[4, 5] Center for Research on Microgrids (CROM), AAU Energy, Aalborg University, Aalborg, Denmark.
Corresponding author[1]: Kazem Zare (kazem.zare@tabrizu.ac.ir)

Abstract: In contemporary electrical networks, reliability stands as a paramount attribute. Since the introduction of distributed generation (DG) and microgrid (MG) concepts has considerably changed the structure of distribution networks, it is necessary to consider reliability aspects while going toward modern smart grids. This study introduces a novel methodology focusing on the partitioning of radial distribution systems into distinct MGs, strategically aimed at minimizing energy not supplied (ENS) to fortify overall system reliability. Two types of faults are considered including DG and busbar failures, and the impact of each kind of fault is investigated. Besides, a new Markov model is proposed to evaluate the reliability of DGs and MGs. Given the stochastic nature of the majority of DGs, the incorporation of energy storage systems (ESSs) can significantly enhance system performance. Therefore, this paper dedicates attention to exploring optimal ESS placement. To address the complex challenge of optimizing system partitioning, a modified version of the group search optimization (GSO) algorithm, named dominated GSO (DGSO) is proposed. The PG&E 69-bus distribution system is studied with two different structures to accurately investigate the effectiveness of the proposed partitioning approach on the system reliability. Moreover, the optimal number of MGs to be constructed within the intended system is determined.

Keywords System Partitioning; Reliability; Microgrid; Distributed Generation; Energy Storage System; Dominated Group Search Optimization Algorithm.

Nomenclature

AGSO	Adaptive Group Search Optimization Algorithm
a	Number of Boundary Lines
BG	Biomass Generator
BL	Boundary Line
b	Number of Installed Energy Storage Systems
DER	Distributed Energy Resources
DG	Distributed Generation
DGSO	Dominated Group Search Optimization Algorithm
ENS	Energy Not Supplied
$\mathbf{ENS_{DG}}$	ENS Caused by DG Failures within a MG
$\mathbf{ENS_{MG}}$	ENS Caused by Busbar Failures within a MG
$\mathbf{ENS'_{MG}}$	ENS Caused by Busbar Failures in Upstream MG
ESS	Energy Storage System
$\mathbf{ES_{Place}}$	Place for Installing Energy Storage System
GA	Genetic Algorithm
GSO	Group Search Optimization Algorithm
LC	Load Curtailment
M	Number of busbars in upstream MG.
MG	Microgrid
N	Number of States Generated for a Stochastic Parameter to Estimate its Value
$\mathbf{num_{DG}}$	Number of DGs in the Distribution System
$\mathbf{num_{Bus}}$	Number of Busbars in the Distribution System
$\mathbf{num_{MG}}$	Number of MGs in the Distribution System
$\mathbf{num_{Up\text{-}MG}}$	Number of Upstream MGs
$\mathbf{P_{DG}}$	Active Power Generated by DG Unit
PDF	Probability Distribution Function
PSO	Particle Swarm Optimization
PV	Photo Voltaic
RES	Renewable Energy Resources
r	Repair Time
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Failure Index
WT	Wind Turbine
$\mathbf{X_P}$	Position of the Producer
$\mathbf{X_{P,R}}$	Position of the Producer of Rangers
$\mathbf{X_S}$	Position of the Scrounger
l	Failure Rate
m	Repair Rate
ρ	Probability of Each Generated State for Stochastic Parameters

1. Introduction

During the last two decades, distribution systems has been undergoing considerable changes due to the vast integration of DERs. Development of DG technologies facilitates the local supply of system consumers [1, 2]. Accordingly, distribution systems can be divided into smaller zones where each zone might rely either on its local production or on power exchange with surrounding zones, which gives rise to the concept of MGs. A MG is known as a cluster of loads, DERs, and ESSs with two operating modes, namely grid-connected and islanded modes [3, 4]. MGs can bring many advantages to distribution systems, but dividing a large distribution system into several smaller MGs increases the complexity of the system operation [5]. System partitioning includes determination of boundaries between MGs and allocation of DERs to each MG, which are essential requirements for power system planning. The optimal allocation of DG units within a distribution system has been comprehensively studied to improve various aspects of the system such as minimizing system losses, improving voltage stability, and reducing environmental pollution [6-10].

If MGs in a distribution system are optimally designed and the boundaries between them are accurately determined, superior performance and control of the smart grid will be obtained. The concept of self-adequacy is introduced in optimal MG construction studies, since increasing the internal supply capacity will result in improving the independent performance of the MG. Hence, minimizing the amount of power flows between MGs is considered as the objective of the planning optimization problem [11-14]. Although the MGs with high supply adequacy operate appropriately in the electricity markets, their power quality, reliability and stability may not be satisfactory. Moreover, the optimal number of MGs is not taken into account in the existing studies. In addition to the supply adequacy concept, the consumer-side properties are also taken into account in optimal MG construction studies. Noteworthy, improving the consumer-side properties leads to more customer satisfaction which is of high importance in the modern competitive electricity markets. To this end, increasing the load factor and decreasing the load variance of constructed MGs are considered the goals of the optimal system partitioning problem in [15]. Despite the acceptable power quality which is obtained by improving the consumer-side properties, investigating the effect of the probable faults on the system operation is also of high importance. The reliable performance of the system under fault conditions, as well as the system's ability to recover from the faults and return to the stable operation, are impressive aspects that are not considered in the above-mentioned studies. Moreover, the number of MGs to be constructed is not optimized.

Reliability is known as a significant index for evaluating the electrical networks whereas various indices have been proposed to assess the system reliability [16, 17]. The optimal design of MGs in a distribution system improves the system reliability which is rarely taken into account in the literature. In [18], SAIFI and SAIDI as widely-used indices for measuring the system’s reliability, are minimized while the optimal places for connect/disconnect switches between MGs are determined. Such objective functions are optimized in [19] by considering optimal placement of DGs, ESSs, and reactive resources in a multi-MG system. However, optimizing both DG allocation and MG construction as well as determining the optimum number of MGs are essential in reliability evaluation of smart grids. Investigating more reliability indices leads to more comprehensive studies. When it comes to smart grids, the conventional formulations for reliability indices should be revised to be applicable in MGs context. Simultaneous operation of several MGs and interactions between them besides the impacts of working in grid-connected or islanded modes should be considered. Failure occurrence in a MG can affect the normal and reliable operation of other zones which is rarely taken into account in previous investigations. DGs, as the local electricity resources, play an important role in enhancing the independency of modern distribution systems. Therefore, considering the effect of DGs interruptions on the system reliability is an important issue that is missed in the existing studies. Accordingly, appropriate models are required to account for failures in the MGs and DGs in distribution systems reliability analysis.

In this paper, optimal MG construction is studied to improve system reliability. To this end, the total amount of ENS is minimized by the optimal placement of interconnection switches between MGs. ENS is the amount of energy that is not delivered to the customers when a failure happens in the system [20]. It is worthy to evaluate system ENS as a measure that indicates the ability of a system in supplying loads during fault conditions. Two types of failures are considered in this paper: DG failures and busbar failures. The impact of each failure on the whole system is investigated and the total ENS is calculated. The optimal ESS placement is also carried out which results in improved utilization of DG capacities and enhanced system performance. Further, a new Markov model is used to assess the reliability of installed stochastic DG units. As the reliable performance of the upstream MG(s) would considerably influence the downstream zones, it is important to assign suitable reliability indices for upstream MGs. To this end, a new Markov model is proposed to assess the reliability of upstream zones and evaluate the whole distribution system reliability. Since the interactions between MGs extremely affect the system reliability, the optimum number of MGs to be constructed in the distribution system is also determined in this paper. Noteworthy, the impacts of probable external failures (such as storms) on the system reliability are not taken into account in this paper.

Due to the existence of redundant connections in power systems and complexity of the required calculations, heuristic optimization algorithms are proposed to find the solution [21, 22]. GSO is a robust heuristic algorithm that operates based on animals group living manner, especially group searching behavior [23]. Various improved versions of GSO algorithm have been proposed and implemented in power system studies representing appropriate performance in finding solutions

[24-27]. A novel improved version of GSO algorithm named as DGSO algorithm is used in this paper. Comprehensive search, appropriate convergence speed, and reaching satisfactory solutions are the main properties of the applied DGSO approach [15]. According to the obtained results for optimal placement of switches and ESSs, DGSO algorithm represents reasonable performance.

The rest of this paper is organized as follows; In Section 2, the problem formulation is presented and, the proposed DGSO algorithm is described comprehensively in Section 3. The implementation procedure of optimization method is provided in Section 4. Simulation results are reported in Section 5 alongside the analysis and evaluations. Ultimately, conclusions are presented in Section 6.

2. Problem Formulation and Reliability Evaluation

Two types of failures are considered in a MG, namely DG and busbar failures. From a MG's point of view, each fault can cause ENS within the damaged MG or other neighboring zones. Therefore, a new Markov model is proposed in this paper in order to appropriately model each system component and facilitate the reliability evaluations. This section is dedicated to explain the proposed Markov models, reliability evaluations, and ENS formulations.

2.1. ENS Caused by DG Failures

The generated power of DG units can be stochastic or constant. The injected power by DGs is consumed by the local loads and the surplus power is absorbed by the installed ESSs to be released during peak load times. When a DG unit fails, it is disconnected from the rest of the system to prevent fault propagation. Therefore, the amount of ENS caused by a failure in a DG unit is equal to its generated energy. Considering the stochastic generation, the ENS value due to DG failures in a distribution system is calculated as [29]:

$$ENS_{DG} = \sum_{i=1}^{num_{DG}} ENS_{DG_i} = \sum_{i=1}^{num_{DG}} \lambda_{DG_i} * r_{DG_i} * (\sum_{n=1}^{N} \rho_n * P_{DG_{i,n}}) \quad (1)$$

It is noteworthy that the probabilistic studies should be carried out to calculate the generated power of DGs with stochastic nature. These investigations involve the assignment of an appropriate PDF to each stochastic parameter. The selected PDF, in conjunction with available historical data, facilitates the derivation of several estimated values and their associated probabilities for future occurrences. Furthermore, the determination of failure rates and repair times of DG units is essential. To achieve this, a Markov model, as introduced in prior works [28, 29], is employed, where it is assumed that each DG unit consists of several components operating in series. Thus, any failure within a component results in the overall failure of the DG unit. Considering the normal/failure states for DG components and determining their failure rates and repair times, a Markov model is formulated, encompassing diverse probable states. Subsequently, the failure rate and repair time corresponding to each DG unit are obtained. The requisite formulations are expounded in the appendix.

2.2. ENS Caused by Busbar Failure in a MG

According to the structure of radial distribution networks, failure in a busbar leads to disconnection of all downstream parts from the grid. When it comes to smart grid studies, if a busbar in a MG fails, all the downstream parts will be separated from each other and the MG goes to islanded mode. Such MG is divided into two parts. The upstream parts of the failed busbar remain connected to the rest of the grid whereas the DG units installed in the downstream part are disconnected from the network to prevent any damage. Accordingly, the loads in the downstream part of the islanded MG experience a lack of power supply. The ENS caused by busbar failures within a MG is calculated as:

$$ENS_{MG} = \sum_{j=1}^{num_{MG}} ENS_{MG_j} = \sum_{j=1}^{num_{MG}} \sum_{i=1}^{num_{bus,j}} \lambda_i * r_i * LC_{i,j} \tag{2}$$

Besides, $LC_{i,j}$ represents the amount of load curtailment in the j^{th} MG due to the outage of the i^{th} busbar. Moreover, $num_{bus,j}$ is the number of busbars located in the j^{th} MG.

2.3. ENS Caused by Busbar Failure in Upstream MGs

When a busbar fails, all the downstream MGs are separated from each other and start operating in islanded mode. Thus, the DG units installed in downstream MGs should supply the consumers. Hence, if the involved DGs are capable of supplying the total loads, there will be no ENS in such zones. Otherwise, the load curtailment will be inevitable. The amount of ENS is equal to the energy demand which cannot be supplied by the installed DGs. Therefore, ENS in a MG caused by the busbar failures in upstream zones is equal to:

$$ENS'_{MG} = \sum_{j=1}^{num_{MG}} ENS'_{MG_j} = \sum_{j=1}^{num_{MG}} \left(1-\eta_j\right) \sum_{i=1}^{num_{UP-MG,j}} \lambda_i * r_i * LC_j \tag{3}$$

where η_j is a probability index to show the ability of the j^{th} MG to supply the total installed loads. It is noteworthy that η_j is derived by dividing the count of states where the power generated by DGs in MG_j surpasses the load demand, by the total number of states during a year. λ_i and r_i denote the failure rate and repair time attributed to busbar failures in the i^{th} upstream MG, respectively. The calculations for λ_i and r_i, are facilitated by an efficient Markov model proposed in this paper. When it comes to reliability evaluations of a downstream MG, the structure of distribution system and the placement of MGs should be considered. This paper explores two distinct structural possibilities: single branch and multi-branch radial distribution systems. The requisite formulations are provided in the appendix. It is worth mentioning that for the inclusion of line failures in the reliability analysis, a parallel procedure to that of busbar failure can be followed. However, in the sake of brevity of the paper, it is not further discussed in this study.

2.4. ENS Calculation and Objective Function Formulation

As previously stated, the failure of a DG unit within a MG results in its disconnection from the entire grid, allowing the remaining components of the system to proceed with normal operations. Hence, DG failure is regarded as an internal failure. On the other hand, a busbar failure leads to its disconnection from the upstream grid. This implies that each MG suffers from its internal busbar failures and also from the faults occurring in upstream busbars. Accordingly, the total system ENS is calculated as follows.

$$\begin{cases} Internal\ ENS = \sum_{i=1}^{num_{DG}} ENS_{DG_i} + \sum_{j=1}^{num_{MG}} ENS_{MG_j} \\ External\ ENS = \sum_{i=1}^{num_{MG}} ENS'_{MG_i} \\ Objective\ Function = Total\ ENS = Internal\ ENS + External\ ENS \end{cases} \tag{4}$$

3. Optimization Algorithm

Since recent decades, heuristic optimization algorithms are developed in all kinds of forms [30, 31]. Heuristic algorithms operate based on searching strategies. The more efficiency of the searching method, the more authority of reaching global optima. Hence, various heuristic optimization algorithms are proposed, improved, and used for optimization problems [32, 33].

This study employs a modified version of GSO algorithm, designated as DGSO algorithm. The GSO algorithm, recognized for its robustness, has shown commendable performance in addressing non-linear, non-convex, and complex problems of power systems. Operating within the GSO framework, members are categorized into three groups: a producer, scroungers, and rangers. At each iteration, the GSO member with the best fitness value is selected as the producer, utilizing its vision ability to explore neighboring points for potential better solutions. Scroungers are directed towards the producer, because it is more probable to find better solutions in the producer vicinity. Rangers, on the other hand, undertake random walks across the search space to ensure a comprehensive search.

AGSO algorithm, a recent proposed version of GSO [25], elects the ranger member with the best position as the "Producer of Rangers" and equipped it with vision ability as well as the main "Producer". Hence, the probability of finding better opportunities is increased. According to the conventional AGSO algorithm, the decision for each scrounger to follow a specific producer is random, potentially leading to missed opportunities within the closer producer's vicinity. Addressing this issue, DGSO algorithm is proposed which is equipped with smart scroungers. The scroungers of DGSO can decide whether to follow the producer or the producer of rangers according to their distances. Therefore, the distance of each scrounger from available producers is calculated. If the mentioned scrounger is closer to the main producer, it should follow the same producer. Otherwise, it should walk through the producer of rangers. To find the nearest producer and joining it, a scrounger should move as follows [15]:

$$\begin{cases} X_{S,i}^{k+1} = X_{S,i}^{k} + r \circ \left(\left| X_P^k - X_{S,i}^k \right| \right) & \left| X_P^k - X_{S,i}^k \right| < \left| X_{P_R}^k - X_{S,i}^k \right| \\ X_{S,i}^{k+1} = X_{S,i}^{k} + r \circ \left(\left| X_{P_R}^k - X_{S,i}^k \right| \right) & \left| X_{P_R}^k - X_{S,i}^k \right| < \left| X_P^k - X_{S,i}^k \right| \end{cases} \tag{5}$$

where k is representative for the iteration number.

4. Implementation of the Proposed Method

In this section, the implementation procedure of the proposed methods and mathematical formulations for the reliability evaluations are elaborated. According to the proposed DGSO method, each member of the optimization algorithm is a vector of decision variables including the potential boundary lines between the MGs and places for installing ESSs. The group members of DGSO algorithm can be formed as $[BL_1, BL_2, \dots, BL_a, ES_{place,1}, ES_{place,2}, \dots, ES_{place,b}]$. Moreover, the number of scroungers, rangers, and iterations are set to 25, 25, and 100, respectively. The implementation process of the proposed method for the system partitioning is depicted in the flowchart shown in Fig.1.

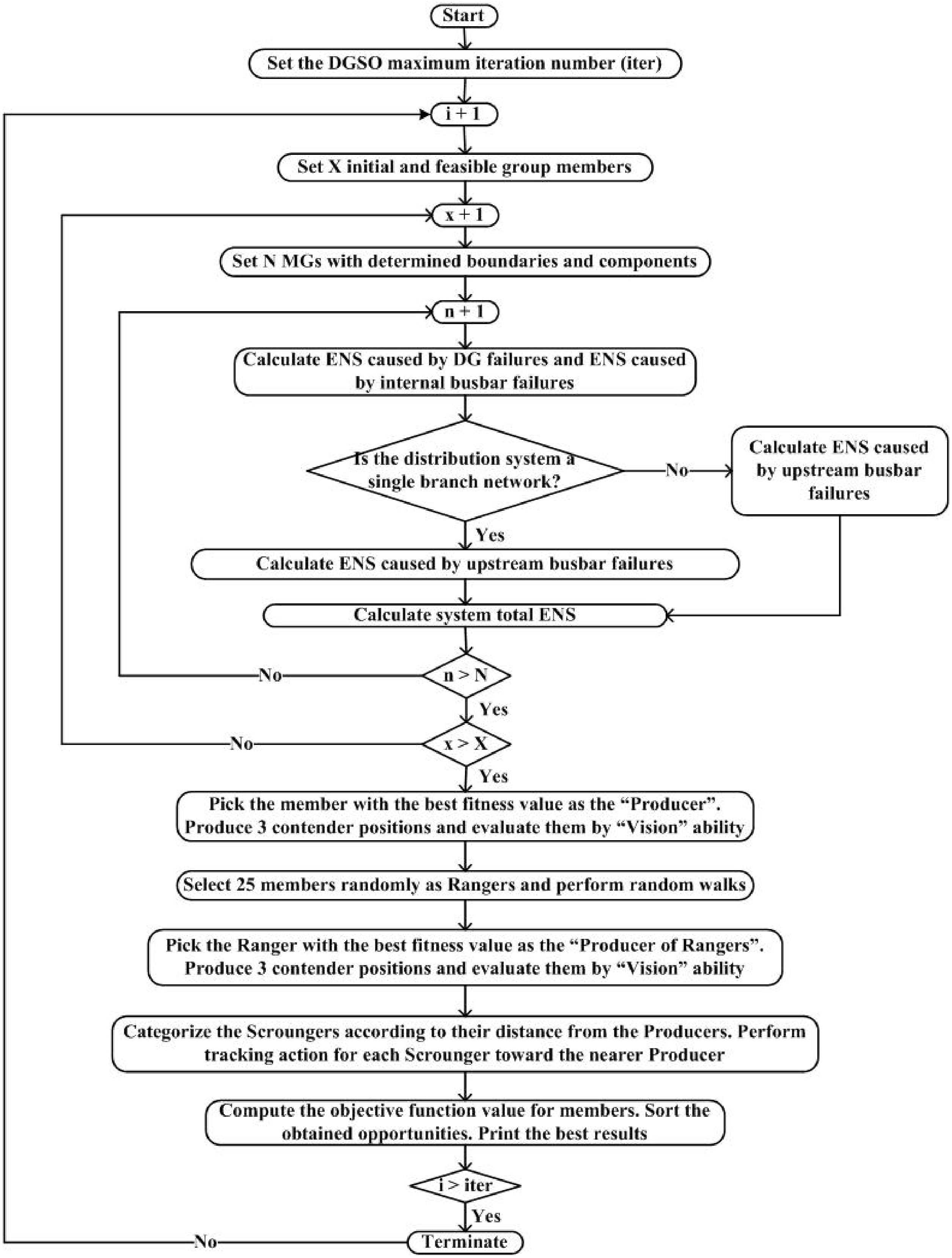


Fig.1. Proposed method for system partitioning.

5. Simulation Results and Numerical Analysis

This section presents the simulation results and assesses the effect of implementing the proposed partitioning method on system reliability. Initially, the analysis assumes a distribution system comprising a single branch, followed by the consideration of a distribution network with multiple branches. The PG&E 69-bus distribution system is selected as the test system. The required data including the system structure, connected loads, and impedances of lines are provided in [34]. The siting and sizing of installed DGs are illustrated in the appendix as Table.B.1. WTs and PV modules are the stochastic DGs whereas BGs are the constant ones. The calculations of generated power by the DGs and consumed power by the loads are sourced from [12]. Besides, the relevant reliability information including failure rate and repair time of system busbars and installed DGs are available in [28, 35]. On the other hand, the mentioned test system is considered with a different structure where all busbars are linearly arranged within a single branch. Notably, the analysis of the single branch structure is pursued to ensure a more precise evaluation. It is assumed that the clustered zones must encompass a minimum of three busbars and a single DG unit to qualify as a MG. Within each MG, the installed DGs/ESSs are mandated to supply a minimum of 20% of the internal load demand during the normal operational conditions, ensuring an acceptable level of supply adequacy within the partitioned zones. The ESS configuration comprises two batteries, each with the maximum power limit of 200 kW.

Furthermore, an Indian high order radial distribution system with 85 busbars is taken into account in the third case to more distinctly illustrate the impact of optimal MG partitioning on the system reliability. The required data including the connections between busbars, involved loads, etc. is available in [36]. The rated values of operating DGs and the installing places of DERs are also represented in [37].

5.1. Case.1

In this case, a single branch form of the considered radial distribution system is studied. The obtained results including the virtual cut set lines between MGs, optimal places for ESSs in addition to calculated values for ENS are reported in Table.1. Moreover, the calculated amounts of ENS caused by internal and upstream failures are depicted in Fig.B.1, and Fig.B.2, respectively. Consequently, Fig.2 represents the obtained values for the system total ENS.

Table.1: Optimization results corresponding to Case.1

MG Num	Boundary Lines	ESS Places	ENS - Internal Failures (MWh/year)	ENS - External Failures (MWh/year)	Total ENS (MWh/year)
2	52	10, 47	128.8064	10.5476	139.354
3	**18, 52**	**34, 54**	**88.577**	**47.7746**	**136.3516**
4	8, 30, 52	54, 60	61.5159	74.9305	136.4464
5	8, 23, 38, 52	14, 17	49.6902	87.3342	137.0244
6	8, 17, 30, 41, 52	22, 27	44.8056	93.5519	138.3575
7	7, 17, 21, 37, 52, 57	56, 61	44.4347	94.0934	138.5281
8	8, 17, 21, 34, 42, 51, 57	40, 50	39.4643	100.2912	139.7555

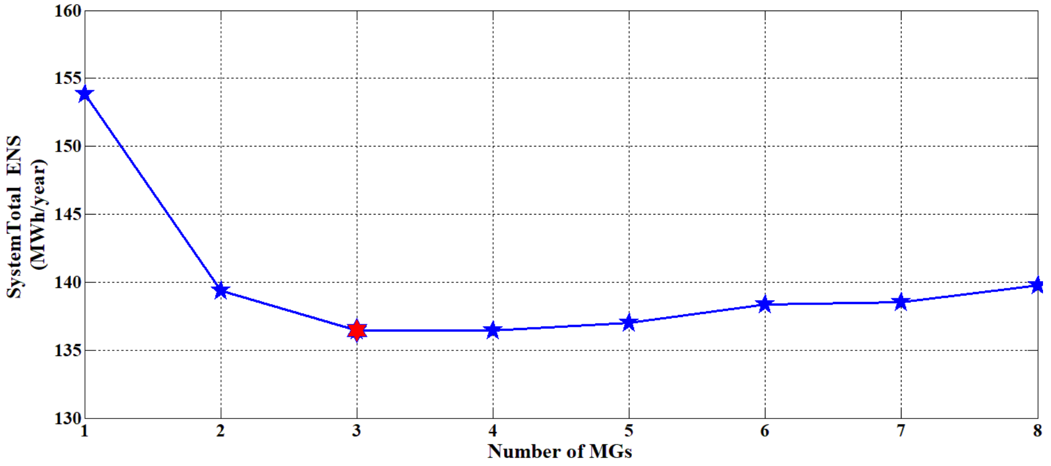
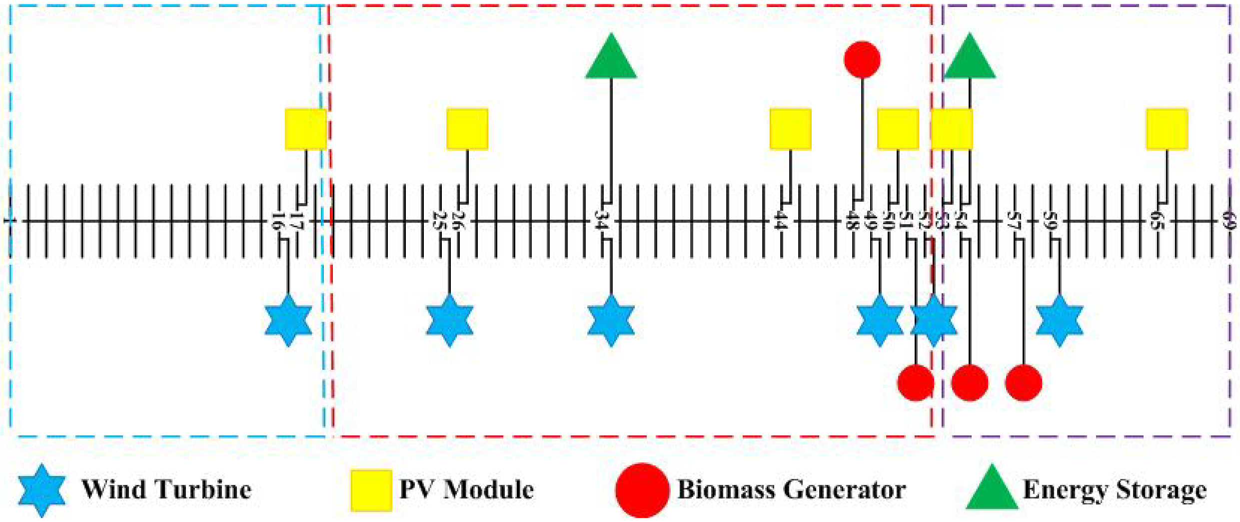


Fig.2. Calculated system total ENS for Case.1.

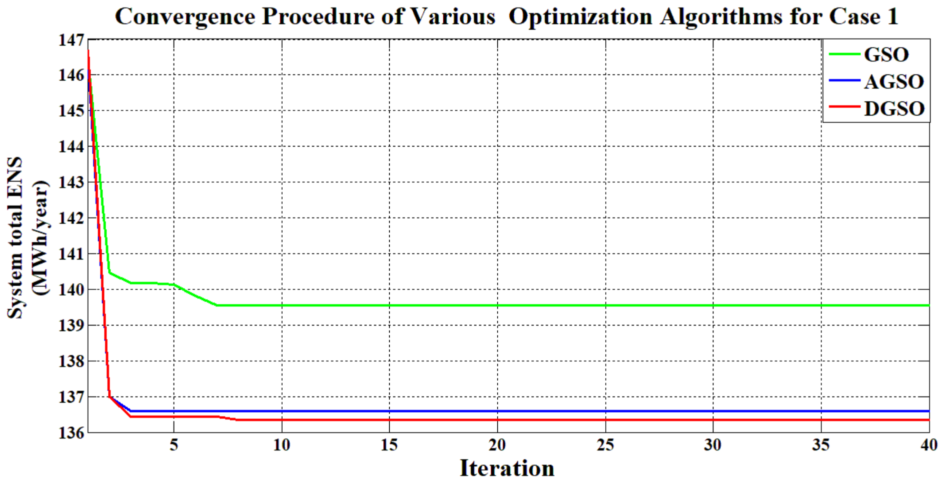
Increasing the number of MGs in a single branch radial distribution system, the size of constructed zones decreases and, the number of upstream MGs increases. According to Fig.B.1, the number of components located in each zone decreases which means that the amount of ENS caused by internal failures reduces. Besides, the number of constructed MGs in the upstream part increases which enhances the ENS caused by the upstream failures as depicted in Fig.B.2. Hence, an optimal number of MGs could be determined, aiming to minimize the total system ENS. Fig.2 indicates that constructing three MGs represents the optimal design for the considered distribution system. A schematic representation of the system, featuring three optimally clustered MGs and the strategically located ESSs, is depicted in Fig.3 (a). Noteworthy, assuming the absence of MGs results in a total ENS of 153.835 MWh/year due to system failures. System partitioning prevents fault propagation, resulting in 10% reduction in the ENS. Further, optimal ESS placement significantly enhances the system performance. Since, installed ESSs absorb the surplus energy during non-peak hours, and release it when the system power demand increases. To indicate the superior performance of the proposed DGSO algorithm, the obtained results for constructing three MGs by using GA, PSO, conventional GSO, AGSO and DGSO algorithms are compared, as provided in Table.2. The convergence procedures corresponding to various optimization techniques are illustrated in Fig.3 (b). Evidently, the convergence rate of the proposed DGSO algorithm markedly surpasses that of alternative algorithms. The DGSO algorithm, as proposed, demonstrates superior performance relative to alternative methods. Its notable strengths lie in the reaching to more appropriate solutions, the execution of a comprehensive search, and a commendable optimization speed.

Table.2: Comparison of obtained results for Case.1 by various optimization algorithms

Optimization Algorithm	Internal ENS (MWh/year)	External ENS (MWh/year)	Total ENS (MWh/year)	time (sec)
GA	89.8811	48.3447	138.2258	19
PSO	90.7694	48.7774	139.5468	21
GSO	90.7688	48.7824	139.5512	17
AGSO	88.7627	47.8211	136.5838	14
DGSO	**88.577**	**47.7746**	**136.3516**	**14**



(a) Schematic representation of optimal MG construction



(b) Convergence procedures of various optimization algorithms.

Fig.3. Schematic results corresponding to Case.1

5.2. Case.2

In this case, the PG&E 69-bus distribution test system is studied. After implementing the optimization procedure, optimal values for control variables are obtained, as provided in Table.3.

To indicate the performance of proposed DGSO algorithm, the MG partitioning problem is solved by other optimization techniques including PSO, GSO, and AGSO algorithms, too. The obtained results for constructing 5 MGs in the considered multi-branch distribution system are reported in Table.4. Noteworthy, constructing more than 8 MGs is impossible due to solution infeasibility and the violation of operational constraints.

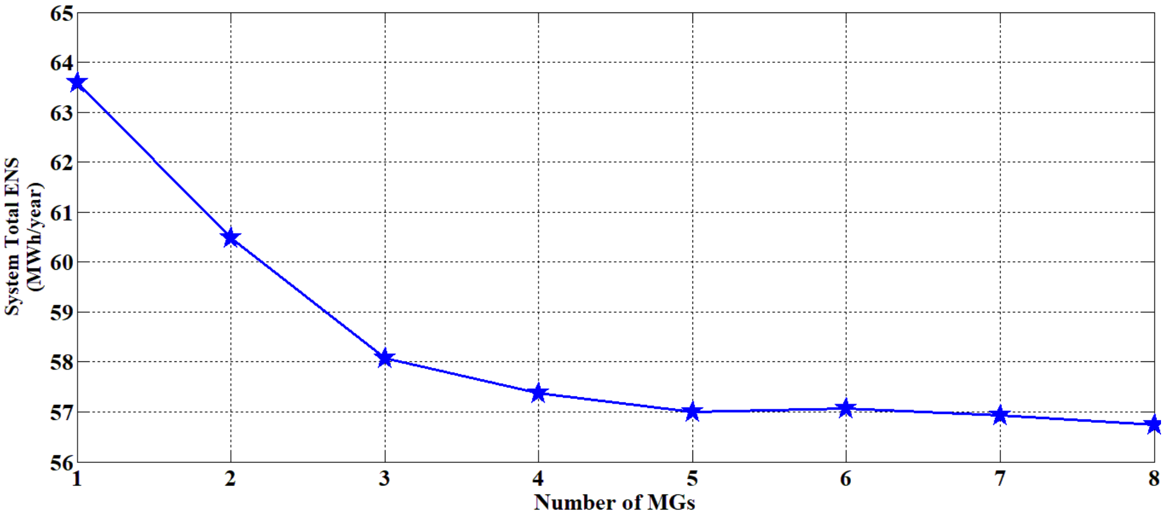
Table.3: Optimization results corresponding to Case.2.

MG Num	Boundary Lines	ESS Places	ENS - Internal Failures (MWh/year)	ENS - External Failures (MWh/year)	Total ENS (MWh/year)
2	61	41, 44	59.8226	0.6518	60.4744
3	10, 61	32, 46	53.7537	4.3248	58.0785
4	10, 15, 61	47, 63	52.196	5.1855	57.3815
5	10, 15, 20, 61	39, 44	51.3971	5.6047	57.0018
6	10, 12, 20, 29, 61	14, 32	51.6792	5.3830	57.0622
7	9, 11, 15, 20, 55, 61	34, 50	37.6845	19.2477	56.9323
8	6, 10, 14, 20, 31, 57, 61	41, 45	34.1664	22.5760	56.7424

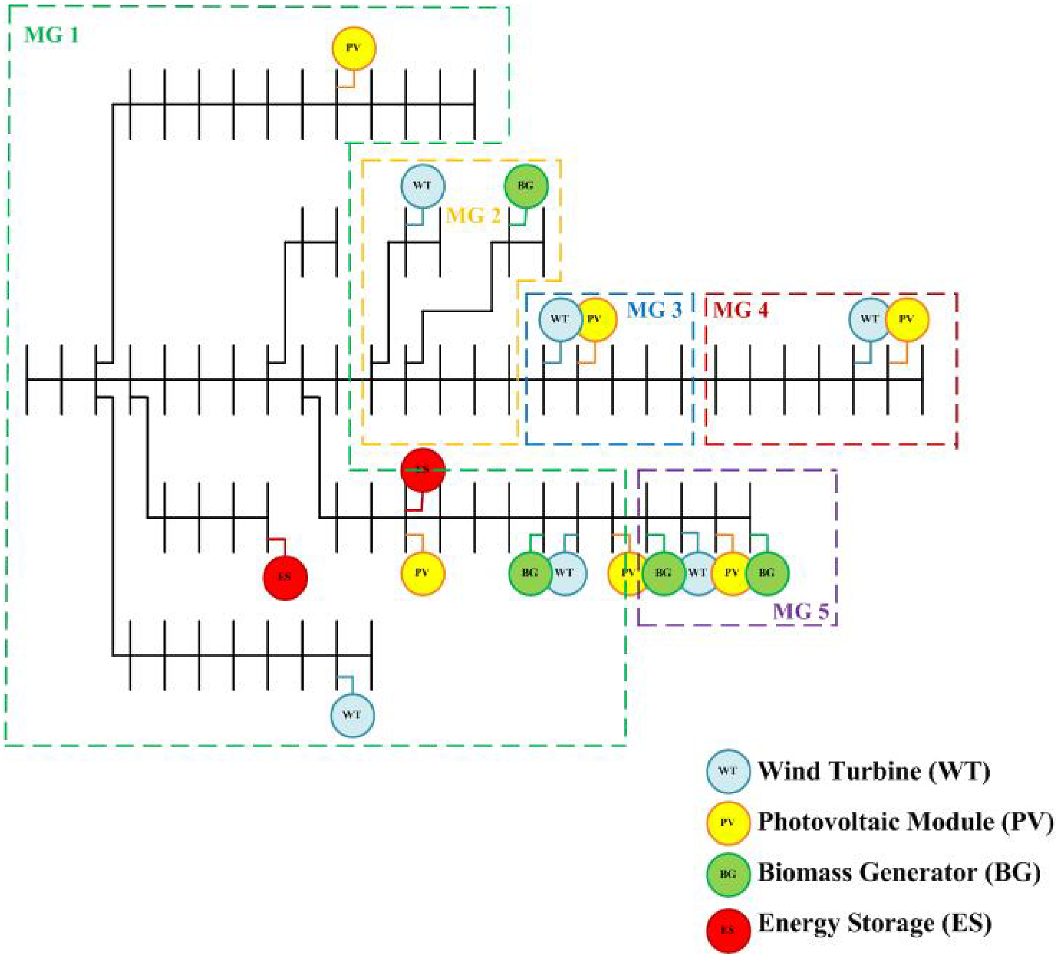
Table.4: Comparison of obtained results for Case.2 by various optimization algorithms.

Optimization Algorithm	ENS - Internal Failures (MWh/year)	ENS - External Failures (MWh/year)	Total ENS (MWh/year)
PSO	52.7432	6.1114	58.8546
GSO	53.566	6.3332	59.8992
AGSO	51.6171	6.002	57.6191
DGSO	**51.3971**	**5.6047**	**57.0018**

Fig.4 (a) illustrates the system's total ENS corresponding to various number of MGs. According to the results, increasing the number of MGs in such distribution system reduces the ENS caused by internal faults, because the number of components in each zone decreases. In a multi-branch distribution system, where the constructed zones are dispersed across different branches rather than linearly arranged, the impact of increasing the number of MGs on ENS resulting from upstream failures can either elevate or remain constant. According to Fig.4 (a), total amount of the system ENS has a downward trend and then, it remains constant. Consequently, multiple optimal numbers of MGs may exist, indicating that the optimal count for the studied distribution system is equal to 5 or more. However, the definitive determination of the optimal number of MGs necessitates the consideration of additional criteria such as construction cost, required infrastructures and etc. Fig.4 (b) presents a schematic representation of the considered distribution system, optimally partitioned into five MGs with the best reliability indices.



(a) System total ENS



(b) Schematic representation of optimal MG construction

Fig.4. Schematic results corresponding to Case.2

5.3. Case.3

This case is dedicated to optimal partitioning of an 85-bus radial distribution system to increase the reliability aspects. Implementing the proposed method in a high-order system leads to more accurate investigations and more explicit analysis. The considered network is a multi-branch radial distribution system including several loads and DG units which can inject only real power. It is assumed that DGs are previously installed in suitable places considering the system performance. By implementing the optimization procedure, optimal boundaries between MGs are obtained. The total amount of ENS corresponding to various number of MGs is depicted in the appendix as Fig.B.3.

From the reliability point of view, partitioning of a large distribution system into several smaller zones leads to a notable reduction in the total ENS and an enhancement in system reliability. As depicted in Fig.B.3, the increase in the number of MGs up to 7 significantly influences the system's ENS. However, beyond 7 MGs, the total ENS exhibits a near-constant trend. Therefore, it could be claimed that constructing 7 or more MGs would be suitable for the studied 85-bus distribution system considering reliability features. Noteworthy to mention, constructing more than 10 MGs is considered impractical based on the assumed operational constraints.

6. Conclusions

This research presents a novel methodology aimed at partitioning extensive distribution systems into multiple MGs to enhance system reliability by minimizing ENS resulting from DGs and busbar failures. The conventional ENS formulations were modified to account for failure impact within individual MG components and their influence on neighboring MGs. Additionally, optimal placement of energy storages was considered to maximize the utilization of installed DGs. The study introduced the DGSO algorithm, an enhanced version of the group search optimization algorithm, utilizing intelligent scroungers to facilitate an exhaustive search, yielding superior solutions. The proposed approach's efficacy was evaluated across three distinct case studies: a single-branch radial distribution system, the PG&E 69-bus system, and an Indian 85-bus test system. The results identified an optimal number of MGs for the single-branch distribution system, while the multi-branch radial system indicated multiple potential values for MG count. The promising outcomes observed in implementing the partitioning strategy within the Indian 85-bus radial distribution system underscore its practical applicability. This study primarily focuses on mitigating ENS resulting from two specific system failures during network partitioning into MGs.

While the research acknowledges the importance of examining additional potential system failures and their impact on system performance through the assessment of diverse reliability indices or the introduction of new measures, it emphasizes the relevance of this work primarily to radial distribution systems. Furthermore, as future research, investigating the influence of MG construction on the reliability of circular systems is suggested.

Acknowledgement

This research is supported by a research grant of the University of Tabriz (S.3044)

References

[1] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer, "Distributed generation: definition, benefits and issues," Energy policy, vol. 33, pp. 787-798, 2005.

[2] S. Zapata, M. Castaneda, M. Jimenez, A.J. Aristizabal, C.J. Franco and I. Dyner, "Long-term effects of 100% renewable generation on the Colombian power market." in Sustainable Energy Technologies and Assessments, vol. 30, pp.183-191, 2018.

[3] D. Neves, P. Andre, and S. A. Carlos. "Comparison of different demand response optimization goals on an isolated microgrid." in Sustainable Energy Technologies and Assessments, vol. 30. pp. 209-215, 2018.

[4] B. Hartono and R. Setiabudy, "Review of microgrid technology," in 2013 international conference on QiR, 2013, pp. 127-132.

[5] A. Jahani, K. Zare, L. M. Khanli, and H. Karimipour. "Optimized Power Trading of Reconfigurable Microgrids in Distribution Energy Market." IEEE Access, vol. 9 pp. 48218-48235, 2021.

[6] P. S. Georgilakis and N. D. Hatziargyriou, "Optimal distributed generation placement in power distribution networks: models, methods, and future research," IEEE Transactions on power systems, vol. 28, pp. 3420-3428, 2013.

[7] M. P. HA, P. D. Huy, and V. K. Ramachandaramurthy, "A review of the optimal allocation of distributed generation: Objectives, constraints, methods, and algorithms," Renewable and Sustainable Energy Reviews, vol. 75, pp. 293-312, 2017.

[8] S. Kumar, K. K. Mandal, and N. Chakraborty, "Optimal DG placement by multi-objective opposition based chaotic differential evolution for techno-economic analysis," Applied Soft Computing, vol. 78, pp. 70-83, 2019.

[9] M. Suresh and E. J. Belwin, "Optimal DG placement for benefit maximization in distribution networks by using Dragonfly algorithm," Renewables: Wind, Water, and Solar, vol. 5, p. 4, 2018.

[10] U. Sultana, A. B. Khairuddin, M. Aman, A. Mokhtar, and N. Zareen, "A review of optimum DG placement based on minimization of power losses and voltage stability enhancement of distribution system," Renewable and Sustainable Energy Reviews, vol. 63, pp. 363-378, 2016.

[11] S. A. Arefifar, Y. A.-R. I. Mohamed, and T. H. El-Fouly, "Supply-adequacy-based optimal

construction of microgrids in smart distribution systems," IEEE transactions on smart grid, vol. 3, pp. 1491-1502, 2012.

[12] N. Daryani, K. Zare, and S. Tohidi, "Design for independent and self-adequate microgrids in distribution systems considering optimal allocation of DG units," IET Generation, Transmission & Distribution, vol. 14, pp. 728-734, 2019.

[13] T. Khalili, M. T. Hagh, S. G. Zadeh, and S. Maleki, "Optimal reliable and resilient construction of dynamic self-adequate multi-microgrids under large-scale events," IET Renewable Power Generation, vol. 13, pp. 1750-1760, 2019.

[14] F. Moghateli, S. A. Taher, A. Karimi, and M. Shahidehpour, "Multi-objective design method for construction of multi-microgrid systems in active distribution networks," IET Smart Grid, vol. 3, pp. 331-341, 2020.

[15] N. Daryani, K. Zare, S. Tohidi, and J. M. Guerrero, "Dominated GSO algorithm for optimal microgrid construction to improve consumer side properties in a distribution system," International Journal of Electrical Power & Energy Systems, vol. 123, p. 106232, 2020.

[16] M. Rausand and A. Høyland, System reliability theory: models, statistical methods, and applications vol. 396: John Wiley & Sons, 2003.

[17] N. Balijepalli, S. S. Venkata, and R. D. Christie, "Modeling and analysis of distribution reliability indices," IEEE Transactions on Power Delivery, vol. 19, pp. 1950-1955, 2004.

[18] S. A. Arefifar, A.-R. M. Yasser, and T. H. El-Fouly, "Optimum microgrid design for enhancing reliability and supply-security," IEEE Transactions on Smart Grid, vol. 4, pp. 1567-1575, 2013.

[19] S. A. Arefifar and Y. A.-R. I. Mohamed, "DG mix, reactive sources and energy storage units for optimizing microgrid reliability and supply security," IEEE Transactions on Smart Grid, vol. 5, pp. 1835-1844, 2014.

[20] H. Hashemi-Dezaki, H. Askarian-Abyaneh, and H. Haeri-Khiavi, "Reliability optimization of electrical distribution systems using internal loops to minimize energy not-supplied (ENS)," Journal of applied research and technology, vol. 13, pp. 416-424, 2015.

[21] F. Olivas, F. Valdez, P. Melin, A. Sombra and O. Castillo, "Interval type-2 fuzzy logic for dynamic parameter adaptation in a modified gravitational search algorithm." Information Sciences, vol. 476, pp.159-175, 2019.

[22] F. Olivas, L. Amador-Angulo, J. Perez, C. Caraveo, F. Valdez and O. Castillo. "Comparative study of type-2 fuzzy particle swarm, bee colony and bat algorithms in optimization of fuzzy controllers." Algorithms, vol. 10(3), p.101, 2017

[23] S. He, Q. H. Wu, and J. Saunders, "Group search optimizer: an optimization algorithm inspired by animal searching behavior," IEEE transactions on evolutionary computation, vol. 13, pp. 973-990, 2009.

[24] N. Daryani, E. Babaei, and A. Shamlou, "Improved Group Search Optimization Algorithm for Multi-Objective Optimal Reactive Power Dispatch," Majlesi Journal of Electrical Engineering, vol. 10, p. 1, 2016.

[25] N. Daryani, M. T. Hagh, and S. Teimourzadeh, "Adaptive group search optimization algorithm for multi-objective optimal power flow problem," Applied soft computing, vol. 38, pp. 1012-1024, 2016.

[26] N. Daryani and K. Zare, "Multiobjective power and emission dispatch using modified group

search optimization method," Ain Shams Engineering Journal, vol. 9, pp. 319-328, 2018.

[27] N. Daryani and S. Tohidi, "Economic dispatch of multi-carrier energy systems considering intermittent resources," Energy & Environment, p. 0958305X18790959, 2019.

[28] T. Adefarati and R. Bansal, "Reliability assessment of distribution system with the integration of renewable distributed generation," Applied energy, vol. 185, pp. 158-171, 2017.

[29] T. Adefarati and R. Bansal, "Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources," Applied Energy, vol. 206, pp. 911-933, 2017.

[30] M.A. Shaheen, H.M. Hasanien, and A. Alkuhayli, "A novel hybrid GWO-PSO optimization technique for optimal reactive power dispatch problem solution," Ain Shams Engineering Journal, vol. 12(1), pp.621-630, 2021.

[31] Y. Li, M. Jia, X. Han, and X.S. Bai, "Towards a comprehensive optimization of engine efficiency and emissions by coupling artificial neural network (ANN) with genetic algorithm (GA)," Energy, vol. 225, p.120331, 2021.

[32] H. Zhou, "A multi-objective scheduling method for smart grid loads based on improved GSO algorithm," Journal of Physics: Conference Series (Vol. 1907, No. 1, p. 012018). IOP Publishing, 2021.

[33] E. Bernal, M.L. Lagunes, O. Castillo, J. Soria and F. Valdez, "Optimization of type-2 fuzzy logic controller design using the GSO and FA algorithms," International Journal of Fuzzy Systems, vol. 23(1), pp.42-57, 2021.

[34] M. E. Baran and F. F. Wu, "Optimal capacitor placement on radial distribution systems," IEEE Transactions on power Delivery, vol. 4, pp. 725-734, 1989.

[35] Y. Attwa and E. El-Saadany, "Reliability based analysis for optimum allocation of DG," in 2007 IEEE Canada Electrical Power Conference, pp. 25-30, 2007.

[36] M. M. Hamada, M. A. Wahab, and N. G. Hemdan, "Simple and efficient method for steady-state voltage stability assessment of radial distribution systems," Electric Power Systems Research, vol. 80, pp. 152-160, 2010.

[37] G. Deb, K. Chakraborty, and S. Deb, "Modified Spider Monkey Optimization-Based Optimal Placement of Distributed Generators in Radial Distribution System for Voltage Security Improvement," Electric Power Components and Systems, pp. 1-15, 2020.

Appendix A

✓ ENS Caused by Failures of WTs and PV modules

In this paper, the reliability of installed WTs and PVs is taken into account and the ENS caused by their failure is calculated. To do so, it is assumed that a WT consists of three main components including WT generator, AC/DC rectifier, and DC/AC inverter and, other parts of the WT are assumed to operate completely reliable [28]. On the other hand, a PV module consists of PV array, DC/DC converter, and DC/AC inverter. By considering normal/failure operation of DG components, knowing the failure rate and repair time of each component, and extracting an appropriate Markov model, the reliability indexes of WTs and PVs are calculated as follows [29]:

$$\lambda_{WT} = \lambda_{WG} + \lambda_{\mathrm{Rec}} + \lambda_{Inv} \tag{A.1}$$

$$\mu_{WT} = \frac{1}{r_{WT}} = \frac{\lambda_{WG} + \lambda_{\mathrm{Rec}} + \lambda_{Inv}}{\left[\left(1+\frac{\lambda_{WG}}{\mu_{WG}}\right)*\left(1+\frac{\lambda_{\mathrm{Rec}}}{\mu_{\mathrm{Rec}}}\right)*\left(1+\frac{\lambda_{Inv}}{\mu_{Inv}}\right)-1\right]} \tag{A.2}$$

$$\lambda_{PV} = \lambda_{Array} + \lambda_{Conv} + \lambda_{Inv} \tag{A.3}$$

$$\mu_{PV} = \frac{1}{r_{PV}} = \frac{\lambda_{Array} + \lambda_{Conv} + \lambda_{Inv}}{\left[\left(1+\frac{\lambda_{Array}}{\mu_{Array}}\right)*\left(1+\frac{\lambda_{Conv}}{\mu_{Conv}}\right)*\left(1+\frac{\lambda_{Inv}}{\mu_{Inv}}\right)-1\right]} \tag{A.4}$$

✓ Single-Branch Radial Distribution System

Assuming that the radial distribution network consists of only one branch, the system busbars are allocated tandem. The schematic of this structure is illustrated in Fig.A.1 (a). For partitioning such systems, MGs would be sited one after the other. If a busbar failure occurs in upstream MGs, all the downstream MGs will be disconnected from the grid. From the reliability point of view, each upstream MG could be considered as a component consisting of several busbars operating in series with each other. By using the proposed Markov model and assuming the equal failure rates and repair times for all distribution system busbars, the required parameters are calculated as follows:

$$\lambda_{UP-MG} = \lambda_1 + \lambda_2 + \cdots + \lambda_M = M * \lambda \tag{A.5}$$

$$\mu_{UP-MG} = \frac{1}{r_{UP-MG}} = \frac{\lambda_1 + \lambda_2 + \cdots + \lambda_M}{\left[\left(1+\frac{\lambda_1}{\mu_1}\right)*\left(1+\frac{\lambda_2}{\mu_2}\right)*\ldots*\left(1+\frac{\lambda_M}{\mu_M}\right)-1\right]} \tag{A.6}$$

$$\mu_{UP-MG} = \frac{1}{r_{UP-MG}} = \frac{M * \lambda}{\left[\left(1+\frac{\lambda}{\mu}\right)^M -1\right]} \tag{A.7}$$

where λ_{Up-MG} , μ_{Up-MG} , and r_{Up-MG} indicate the failure rate, repair rate, and repair time corresponding to the busbar failures in an upstream MG, respectively.

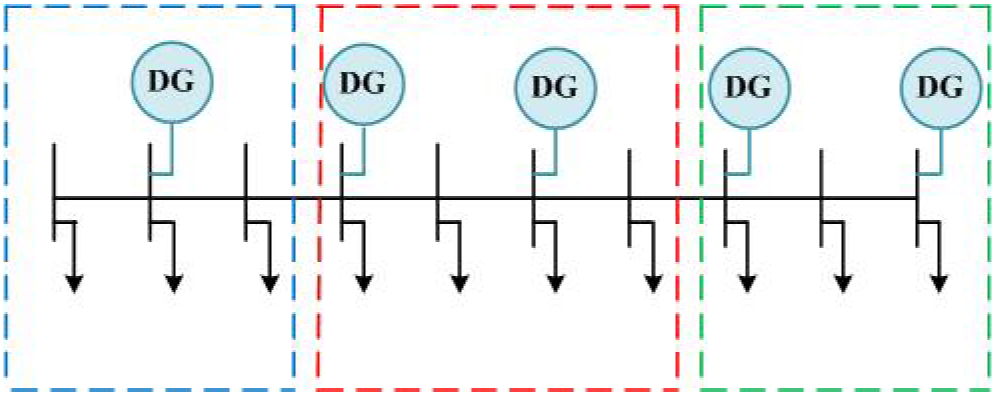
✓ Multi-Branch Radial Distribution System

If a multi-branch radial distribution system is studied, the impact of busbar failures in upstream MGs on the downstream zones will be different. When the amount of ENS caused by the upstream-side failures is calculated, the upstream busbars will be in the same path connecting the main grid and downstream zone or not. The branches located in the same path are considered as components that are operating in series which means failure occurrence in one of such busbars leads to disconnection of the downstream zone from the main grid. Fig.A.1 (b) shows the schematic of a radial distribution system with two MGs. MG2 is located in downstream part of MG1. Since MG1 consists of several branches, failure occurrence in some busbars (buses 1-6) will lead to islanded operation of MG2. Then, λ_{Up-MG}, μ_{Up-MG} , and r_{Up-MG} indices are calculated as follows, where M_{Path} is the number of busbars located in the path connecting the MG to the main grid.

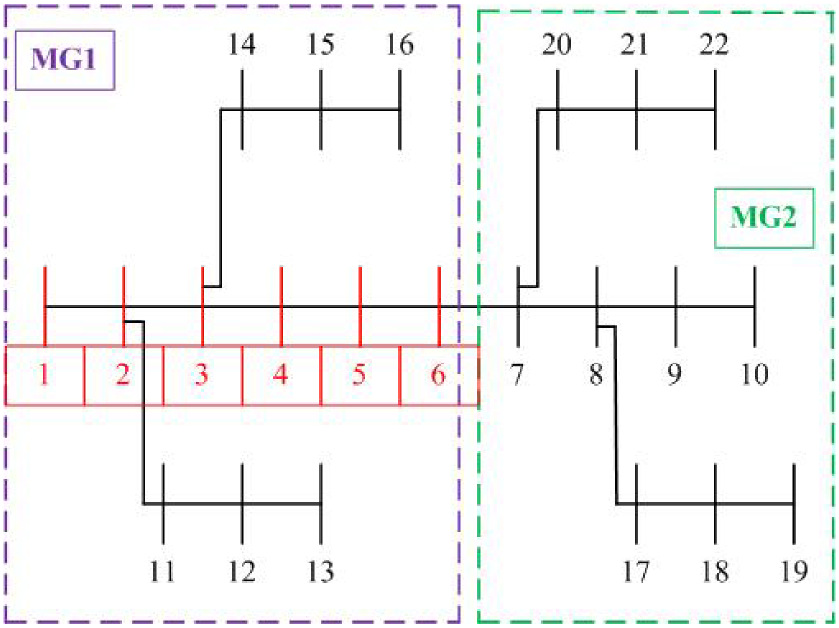
$$\lambda_{UP-MG} = \lambda_1 + \lambda_2 + \cdots + \lambda_{M_{Path}} = M_{Path} * \lambda \tag{A.8}$$

$$\mu_{UP-MG} = \frac{1}{r_{UP-MG}} = \frac{\lambda_1 + \lambda_2 + \cdots + \lambda_{M_{Path}}}{\left[\left(1+\frac{\lambda_1}{\mu_1}\right) * \left(1+\frac{\lambda_2}{\mu_2}\right) * \cdots * \left(1+\frac{\lambda_{M_{Path}}}{\mu_{M_{Path}}}\right) - 1\right]} \tag{A.9}$$

$$\mu_{UP-MG} = \frac{1}{r_{UP-MG}} = \frac{M_{Path} * \lambda}{\left[\left(1+\frac{\lambda}{\mu}\right)^{M_{Path}} - 1\right]} \tag{A.10}$$



(a) Single branch



(b) Multi-branch

Fig.A.1. Schematic representation of a radial distribution system

Appendix B

Table.B.1: Specifications of installed DGs for Case.1 and Case.2 [15].

DG Type	Installing Places	Ratings (kW)
WT	16, 25, 34, 49, 52, 55	50, 50, 50, 50, 75, 75
PV Modules	17, 26, 44, 50, 53, 65	25, 50, 25, 25, 25, 25
BG	48, 51, 54, 57	150, 150, 150, 100

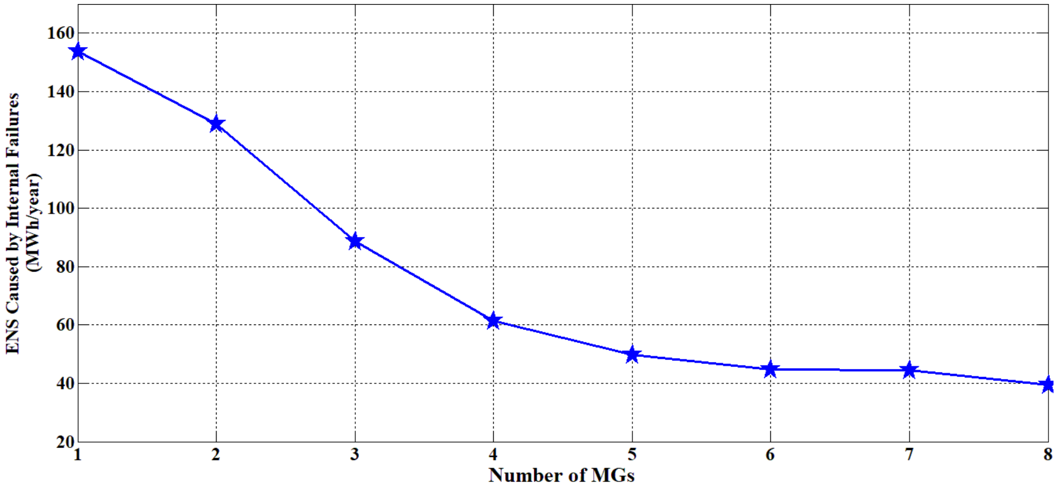


Fig.B.1 ENS caused by internal failures for Case.1

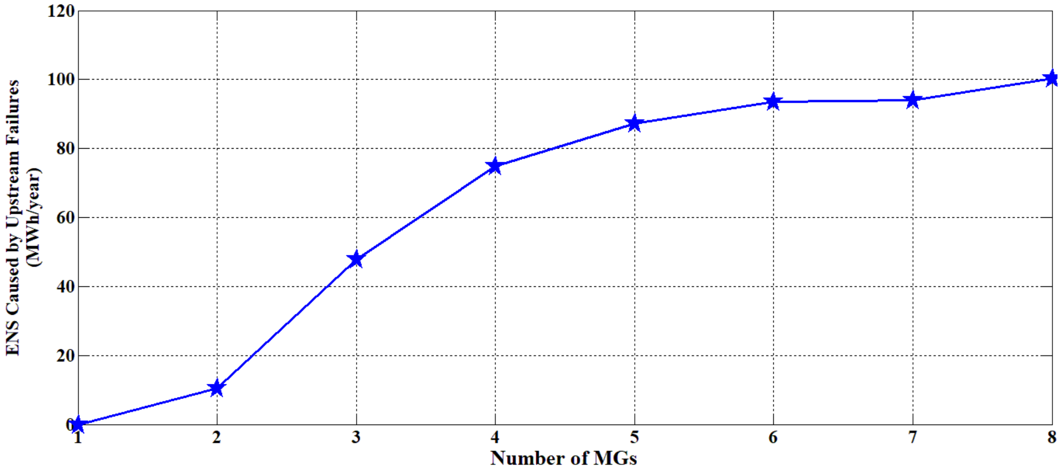


Fig.B.2 ENS caused by upstream failures for Case.1

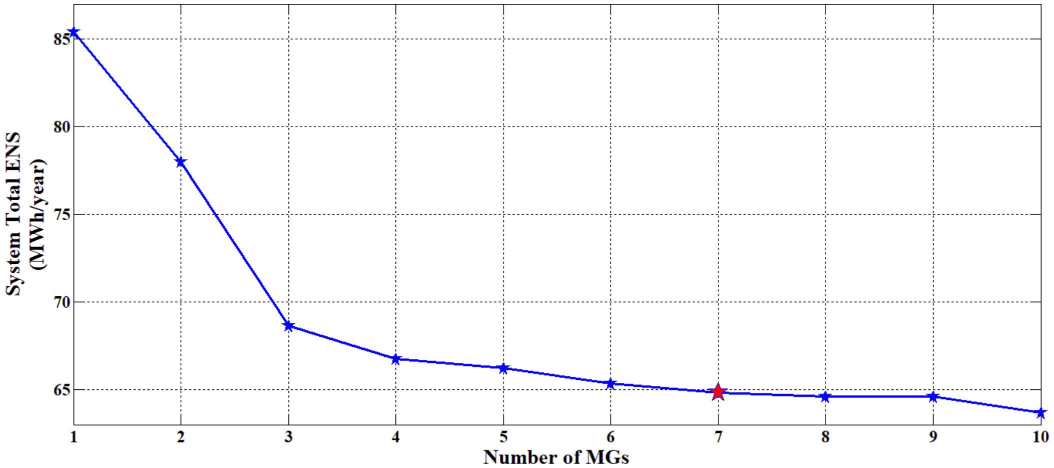


Fig.B.3. System total ENS for Case.3