

A Method for Reliability Improvement of Microgrids

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Abstract—This study describes a method for reliability improvement of microgrids via feeder reconfiguration. The work presented in this paper is developed based on a linearized network model in the form of DC power flow and linear programming model. The radial topological structure of the microgrid is preserved using a graph theoretic method. The optimal status of sectionalizing and tie-switches are identified using an intelligent binary particle swarm optimization based search method. The probabilistic reliability assessment is conducted using a method, which is developed based on minimal cut-sets. Several case studies are carried out on a modified 33 buses microgrid. The test results show that the amount of annual unserved energy, the number of affected households, and the number of affected consumers can be significantly reduced using the proposed method.

Index Terms—Microgrid, feeder reconfiguration, reliability, minimal cut-set, particle swarm optimization.

I. INTRODUCTION

As the penetration level of renewable energy sources based distributed generation increases within the present distribution systems, it is likely that distribution systems will evolve into autonomous microgrids, in order to realize the economic and reliability benefits of distributed generators. Therefore, a microgrid can be simply considered as a distribution system or a part thereof, with embedded distributed generation. Microgrids have a significant impact on service restoration and can assist in reducing the downtime and cost of interruptions of large numbers of consumers during abnormal and fault conditions.

Similar to distribution systems, microgrids are configured radially for best control and coordination of their protective devices. Nonetheless, with the radial topological structure, the failure of any single component between the load point and the source node would cause service interruptions and may result in disconnecting several load points. Bus transfer or feeder reconfiguration can be used to minimize the duration and frequency of service interruptions, and thereby improve the reliability of the microgrid. Feeder reconfiguration aims at changing the topological structure of the microgrid by altering the status of sectionalizing switches, which are normally closed, and tie-switches, which are normally open, to achieve certain objectives such as reliability enhancement. Prior research on feeder reconfiguration has sought to reduce system losses [1]–[5]; in this work we develop a method to reconfigure feeders so as to improve service reliability.

Over the past years, there has been an increasing interest in improving distribution system reliability and security using distribution system reconfiguration. Ref. [6]–[11] proposed methods based on swarm intelligence for distribution system reliability improvement using feeder reconfiguration. The expected energy not supplied (EENS), alternatively known as the expected unserved energy (EUE), expected demand not supplied (EDNS), and the expected outage cost (ECOST) are some examples of the reliability metrics used in the literature. The energy index of reliability (EIR) has also been proposed in recent studies concerned with reliability and security enhancement of passive and active distribution systems [11]. In this paper, a method for reliability assessment and enhancement of microgrids is presented. This method is developed based on linear programming model and particle swarm optimization (PSO) based search method. The probabilistic reliability assessment is conducted using first-order minimal cut-sets based method. We demonstrate the effectiveness of the proposed method on 33 buses microgrid and we consider different loading scenarios. We estimate the number of affected households and the number of affected consumers based on data from the Energy Data via World Energy Council (enerdata) [12]. We show that the amount of the annual unserved energy, the number of the affected households, and the number of the affected consumers can all be reduced using the proposed method.

II. IMPORTANCE OF IMPROVING THE RELIABILITY OF MICROGRIDS

A large number of the present power distribution systems and microgrids are being stressed and operated at heavily loaded conditions due to the rapid increase in electricity demand, lack of investment in distribution infrastructures, and imposition of certain economic and environmental constraints. With the advent of digital loads and newer appliances, distribution systems and microgrids are expected to conform to higher reliability and power quality standards than in the past. Statistics have shown that the vast majority of service outages have taken place at distribution system level [13], [14]. Ref. [14] has reported that power distribution systems contribute for up to 90% of overall consumers reliability problems. A study conducted by the Power System Outage Task Force

(PSOTF) [15] after the massive blackout of the US and Canada that took place in August 2003 has indicated that stressed systems can be a major source for service interruptions. The annual cost of these service interruptions could attain billions of dollars according to the Electric Power Research Institute (EPRI) [16]. It has therefore become necessary to develop more effective methods to enhance the reliability and security of active distribution systems and microgrids.

III. OVERVIEW OF MODELS AND METHODS

A. Modeling Aspects

For reliability assessment studies, probabilistic modeling techniques are utilized to represent various system components. The availability of any component i in the system can be represented as [13],

$$P_i = \frac{1/\lambda_i}{1/\lambda_i + 1/\mu_i} = \frac{\mu_i}{\mu_i + \lambda_i} \quad (1)$$

where λ_i is the failure rate of component i and μ_i is the repair rate of component i , respectively.

In this paper, it is assumed that each component in the system can only reside in an up-state (*available*) or down-state (*unavailable*). Therefore, a two-state model is used to model various system components [13], [14]. For distribution feeders, a discrete probability density function is constructed for every distribution line. If a distribution feeder is tripped for certain system state, the line is removed from the bus admittance matrix and its capacity is set equal to zero.

B. Reliability Assessment Method

The work presented here uses the minimal cut-set method [13], [14], [17], [18] to conduct the task of reliability evaluation. It is known that the components of a cut-set are connected in parallel, but the minimal cut-sets are connected in series. Therefore, we can define the minimal cut-set as follows: if all components in the cut-set fail, then the system will fail, but if any component in the system does not fail, the system will succeed [17]. Now, let us assume component independence and assume the cut-sets of the system are $C_1, C_2, \dots, C_m$. Let us denote the probability of failure of components in the cut-set C_1 as $P(C_1)$. The unreliability of the system can therefore be calculated as [17],

$$Q_{system} = P(C_1 \cup C_2 \cup \dots \cup C_m) \quad (2)$$

The reliability of the system can be represented as,

$$R_{system} = 1 - Q_{system} \quad (3)$$

Assume independent events, the upper bound of Q_{system} can be further approximated as [17],

$$P(C_1 + C_2 + \dots + C_m) \cong P(C_1) + P(C_2) + \dots + P(C_m) \quad (4)$$

The lower bound for the system reliability can be approximated as [17],

$$R_{system} \geq 1 - [P(C_1) + P(C_2) + \dots + P(C_m)] \quad (5)$$

IV. RELIABILITY EVALUATION USING LINEAR PROGRAMMING AND DC POWER FLOW

A. Objective Function and Constraints

Linearized models are usually used for power system planning studies because they are flexible and reliable compared to their nonlinear counterparts [9], [11], [19]–[21]. The work presented here is developed based on a linearized network model in the form of DC power flow and linear programming similar to that proposed by Mitra and Singh in [21].

The objective function used in this paper aims at minimizing the amount of total load curtailment. Mathematically, the objective function is represented as [21],

$$\text{Loss of Load} = \min \left(\sum_{t=1}^{N_b} P_{C_t} \right) \quad (6)$$

Subject to

- 1) Power Balance Equations

$$\hat{B}\delta + P_G + P_C = P_D \quad (7)$$

- 2) Active Power Constraints

$$0 \leq P_G \leq P_G^{max} \quad (8)$$

- 3) Forward and Reverse Flow Capacities

$$\begin{aligned} b\hat{A}\delta &\leq J_f^{max} \\ -b\hat{A}\delta &\leq J_r^{max} \end{aligned} \quad (9)$$

- 4) Load Curtailment Constraints

$$0 \leq P_C \quad (10)$$

- 5) Angle Constraints

$$\delta \text{ is unrestricted} \quad (11)$$

- 6) Radial Topology Constraints

$$\varphi(l) = 0 \quad (12)$$

where

- N_b = Number of buses
- N_f = Number of distribution feeders
- P_G = Vector of real power generation ($N_b \times 1$)
- P_D = Vector of active power demand ($N_b \times 1$)
- P_C = Vector of load curtailment ($N_b \times 1$)
- $\hat{B}$ = Augmented node susceptance matrix ($N_b \times N_b$)
- θ = Vector of bus voltage angles ($N_b \times 1$)
- b = Diagonal matrix of line susceptances ($N_f \times N_f$)
- $\hat{A}$ = Element-node incidence matrix ($N_f \times N_b$)
- J_f^{max} = Vector of forward line flows ($N_b \times 1$)
- J_r^{max} = Vector of reverse line flows ($N_b \times 1$)

The ($N_b \times N_b$) augmented node susceptance matrix is calculated as,

$$\hat{B} = \hat{A}^T b \hat{A} \quad (13)$$

where $\hat{A}^T$ is the transpose of the element-node incidence matrix.

B. Calculation of Reliability Metrics

The reliability index utilized in this paper is the expected unserved energy (EUE). It is evident that (7) is augmented by a fictitious generator that is equivalent to the required curtailment since the problem aims at minimizing the total load curtailment. Further, in order to get a feasible solution for the minimization problem, we assume that one of the bus angles is zero in the above formulation.

The expected unserved energy reliability index can be calculated as,

$$EUE = 8760 \times \sum_{u=1}^{N_c} LOL(u) \times Prob(u) \quad (14)$$

where $LOL(u)$ is the loss of load of state u , which is equivalent to load curtailment of state u , $Prob(u)$ is the probability of state u , and N_c is the number of contingencies.

It is worth mentioning here that most microgrids are still configured radially for best control and coordination of their protective devices. Therefore, we include (12) in the proposed solution so that the radial topology constraints are imposed. The implementation of the radial topology constraints is demonstrated in the subsequent section.

C. Implementation of the Radial Topology Constraints

One of the practical aspects of the presented work is that it retains the radial structure of the microgrid system. We develop this condition based on graph theory [22], [23] and impose it by adding (12) to the solution procedures. The procedures of formulating this constraint are explained as follows: suppose we have a graph $G(V, E)$ with n vertices (nodes) $V = \{v_1, v_2, \dots, v_n\}$ and m edges (branches) $E = \{e_1, e_2, \dots, e_m\}$. We define the $(n \times m)$ vertex-edge incidence matrix $A[a_{ij}]$ of this graph as,

$$A = \begin{cases} 1, & \text{if an edge runs from vertex } i \text{ to vertex } j \\ -1, & \text{if an edge runs from vertex } j \text{ to vertex } i \\ 0, & \text{if vertex } i \text{ is not connected to vertex } j \end{cases} \quad (15)$$

From (15), it is evident that there are exactly two ones in every column of A . Consequently, we could obtain any row of A from the remaining rows, which signifies that A is linearly dependent. If we take out any row from A , the rank of the resultant matrix should be $\leq n$, which, in other words, means that the resultant matrix is linearly independent. Such matrix is denoted as the reduced incidence matrix A_r , and whose dimensions of $(n-1) \times m$ and a rank of $n-1$. The algorithm used in this work is developed based on the following theorem [22], [23].

Theorem: Any sub-matrix in A_r with dimensions $(n-1) \times (n-1)$, is non-singular if and only if the $n-1$ edges corresponding to the $n-1$ columns of this matrix constitutes a spanning tree.

Therefore, for every possible configuration, we evaluate the determinant of the reduced incidence matrix, or any sub-matrix in it, so that, if $\det[A_r] = \pm 1$, this means that the radial topology is preserved. On the other hand, if $\det[A_r] = 0$, this

means that the system has at least one loop and, therefore, the configuration is infeasible. We obtain the number of loops in every configuration, $\varphi(l)$, from Euler's formula [22] as,

$$\text{No. of Loops} = \text{No. of Edges} - \text{No. of Vertices} + 1 \quad (16)$$

To better understand the spanning tree algorithm developed herein, let us consider the graph shown in Fig. 1. This graph consists of 4 vertices and 5 edges. The incidence matrix describes this graph has one column for each vertex and one row for each edge of the graph. The incidence matrix of the graph depicted in Fig. 1 can thus be represented as,

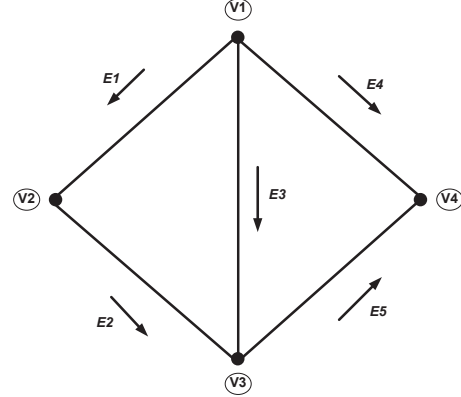


Fig. 1: A graph with $n = 4$ vertices and $m = 5$ edges

$$A = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ -1 & 0 & 1 & 0 \\ -1 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 \end{bmatrix} \quad (17)$$

Let us draw our attention to the loop forms by the vertices V_1, V_2 , and V_3 and the edges E_1, E_2 , and E_3 , respectively. The matrix describes these vertices and edges can be expressed as,

$$A_r = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ -1 & 0 & 1 \end{bmatrix} \quad (18)$$

As can be seen from (18) the summation of the first two rows yields the third row, which indicates that the matrix described by (18) is linearly dependent. The number of loops in the graph shown in Fig. 1 can be determined using (16), which is in this case equals 2.

V. FORMULATION OF THE OPTIMAL FEEDER RECONFIGURATION PROBLEM

This section formulates the optimal feeder reconfiguration problem for reliability improvement. It reviews the basics of particle swarm optimization technique. It then develops an intelligent search method based on binary particle swarm optimization to seek all possible combinations of tie and sectionalizing switches that minimize the total load curtailment, and thereby improve the reliability of the microgrid.

A. Binary Particle Swarm Optimization

Particle swarm optimization (PSO) is a population-based optimization technique inspired by the social behavior of flocks of birds or schools of fish, which is described in detail in [24], [25]. In PSO, the positions and velocities of the particles are initialized with a population of random feasible solutions and search for optima by updating generations. In PSO, the movement of the particles, which represents the potential solutions, is governed by the individual best and the group best. Using these components, a vector that determines the direction and magnitude of each particle in the swarm can therefore be represented as,

$$v_i = v_{i-1} + k_1 \times rand \times (Ppbest_i - x_i) + k_2 \times rand \times (Pgbest - x_i) \quad (19)$$

where $rand$ is a uniformly distributed random number between $[0,1]$, $Ppbest_i$ is the particle best position from the probability of a state prospective particle i has ever encountered, $Pgbest$ is the group of particles best position from the probability of a state prospective the group has ever encountered. Further, c_1 and c_2 are acceleration factors. These acceleration factors are usually chosen so that $k_1 + k_2 = 4$, with $k_1 = k_2 = 2$.

The change in particles positions can be defined by a sigmoid limiting transformation function and a uniformly distributed random number in $[0,1]$ as following,

$$x_{id} = \begin{cases} 1, & \text{rand}(0,1) < S(v_{id}) \\ 0, & \text{otherwise} \end{cases} \quad (20)$$

where, x_{id} is the d^{th} component of particle i and $S(v_{id})$ is the sigmoid function of d^{th} 's component of particle i which can be expressed as,

$$S(v_{id}) = \frac{1}{1 + e^{(-v_{id})}} \quad (21)$$

B. Implementation of the Proposed Method

The main steps of the reliability evaluation and finding the optimal configuration using the proposed PSO based search method are summarized in this section and are also depicted in Fig. 2,

- 1) Initialize the positions and velocities of the particles, x_i and v_i respectively.
- 2) Check if there are particles already exit in the database, if so, set load curtailments of the existing particles to the system peak load.
- 3) Check the radial topology constraints for each particle.
- 4) Perform reliability evaluation for each particle by solving the linear programming optimization problem.
- 5) Calculate the expected load curtailments for each particle and for every system state.
- 6) Update personal best and global best.
- 7) Check for convergence. If the stopping criteria is met, stop. Otherwise, update particles velocities and particles positions and go to 2.

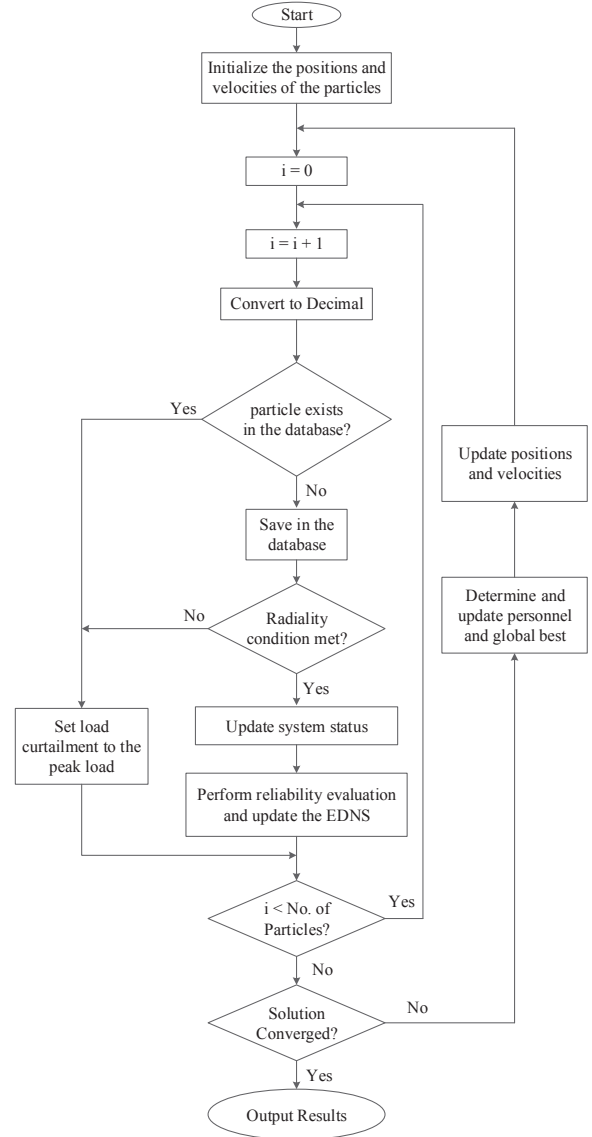


Fig. 2: Flowchart of the proposed method

VI. NUMERICAL EXAMPLE AND DISCUSSION OF RESULTS

The test system used in this paper is 33 buses radial distribution system [3]. This system has been modified to behave like a microgrid by adding proper amount of renewable energy sources based distributed generation units as shown in Fig. 3. The load data and branch data of the original system can be found in [3]. The total real and reactive power loads on the 33 buses system are assumed to be 3715 kW and 2300 KVar, respectively. The system consists of 33 buses, 32 branches, 3 laterals, and 5 tie-lines. For the initial configuration, the normally open switches (tie-lines) are {S33, S34, S35, S36, S37}. The normally closed switches are S1 to S32.

The 33 buses system is modified by adding three distributed generation units (DG) at bus 7, bus 14, and bus 32, respec-

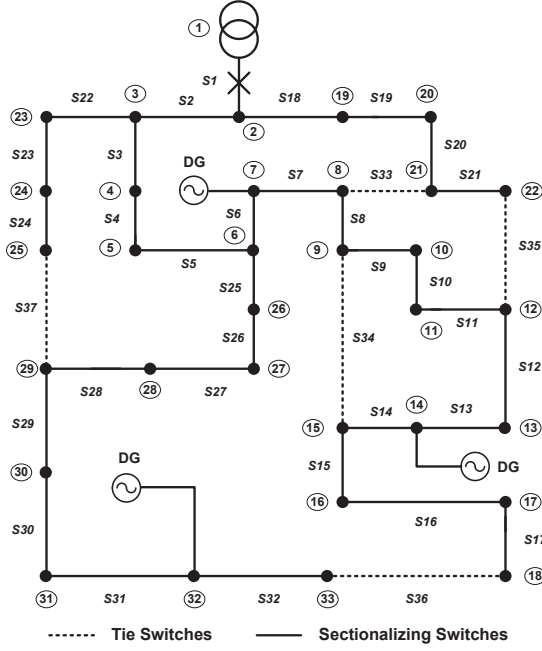


Fig. 3: Initial configuration of the 33 buses microgrid

tively. The total penetration level of the distributed generation units in the test microgrid is assumed to be 10%. The data of the distributed generation units used in this paper is depicted in Table I. In this work, it has been assumed that the synchronous generators based distributed generation units can supply both real and reactive power. The controlled PV generator is assumed to be working at the maximum power point. In accordance with IEEE standard 1547–2003 [26], distributed generation units are not favored in regulating bus voltages at the installation node [26]. Therefore, the DG units used in this work are modeled as negative power injections at the installation nodes. Furthermore, these distributed generation units are assumed to be driven by consumers. Consequently, their optimal sizes and locations are not germane to the work presented in this paper.

TABLE I: Distributed Generators Data

Installation Bus	DG Type	Output Power	Power Factor
7	Synch. Gen.	170 kVA	0.95
14	Controlled PV	100 kW	unity
32	Synch. Gen.	170 kVA	0.90

The proposed method of feeder reconfiguration is demonstrated on 33 buses microgrid. The parameters of the proposed search method have been selected so that: number of particles = 50, acceleration factors $k_1 = 2$, and $k_2 = 2$, and the maximum number of iterations = 1000. We consider various loading conditions that include light loading conditions, in which the total load is reduced by 40%, nominal loading

conditions, in which peak loads are considered, and heavy loading conditions, in which the total load is increased by 40%. Two case studies are performed in this paper. These case studies are presented in the subsequent section.

A. Case Study I

In this case study, the failure rates of all components such as power transformer, circuit breaker, sectionalizing and tie-switches, distribution feeders, and buses are taken into consideration. It has been further assumed that every distribution line has a sectionalizing switch. The optimal feeder reconfiguration method for reliability improvement is applied on the 33 buses microgrid. For nominal loading conditions, the optimal set of the sectionalizing and tie-switches that yield minimum load curtailment were {S7, S10, S13, S27, S36}. The reliability results of this case study are summarized in Table II. As can be seen from Table II, for the nominal load scenario, the EUE is reduced from 74222.1 kWh/year, for the initial configuration, to 64658.4 kWh/year after the microgrid is reconfigured. This is 12.88% reduction in the annual expected unserved energy.

According to the Energy Data via World Energy Council (enerdata) [12], the typical household power consumption in the US is about 11,700 kWh each year. This is for an average household size closer to 2.5 people. Further, according to [12] each American uses about 4,500 kWh per year in his home. We use these figures here to calculate the average number of the affected households for the initial configuration and the optimal configuration, which is obtained by the proposed method. For nominal loading conditions, the average number of the affected households before reconfiguration is estimated to be 6.34 households. The number of the affected consumers before reconfiguration was 16.5 consumers. However, these figures have been respectively reduced to 5.5 and 14.4, after the system has been reconfigured. Fig. 4 depicts the optimal configuration of the 33 buses microgrid for the case of nominal loading conditions.

For the light loading conditions, the average number of the affected households before reconfiguration was 2.54 households. The number of the affected consumers before reconfiguration was 6.6 consumers. However, these figures have been respectively reduced to 2.21 and 5.7, after the system has been reconfigured. Similar conclusions are drawn for heavy loading conditions as can be seen from Table II.

B. Case Study II

This case study investigates the effect of higher failure rates of components on the reliability of the test microgrid. In this case study, the failure rates of distribution feeders, sectionalizing switches, and buses are increased by 15%, 10%, and 5%, respectively. It has been further assumed that every distribution line has a sectionalizing switch. The optimal feeder reconfiguration method for reliability improvement is applied on the 33 buses microgrid. For nominal load conditions, the optimal set of the sectionalizing and tie-switches that yield minimum load curtailment were {S7, S10, S13, S27, S36}. For comparison purposes, the reliability index EUE

TABLE II: Reliability Results of The Test Microgrid - Case Study I

Network Status & Loading Conditions		Best Set of Tie & Sectionalizing Switches	EUE kWh/year	Number of Affected Households	Number of Affected Consumers
Light Load (40% Reduction)	Initial Configuration	S33, S34, S35, S36, S37	29688.9	2.54	6.6
	Optimal Configuration	S7, S10, S13, S27, S36	25836.3	2.21	5.7
Nominal Load (Peak Load)	Initial Configuration	S33, S34, S35, S36, S37	74222.1	6.34	16.5
	Optimal Configuration	S7, S10, S13, S17, S27	64658.4	5.5	14.4
Heavy load (40% Increase)	Initial Configuration	S33, S34, S35, S36, S37	103911	8.88	23.1
	Optimal Configuration	S7, S10, S13, S27, S36	90427	7.73	20.1

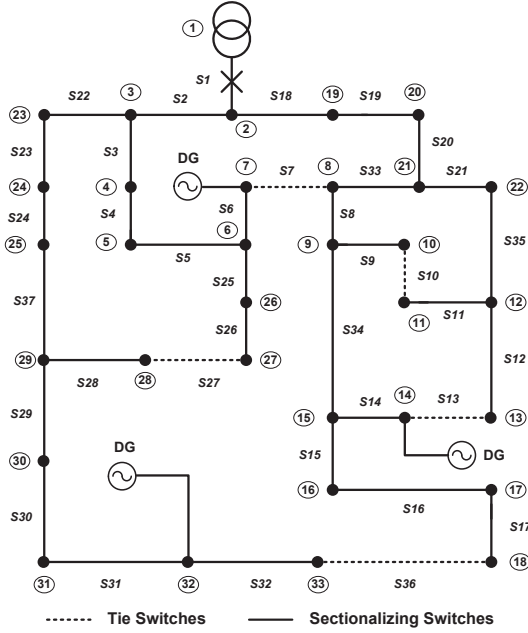


Fig. 4: Optimal configuration of the 33 buses microgrid for nominal loading conditions - Case Study I

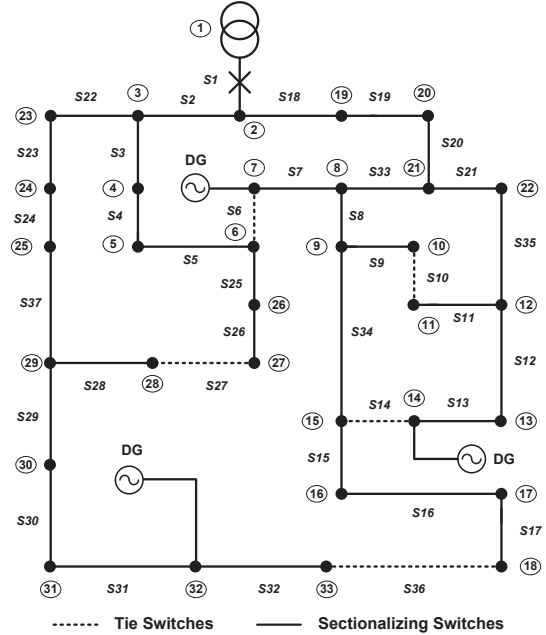


Fig. 5: Optimal configuration of the 33 buses microgrid for nominal loading conditions - Case Study II

is estimated before and after reconfiguration. The results of this case study are summarized in Table III. As can be seen from Table III, for the nominal load scenario, the EUE is reduced from 78776.1 kWh/year, for the initial configuration, to 68049.2 kWh/year after the microgrid is reconfigured. This is approximately 13.62% reduction in the annual expected unserved energy.

As can be seen from Table III, for nominal loading conditions, the average number of the affected households before reconfiguration is estimated to be 6.73 households. The number of the affected consumers before reconfiguration was 17.5 consumers. Nonetheless, the average number of affected households and affected in-service consumers have been respectively reduced to 5.82 and 15.1 for the optimal configuration. Fig. 5 depicts the optimal configuration of the 33 buses microgrid for the case of nominal loading conditions.

For the light loading conditions, the average number of the affected households before reconfiguration was 2.69 households. Further, the number of the affected consumers before

reconfiguration was 7.0 consumers. However, the average number of the affected households and the affected consumers have been respectively reduced to 2.33 and 6.0 for the optimal configuration. Detailed reliability results for different loading conditions are given in Table III.

VII. CONCLUSION

This paper has proposed a method for reliability improvement of microgrids using optimal feeder reconfiguration. The work presented in this paper is developed based on a linearized network model in the form of DC power flow and linear programming model. We have proposed a method based on particle swarm optimization to seek for all possible combinations of sectionalizing and tie-switches that improve the reliability of the test microgrid. Furthermore, we have used a method based on first-order minimal cut-sets to perform the probabilistic reliability assessment. In addition, we have developed a graph theoretic method to preserve the radial topology constraints of the test microgrid. We have demonstrated the effectiveness

TABLE III: Reliability Results of The Test Microgrid - Case Study II

Network Status & Loading Conditions		Best Set of Tie & Sectionalizing Switches	EUE kWh/year	Number of Affected Households	Number of Affected Consumers
Light Load (40% Reduction)	Initial Configuration	S33, S34, S35, S36, S37	31510.4	2.69	7.0
	Optimal Configuration	S7, S10, S13, S27, S36	27219.7	2.33	6.0
Nominal Load (Peak Load)	Initial Configuration	S33, S34, S35, S36, S37	78776.1	6.73	17.5
	Optimal Configuration	S6, S10, S14, S27, S36	68049.2	5.82	15.1
Heavy load (40% Increase)	Initial Configuration	S33, S34, S35, S36, S37	110287	9.43	24.5
	Optimal Configuration	S6, S10, S14, S26, S36	95340.6	8.15	21.2

of the proposed reliability assessment method on 33 buses microgrid. We show that the amount of the annual unserved energy, the number of the affected households, and the number of the affected consumers can be significantly reduced using the proposed reliability enhancement method.

The method proposed in this paper is appropriate to use for several power system planning studies. Improvements of the proposed method to handle operational and online applications are being in progress and will be reported shortly in due course.

REFERENCES

- [1] A. Merlin and H. Back, "Search for minimum loss operating spanning tree configuration in an urban power distribution system," in *Proc. of 5th Pow. Sys. Comput. Conf.*, Cambridge, U.K., pp. 1–18, 1975.
- [2] D. Shirmohammadi and H. W. Hong, "Reconfiguration of electric distribution networks for resistive line losses reduction," *IEEE Trans. Pow. Del.*, vol. 4, no. 2, pp. 671–679, April 1989.
- [3] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Trans. Pow. Del.*, vol. 4, no. 2, pp. 1401–1407, April 1989.
- [4] H.-D. Chiang and R. Jean-Jumeau, "Optimal network reconfigurations in distribution systems. II. Solution algorithms and numerical results," *IEEE Trans. Power Del.*, vol. 5, no.3, pp. 1568 - 1574, Jul. 1990.
- [5] S. Elsaiah and J. Mitra, "A Method for minimum loss reconfiguration of radial distribution systems," in *Proc. of the IEEE Power and Energy Society General Meeting and Exposition*, Denver, Colorado, USA, July 26-31, 2015.
- [6] S. Chakrabarti, G. Ledwich, and A. Ghosh, "Reliability driven re-configuration of rural power distribution systems," in *Proc. of Third International Conference on Power Systems*, pp. 1–6, 2009.
- [7] B. Amanulla, S. Chakrabarti, and S.N.Singh, "Reconfiguration of power distribution systems considering reliability and power loss," *IEEE Trans. Pow. Del.*, vol. 27, no. 2, pp. 918–926, April 2012.
- [8] H. Falaghi, M. R. Haghifam, and C. Singh, "Ant colony optimization based method for placement of sectionalizing switches in distribution networks using a fuzzy multi-objective approach," *IEEE Trans. Pow. Del.*, vol. 24, no. 1, pp. 268–276, Jan. 2009.
- [9] S. Elsaiah, M. Benidris, and J. Mitra, "Reliability improvement of power distribution system through feeder reconfiguration," in *proceedings of the 13th IEEE International Conference on Probabilistic Methods Applied to Power Systems*, PMAPS, Durham, UK, 2014.
- [10] J. Mitra, M. R. Vallem and C. Singh, "Optimal Deployment of Distributed Generation Using a Reliability Criterion," *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, May/June 2016.
- [11] J. Mitra, S. Patra, S. Ranade, and M. R. Vallem "Reliability-specified generation and distribution expansion in microgrid architectures," *WSEAS Trans. on Pow. Syst.*, vol. 1, no. 8, pp. 1446–1453, Aug. 2006.
- [12] <http://shrinkthatfootprint.com/average-household-electricity-consumption>. Available at: <http://www.wec-indicators.enerdata.eu>.
- [13] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*. Second edition, New York: Plenum, 1996.
- [14] R. E. Brown, *Electric Power Distribution Reliability*. Marcel Dekker Inc., 2002.
- [15] U.S.-Canada Power System Outage Task Force, Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, Apr. 2004. Available at: <https://reports.energy.gov/BlackoutFinal-Web.pdf>.
- [16] The Cost of Power Disturbances to Industrial and Digital Economy Companies. Primen, EPRI, Available at: <http://www.empoweret.com/wp-content/uploads/2008/09/cost-of-power-outages.pdf>
- [17] R. Ramakumar, *Engineering Reliability Fundamentals and Applications*. Prentice Hall; 1st edition, 1996.
- [18] IEEE Standard 493-1997, Chapter 8: Basic Concepts of Reliability Analysis by Probability Methods.
- [19] S. Elsaiah, M. Benidris, and J. Mitra, "An analytical approach for placement and sizing of distributed generators on power distribution system," *IET Generation, Transmission, and Distribution*, Vol. 8, No. 6, pp. 1039 - 1049, June 2014.
- [20] S. Elsaiah, M. Benidris, and J. Mitra, "Fast economic power dispatch method for power system planning studies," *IET Generation, Transmission, and Distribution*, Vol. 9, No. 5, pp. 417 - 426, April 2015.
- [21] J. Mitra and C. Singh, "Incorporating the DC load flow model in the decomposition-simulation method of multi-Area reliability evaluation," *IEEE Trans. on Power Systems*, Vol. 11, No. 3, pp. 1245–1254, Aug. 1996.
- [22] Graph Matrices. Available online at: <http://www.com-palg.inf.elte.hu/tony/Oktatas/TDK/FINAL/Chap.2010.PDF>.
- [23] R. Diestel, *Graph Theory*. Elec. Ed Springer-Verlag New York: 2000.
- [24] J. Kennedy and R. Eberhart, "Particle swarm optimization," *IEEE International Conference on Neural Networks*, pp. 1942-1948, 1995.
- [25] J. Kennedy and R. Eberhart, "A Discrete binary version of the particle swarm algorithm," *IEEE International Conference on Computational Cybernetics and Simulation*, pp. 4104-4108, 1997.
- [26] *IEEE Standard for Interconnecting Distributed Resources with Electric Power systems*, IEEE Std., 1547-2003, pp. 1–16.