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Implementation of Boolean PSO for Service Restoration Using Distribution Network Reconfiguration Simultaneously With Distributed Energy Resources and Capacitor Banks

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Abstract: Power system faces great challenges as it is liable to extreme stress conditions leading to its instability. Therefore, it is essential to keep the system stability and the islanded area energized to avoid complete blackout. This paper proposes a new application based on the integration of the Boolean algebra and particle swarm optimization (PSO) in binary space for service restoration of islanded sections of the distribution system. The goal is to explore the positive role of the reconfiguration strategy, the distributed energy resources (DERs) and the capacitor banks (C-Bs) on the stability, reliability and power losses of the distribution networks. Moreover, the work presented herein refers to the possibility of continuously supplying the loads especially under islanding conditions after disconnection from the external grid. Different scenarios depending on the system operating conditions, normal or contingency, are studied with the objective of improving the system voltage stability index (VSI) taking into consideration different operating constraints. Typical IEEE distribution systems consisting of 33 and 69 buses are simulated and the simulation results show the validation and resilience of the proposed approach compared with other existing methods.

Keywords: Boolean PSO, Capacitor banks, Distributed energy resources, Feeder reconfiguration, Voltage stability index

1. Introduction

Distribution networks are generally structured in a mesh arrangement but operated in the radial configuration for effective co-ordination of their protective schemes and reduction of the fault level. Reconfiguration of the radial distribution system (RDS) is a very effective and efficient means to improve system voltage stability, reduce distribution network losses and enhance system reliability. All earlier attempts differ from each other in the way of optimal problem formulation and the employed solution techniques. Most of works published in the existing literature seek to reduce real power losses in distribution network, balance load distribution, improve voltage profile and restore service [1-4]. Extensive research work has been carried out in the area of reconfiguration of RDS based on different techniques. J. Moshtagh [5] suggested non-dominated sorting genetic algorithm II (NSGA-II) in order to solve the multi-objective problems in distribution systems reconfiguration. An efficient hybrid evolutionary algorithm based on PSO and honey bee mating optimization (DPSO-HBMO) algorithms was introduced to solve the distribution network reconfiguration (DNR) problem [6]. DNR method considering data uncertainties (NR) was introduced in [7]. In addition, imperialist competitive algorithm (ICA) [8], artificial bee colony (ABC) [9], harmony search algorithm (HAS) [10], and self-adaptive modified clonal search algorithm (SAMCSA) [11] were presented.

Meanwhile, the integration of the distributed energy resources (DERs) monitor and control in distribution networks [12] has a great impact on voltage stability improvement, system losses reduction, system load ability and resiliency enhancement [13]. The combination of renewable energy and energy storage, DERs, is deemed as an opportunity to better take advantage of the intermittent and unpredictable local generation in distribution systems, especially in the case of islanding [14]. However, the DERs are required to equip with reactive power devices such as capacitor banks (C-Bs) to provide reactive power as well as to control the voltage at their terminal bus.

GA [15], particle swarm optimization (PSO) [16], moth swarm algorithm (MSA) [17], and cuckoo search algorithm (CSA) [18] were studied for solving the C-Bs allocation problem. The proposed PSO has also been applied on the IEEE 33 and IEEE 118-bus systems with different penetration levels of DERs in [19]. Several proposed algorithms are applied for solving the DNR and DER allocation optimization problems [20] and the DNR and C-Bs allocation [21]. Many researchers have a great effort in determining the optimal allocations of the DER and C-Bs [22]. In [23], the authors presented three improved forms of GA, PSO, and cat swarm optimization (CSO) algorithms to efficiently solve the problem of simultaneous allocation of C-Bs and DERs in RDSs with considering load variations. A hybrid ICA/GA method has been suggested with objective function of minimizing power losses, enhancing buses voltage, improving VSI, transmission and distribution relief capacity for both utilities and customers, and load balancing [24].

Most of the published work had considered DER, C-Bs allocations and DNR as independent problems or studied two of them simultaneously. The main purpose of this work is to explore the positive role of the reconfiguration strategy, the DERs and the C-Bs on the stability, reliability and power loss of the distribution networks using a new optimization technique based on Boolean PSO. This should guarantee the continuity of supplying the loads, without loss of generality under islanding conditions after disconnection from the external grid. Different scenarios are formulated to find out the best alternative. Two standard test systems are utilized in order to validate the proposed method. The main contribution of this work can briefly be summarized as:

1- A new optimization technique based on Boolean PSO for service restoration of islanded sections of the distribution system is applied.
2- The DNR problem is optimally solved via the proposed technique with an objective of maximizing the VSI taking into consideration different constraints.
3- Optimal allocation of DERs and C-Bs strengthen the efficiency of distribution system.
4- The economic and reliability benefits of the DNR with installing DERs and C-Bs simultaneously are investigated.
5- Different scenarios depending on the system operating conditions, normal or contingency, are studied.

The last sections of this paper are organized as follows. Section 2 describes the Boolean PSO approach. Section 3 reports the problem formulation details of the reliability assessment and economic calculations. Section 4 shows the results of cases studied of distribution network. The last section contains concluding remarks.

2. The Boolean PSO

The PSO is considered as a one of the artificial intelligent optimization methods inspired by nature. The PSO has been successfully applied to optimize various continuous function optimization problems [25]. However, it is not designed for discrete function optimization problems. The Boolean PSO is a new binary version of the PSO. As in PSO, the Boolean PSO launches a random number of particles of population. Each particle changes its searching area based on two best values "P_{best} and G_{best}" in each iteration. When P_{best} and G_{best} are obtained, a particle updates its velocity and hence its position. Based on Eq. (1) and Eq. (2), the algorithm will check the results every iteration until the best solution is found or terminate conditions are satisfied.

$$v_{id}^{new} = w.v_{id} + c_1.(P_{best} \oplus x_{id}) + c_2 .(G_{best} \oplus x_{id}) \quad (1)$$

$$x_{id}^{new} = x_{id} \oplus v_{id}^{new} \quad (2)$$

where, v_{id}^{new}: The new value of the particle speed, i is the particle number and d is the selected search space number;
x_{id}^{new} : The new value of the particle position;
P_{best} & G_{best} : The best quantities of individual local and global search for each particle.
c_1, c_2 & w : The acceleration and inertia coefficients represented as binary bits stochastically set from the system parameters.
$(\cdot), (+)$ & $(\oplus)$: The "AND", "*OR*", and "*XOR*" operators, respectively.

3. Problem formulation

3.1 Objective Function

The objective function, Eq. (3), is to maximize the VSI in the RDS while satisfying both system equality and inequality constraints.

$$Maximizing \quad OF = \max\,(VSI_i) \quad (3)$$

$$VSI_i = V_i^4 - 4 \times V_i^2 \times \left(PC_i \times R_{ij} + QC_i \times X_{ij}\right) - 4 \times \left(PC_i \times X_{ij} - QC_i \times XR_{ij}\right)^2 \quad (4)$$

where, R_{ij} *and* X_{ij}: The line resistance and reactance between bus i and j in per unit;
V_i : The sending bus voltage in per unit;

PC_i *and* QC_i : The total power transfers from bus i to bus j (load bus).

3.2 Constraints

The objective function has to be maximized subject to the following constraints

- *Active power losses:* The implementation of the traditional methods such as Newton-Raphson technique, fails to meet the required analysis of the radial system network due to its topology and characteristic. Therefore, the algorithm of radial load flow analysis (RLFA) is used to analyze the power flow in the tested IEEE RDSs. The detailed description of the algorithm is introduced in [26]. To calculate the losses Eq. (5), the current flow through all the branches of the system should be known by solving the RLFA.

$$P_{loss} \le \sum_{i=1}^{N_{line}} R_i \times LSC_i^2 \qquad (5)$$

where the LSC_i and R_i are the section current and resistance for line *i*.

- *Reconfiguration* constraint: The feasible topology structure for the system should be radial under normal conditions and it shouldn't include any islanded systems.

$$g \in G \qquad (6)$$

where g is the topology structure after reconfiguration and G represents the set of all feasible topology structures.

- *Bus voltage constraint:* The bus voltage magnitude at each bus must be maintained within the following range:

$$V_{min} \le |V_i| \le V_{max} \qquad (7)$$

where, V_{max} and V_{min} are the maximum and minimum values of voltages and their values are taken as 1.05 and 0.95 p.u., respectively.

- *Thermal constraint:* The current follow through line should not be more than the thermal limit of the line, and it can be given as:

$$\mathrm{I_i} \le \mathrm{I_i^{max}} \qquad (8)$$

The $\mathrm{I_i^{max}}$ is the maximum current design to pass in line i

- *Active and reactive power generation of DERs*

$$P_{DER}^{min} \le P_{DER} \le P_{DER}^{max} \qquad (9)$$

$$Q_{DER}^{min} \le Q_{DER} \le Q_{DER}^{max} \qquad (10)$$

where, P_{DG} and Q_{DG} are the active and reactive powers generated from the installed DER, respectively.

- *Power balance for DERs connection*

$$P_s + \sum_{i=1}^{N} P_{DERi} = P_D + P_{loss} \qquad (11)$$

where, N is the total number of DERs, P_s is the feeder power, and P_D is the load power.

3.3 System Reliability Enhancement

From the perspective of reliability enhancement, some utilities prefer to reduce the expected energy not supplied (EENS). The EENS can be quantified as:

$$EENS = \sum_{i=1}^{n} T_i \times P_{a,i} \qquad (12)$$

where $P_{a,i}$: The average load connected at bus i,
T_i : The annual outage time (AOT).

The AOT of bus i can be calculated with equipment parameters as:

$$T_i = \sum_{K=1}^{m} \lambda_k \times \gamma_k \qquad (13)$$

where m: The total number of equipment at bus i.
λ: The annual equipment failure rate.
γ: The average repair time.
k: The kth equipment at bus i.

3.4 Economic Calculation

It is assumed that the failure rate of a component is 0.2 f/km. yr, the lateral section between two buses is 1.5 km and the feeder section between two buses is 2.0 km. In addition, the repair time of a component is 4 h for a branch in main feeder section and 2 h for laterals. The proposed ratings used for studying the simulated systems in this work are in [27-28].

4. Simulation Results

In order to evaluate the effectiveness and satisfactory performance of the proposed method, the 33 and 69-buses IEEE RDSs are used [26]. Two different scenarios are studied in order to explore the impact of the DNR, DERs and C-Bs on the performance of IEEE RDS. These are

Scenario I: Network reconfiguration has been established only without adding DER units or C-Bs.
Scenario II: The optimal installation of DERs concomitantly with C-Bs is performed based on the optimal configured system of *Scenario I.*

The implementation is based on two strategies:

Strategy #1: Credible contingency (normal load demand)
Strategy #2: Non-credible contingency (faults effect)

During normal operation, the system is able to detect variations in the load demand at each node of the network (Strategy #1) and adopts the required operation criteria. Also, during the fault time (Strategy #2) the system will be able to secure the continuous service simultaneously after the protection systems isolate the fault. Based on the fault location, the system can classify the isolated line into three cases.

Case 1: If the isolated faulted line can be replaced by more than one tie line to secure the continuous feeding to the isolated branches, it is called (multi option lines).
Case 2: If the isolated faulted line can be replaced by only one tie line to secure the continuous feeding to the isolated branches, it is called (single option line)
Case 3: If the isolated faulted line can't be replaced by any tie line, the service will be discontinued for the isolated branches. This case called (*critical line)*.

4.1 Scenario I

The distribution system consists of numerous sectionalizing and tie-switches. The system designed to operate in radial configure, based on the presented objective function in equation (3), the reconfiguration process is to change the on/off status of distribution feeder switches under some conditions to transfer the loads from one line to an adjacent line.

The Boolean PSO based on MATLAB program is applied for solving the DNR problem on the IEEE-33 and 69-bus systems. Both systems have five tie switches, therefore five particles are selected. The dimension of each particle is obtained by assuming that each of these particles is closed making a loop and, hence all lines closing this loop become a visible solution for this particle. The number of iterations to reach the optimal solution equals 50. Fig. 1 shows the flow chart of the Boolean PSO.

- *Strategy #1*

Figure 2 shows the system configuration after applying the strategy #1 while table1 illustrates comparison results of the IEEE 33 & 69-bus systems before and after reconfiguration. The results before the configuration are taken from applying the RLFA to calculate the VSI. It is remarked that the system voltage profile is improved, where the minimum bus voltage (V_{min}) is raised from 0.9131 to 0.9378 p. u and from 0.9092 to 0.9428 p.u for the IEEE 33 & 69- bus systems, respectively. The minimum VSI is increased as shown in fig. 3 (a) and (b). Moreover, the system power loss is reduced by 31.16% and 55.72% as shown in fig 4 (a) and (b).

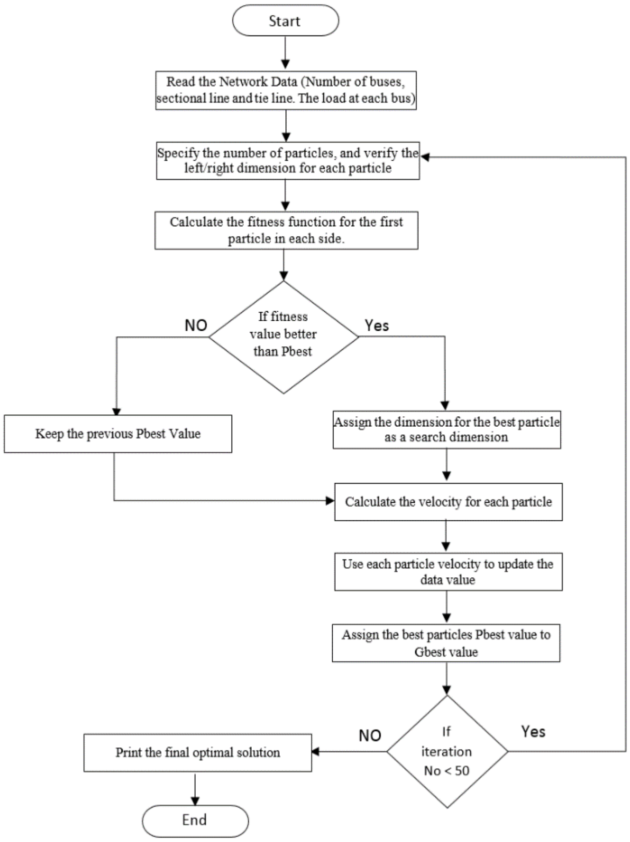
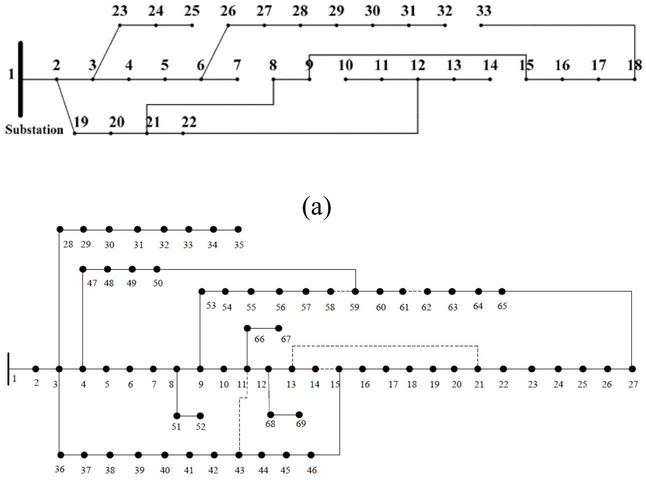


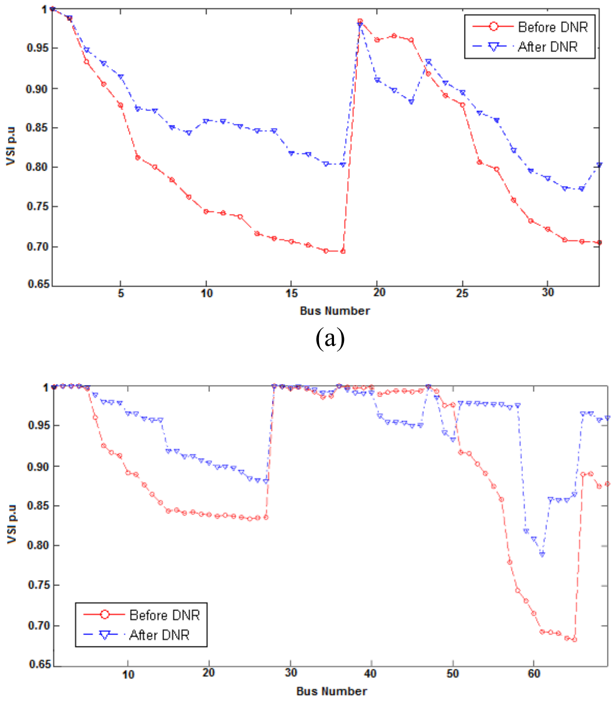
Fig. 1. The Boolean PSO flowchart



(a)

(b)

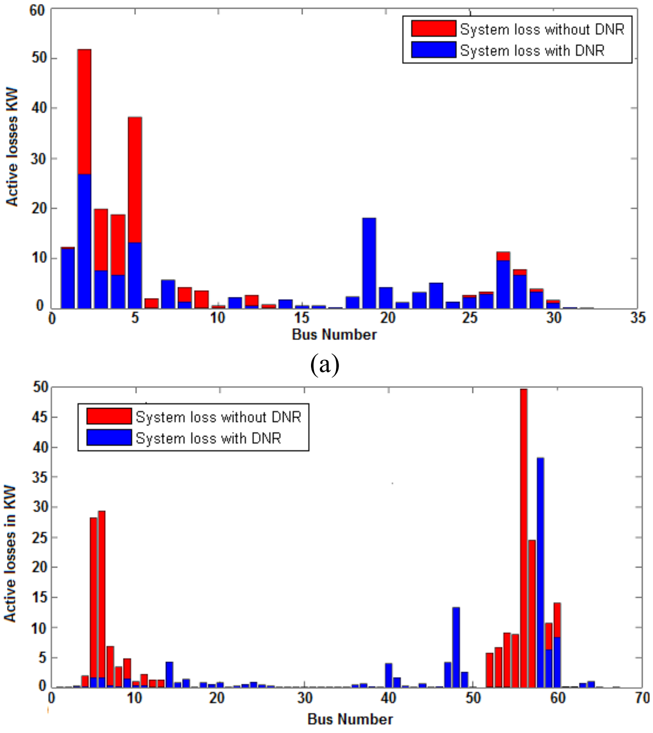
Fig. 2. The IEEE 33 & 69-bus systems after reconfiguration. (a) IEEE 33-bus, (b) IEEE 69-bus



(a)

(b)

Fig.3. The VSI profile (*strategy #1* of *Scenario I*)
(a) IEEE 33-bus, (b) IEEE 69-bus



(a)

(b)

Fig. 4. The active and reactive losses (*strategy #1* of *Scenario I*)
(a) IEEE 33-bus system, (b) IEEE 69-bus system

To ensure the validity of Boolean PSO algorithm, a comparison with other optimization methods is given in tables 2 and 3. Table 2 shows the comparison with DPSO-HBMO [6], NR [7], ICA [8], ABC [9], and HAS [10] methods for 33-bus system. On the other hand, the comparison with other optimization methods; NSGA-II [5], NR [7], ICA [8], and SAMCSA [11] are presented and summarized in table 3 for the 69-bus system. From tables 2 and 3, it is shown that the proposed method gives more accurate results as it gives a reduction of the total power loss compared with other techniques.

➢ *Strategy #2*

In this case, the implementation of system reconfiguration is represented as a solution of the contingency problem to make the system more reliable. The EENS is used as a typical quantity to evaluate the distribution network reliability. Its value can be determined according to the location of the fault branch. To secure the continuous service after isolating the faulted branch, the load buses can be segregated according to system structure into three levels as mentioned before. Assuming that all tie lines in the system are closed making a mesh structure network and checking all lines in the network. If the faulty line belongs to more than one loop, the continuous supply will not be affected by isolating this line and the DNR algorithm has more solutions to get the optimal one and close the corresponding tie line simultaneously (*case 1*). In case if faulty line belongs to only one loop, there will be only one option solution that is to isolate the faulted line and feed the isolated branches from another side in the loop (*case 2)*. In case if the faulty line does not belong to any loop, there will be discontinuity of supply and this case is undesirable (*case 3)*. As shown in Fig. 5 (a) & (b) the gray color represents the multi-option lines, the yellow color performs the single option lines and the red color tackles the critical lines in the tested IEEE 33 & 69-bus systems.

To ensure the effectiveness of the proposed method, a random line is selected from each type to be isolated and then, Boolean PSO algorithm is implemented to solve the DNR problem. Table 4 lists the line number of each type and the selected test lines. Based on the basic configuration, the simulation results of applying the three cases are listed in table 5 which shows the ability of the system to maintain a continuous supply in the first and second cases but it fails to maintain the required supply in the last case.

Table 1. Simulation results of the IEEE 33 & 69-bus systems after reconfiguration

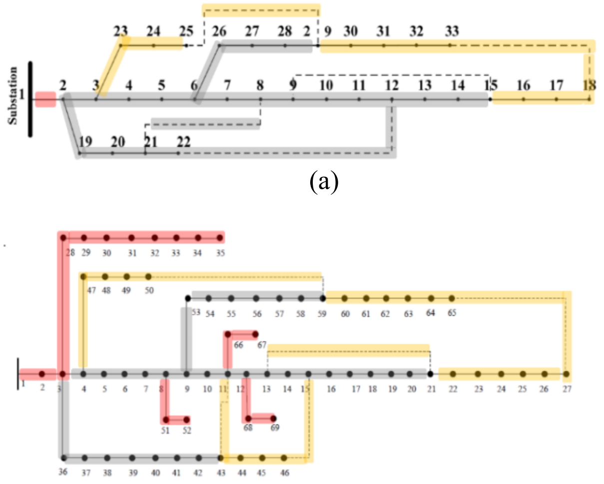
	IEEE 33-bus system		IEEE 69-bus system	
	Basic System	System after Reconfigure	Basic System	System after Reconfigure
VSI_{min} @ Bus no	0.6941 p.u @ Bus 18	0.7728 @ B18	0.6829 @ B65	0.7895 @ B61
Line number opened tie switch	33 – 34 – 35 – 36 – 37	37 – 7 – 9 – 32 – 14	69 – 70 – 71 – 72 – 73	61 – 14 – 58 – 69 – 70
Total active power losses	202.68 kW	139.51 kW	224.93 kW	99.59 kW
Active power reduction	***	31.11%	***	55.72 %
Total reactive power losses	135.18 kvar	102.305 kvar	102.13 kvar	114.66 kvar
V_{min} @ Bus no	0.9131 p.u @ Bus 18	0.9378 p.u @ B18	0.9092 @ B65	0.9428 @ B61

Table 2. Comparison results of different optimization techniques (33-bus system)

Case	V_{min} (p.u) @bus No	Tie Switch	P_{loss} (kW)	% Loss Reduction	Q_{loss} (kvar)
Basic system	0.9133 @ B18	33 – 34 – 35 – 36 – 37	202.52	----	135.13
Boolean –PSO	0.9378 @ B18	37 – 7 – 9 – 32 – 14	139.51	31.11%	102.305
DPSO-HBMO	0.9378 @ ----	7 – 9 – 14 – 32 – 37	139.53	31.10%	---
NR method	0.9416 @ B32	9 – 28 – 32 – 14 – 7	140.00	30.92%	104.09
ICA	0.9378 @ B18	7 – 9 – 14 – 32 – 37	139.53	31.10%	---
ABC method	0.9378 @ ----	7 – 9 – 14 – 32 – 37	139.53	31.10%	---
HAS	0.9335 @ ----	7 – 10 – 14 – 36 – 37	142.67	29.67 %	---

Table 3. Comparison results of different optimization techniques (69-bus system)

Case	V_{min} (p.u) @bus No	Tie Switch	P_{loss} (kW)	% Loss Reduction	Q_{loss} (kvar)
Basic System	0.9092 @ B65	69 – 70 – 71 – 72 – 73	224.931	----	102.133
Boolean –PSO	0.9428 @ B61	61 – 14 – 58 – 69 – 70	99.594	55.72%	114.666
NSGA-II	0.9378 @ B61	61 – 69 – 58 – 13 – 12	99.911	55.57%	---
NR Method	0.9406 @ B61	13 – 21 – 46 – 53 – 67	102.54	54.41%	---
ICA	0.9428 @ B61	69 – 13 – 14 – 50 – 47	99.62	55.70 %	---
SAMCSA	0.9428 @ B61	69 – 13 – 14 – 50 – 47	99.62	55.70 %	---



(a)

(b)

Fig. 5. Colored segregated based on line type
(a) IEEE 33-bus, (b) IEEE 69-bus

From the results, it is also shown in *Case 1* the proposed method has the ability to obtain the optimal solution as it has different solution choices, while *Case 2* has only a single solution. The impact of the system reconfiguration on the reliability enhancement is listed in table 6. It is seen that the EENS is reduced to 6315.5 and 70032 kWh/yr for the IEEE 33 and 69- bus systems, respectively after reconfiguration. In addition, the cost of EENS is decreased to 31072 and 344557.4 ($/yr) for the two networks

4.2 Scenario II

The main objectives of the DNR are voltage stability enhancement and real power loss reduction. However, the reconfiguration method can only perform this up to a certain point. Meanwhile, further improvement for voltage stability can be realized via the optimal installation of DERs concurrently with C-Bs. Therefore, simultaneous network reconfiguration and optimal placement of DERs and C-Bs units are proposed in this scenario. The Boolean PSO technique is used to determine the optimal allocations of the DER and C-Bs required for maximizing the VSI, where the Boolean PSO finds out their locations and the PSO determines their capacities.

In this scenario, the optimal reconfiguration problem is formulated without installing DERs or C-Bs (*Scenario I)*. Then, the optimal allocations of the DERs concurrently with the C-Bs are performed based on the optimal configured system.

➢ *Strategy #1*

Figs. 6-8 and table 7 depict the simulation results for IEEE 33 and 69-bus systems. It is shown that the system VSI has increased from 0.7728 p.u to 0.9763 p.u after adding five DERs and five C-Bs for the IEEE 33-bus system. The corresponding value has improved from 0.7895 p.u to 0.9874 p.u. after installing four DERs and four C-Bs for the 69-bus system. Moreover, there is a reduction of the system active and reactive power losses and the voltage profile is improved.

The annual net saving of the optimal system configuration without DERs and C-Bs are 35399.16 $/yr. and 65878.704 $/yr. for the IEEE 33 and 69-bus systems, respectively as shown in table 8. After performing the optimal allocations of the DERs and C-Bs, these values become 102039.984 $/yr and 116882.92, respectively. In spite of cost of the DERs & C-Bs for the two networks of 1166832 $/yr & 13600 $/yr and 1163328 $/yr & 12230 $/yr, respectively, there are annual net savings of 671855.984$/yr. (32.62 %) and 686316.92 $/yr. (32.51 %), respectively.

Table 4. System line segregation according to system structure

System	IEEE 33-bus system		IEEE 69-bus system	
	Line number	Test line	Line number	Test line
Multi- option line	2:14,18:21, 25:28, 33:35	9	3:20, 35:42, 52:58	58
Single-option line	15:17,22:24, 29:32,36,37	17	21:26, 43:49, 59:64	62
Critical line	1	1	1, 2, 27:34, 50, 51, 65:68	27

Table 5. The DNR result after subjecting the system to different fault cases (s*trategy #2 of scenario I*)

	IEEE 33-bus system			IEEE 69-bus system		
	Case #1	Case #2	Case #3	Case #1	Case #2	Case#3
Fault line	9	17	1	58	62	1
VSI_{min} @ Bus no	0.7728 @ B18	0.7392 @ B18	0	0.7895 @ B61	0.7851 @ Bus 61	0
Line number (opened tie switch)	37 – 7 – 9 – 32 – 14	37 – 7 – 9 – 17 – 14	Fail	61 – 14 – 58 – 69 – 70	62 – 14 – 58 – 69 – 70	Fail
Total active power losses	139.51 kW	147.55 kW	***	99.59 kW	100.65 kW	***
Active power reduction	31.11%	31.11%	***	55.72 %	55.13 %	***
Total reactive power losses	102.305 kvar	104.99 kvar	***	114.66 kvar	116.78 kvar	***
V_{min} @ Bus no	0.9378 @ B18	0.9275 @ B18	0	0.9428 @ B61	0.9414 @ Bus 62	0

Table 6. The reliability enhancement result for the tested IEEE 33 &69-bus systems (s*trategy #2 of scenario I*)

	IEEE 33-bus system		IEEE 69-bus system	
	Basic System	After Reconfiguration	Basic System	After Reconfiguration
EENS (kWh/yr)	45934	6315.5	79116	70032
Cost of EENS ($/yr)	225995.28	31072	389249	344557.4

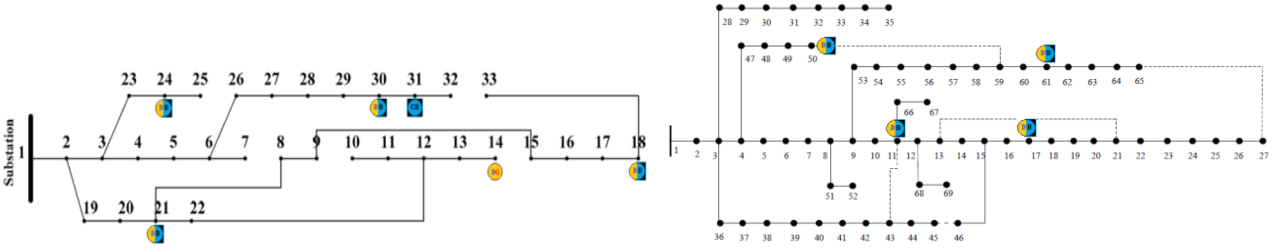


Fig. 6. The optimal locations of DERs and C-Bs to the configured system

(a)The IEEE 33-bus system, (b)The IEEE 69-bus system

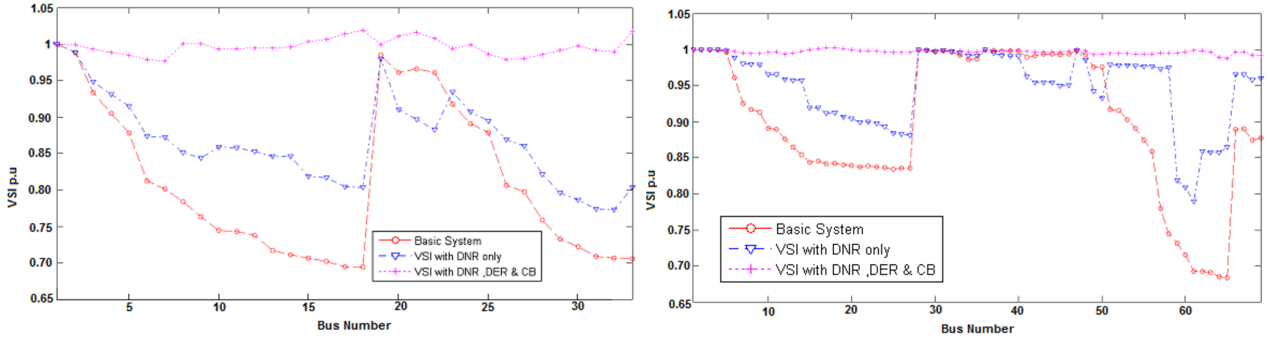
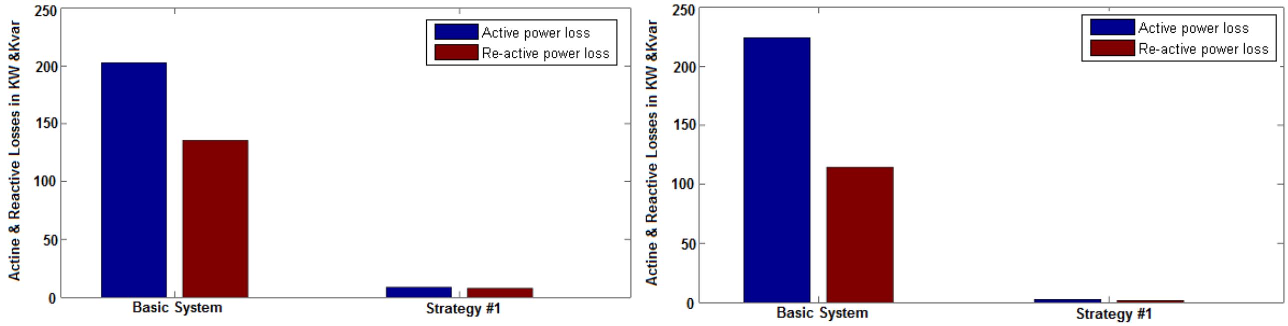


Fig. 7. The system results of *strategy #1* of *scenario II* (a) The IEEE 33-bus, (b) The IEEE 69-bus



(a) (b)

Fig. 8. Active and reactive power loss (a) The IEEE 33-bus system (b) The IEEE 69-bus system

The impact of the DNR with the implementation of DERs and C-Bs on the reliability enhancement is very effective where it is shown that the merging of both methods covers all lines in the case of contingency condition making the EENS zero with percentage saving of 100% for the IEEE 33-bus system. The corresponding value for the IEEE 69-bus system equals 2274.024 with a saving of 99.06% as shown in table 9.

- ➢ *Strategy #2*

The effectiveness of proposed approach during fault condition is studied considering *Scenario II*. A random line is selected from each type to be isolated. Tables 10 and 11 illustrate the results of the proposed approach for the IEEE 33 & 69-bus systems with the three cases.

From the results of table 10, it is shown for example that in *case 1*, after optimal allocations of the DERs and C-Bs to the configured system via the Boolean PSO and by tripping line 9 for the IEEE 33-bus system, the voltage profile is improved. The minimum VSI is increased from 0.7728 to 0.9892 p. u. The system power loss is reduced by 95.72%. Moreover, the results depict the ability of the proposed method to obtain the optimal solution for the three cases. The same remarks can be concluded from the results of the IEEE 69- bus system, table 11, where, the minimum VSI is increased from 0.7895 to 0.9879 p. u. The system power loss is reduced by 98.83%.

Compared with the results of the original case, the integration of the DNR with the DERs and C-Bs enables the system to maintain a continuous supply in the three different cases.

5. Conclusions

A new application of Boolean PSO is tackled in this work with the objective of maximizing the VSI taking into consideration different equality and inequality constraints. The new idea for selecting the particle number and each particle dimension succeeded to simplify the DNR, DERs and C-Bs allocations problem. Firstly, the switching operation plan for feeder reconfiguration has been optimally identified. Then the DERs and C-Bs are optimally allocated simultaneously after network reconfiguration. Different strategies are proposed depending on the system operating conditions, normal or contingency, of the distribution system. It has been proven that, combining the DNR, with DERs and C-Bs has a great impact to improve the VSI, losses, and reliability of the system with a net saving around 33%. The proposed technique is capable to manage the distribution system in abnormal conditions like islanding and separation from the external grid with a net saving around 99%.

Table 7. Results of solving DERs and C-Bs problem based on optimal configuration of the IEEE 33 & 69-bus systems (*strategy #1* of *scenario II*)

	IEEE 33-bus system		IEEE 69-bus system	
	Basic System	Final Result	Basic System	Final Result
Tie No	37 – 7 – 9 – 32 – 14	37 – 7 – 9 – 32 – 14	61 – 14 – 58 – 69 – 70	45 – 73 – 72 – 69 – 70
Connected DERS. (#bus, Size kW)	--	(#30, 930) (#21,700) (#24,1040) (#18,380) (#14,280)	0	(#61, 1680) (#17,460) (#50, 720) (#11,460)
Total DERs installed Active Power	0	3.33 MW	0	3.32 MW
Connected C-Bs. (#bus, Size kvar)	--	(#30,600) (#21,600) (#31,300) (#24,450) (#18,150)	0	(#61, 1200) (#17,300) (#50, 300) (#11,150)
Total C-Bs installed reactive power	0	2.10 kvar	0	1.95 kvar
Total system Losses Active / Reactive Power	139.51 kW / 102.3 kvar	8.72 kW / 7.57 kvar	102.139 kW / 114.66 kvar	2.55 kW / 1.67 kvar
VSI_{min} @ Bus no	0.7728 p.u @ Bus 18	0.9763 p.u @ Bus 7	0.7895 p.u @ Bus 61	0.9874 p.u @ Bus 65
System Bus Voltage V_{min} @ Bus no	0.9378 p.u @ Bus 18	0.9940 p.u @ Bus 7	0.9428 p.u @ Bus 61	0.9968 p.u @ Bus 65

Table 8. Economic results after connecting DERs with C-Bs on the reconfigured IEEE 33 &69-bus systems (*strategy #1* of *scenario II*)

	IEEE 33-bus system		IEEE 69-bus system	
Economic Indices	DNR Only	DNR + DERs+ C-Bs	DNR Only	DNR + DERs+ C-Bs
Saving cost due to energy loss reduction ($/yr)	35399.16	102039.984	65878.704	116882.92
Saving cost due to demand energy reduction($/yr)	0	1750248	0	1744992
Compensation cost ($/yr) using DERs	0	1166832	0	1163328
Compensation cost ($/yr) Using C-Bs	0	13600	0	12230
Net saving ($/yr)	35399.16	671855.984	65878.704	686316.92
% Net saving (%)	1.72%	32.62 %	3.07%	32.51 %

Table 9. Reliability enhancement results of adding DERs with C-Bs in addition to appling DNR to IEEE 33 & 69-Bus systems (*strategy #1* of *scenario II*)

	IEEE 33-bus system		IEEE 69-bus system	
	Basic System	DNR& (DERs+C-Bs)	Basic System	DNR& (DERs+C-Bs)
Total Energy	49450	0	49450	462.2
EENS (kWh/yr)	79116	0	79116	2274.024
Cost of EENS ($/yr)	389249	0	389249	3638.4384
Saving of EENS ($/yr)	---	100.0%	---	99.06%

Table10. Comparison of the contingency cases in case of DNR only and DNR with (DERs and C-Bs) for IEEE 33-bus system (*strategy #2* of *scenario II*)

Case 1: Trip line No.9	DNR only	DNR and (DERs with C-Bs)
VSImin @ Bus no	0.7728 @ B18	0.9892 @ B10
Opened Tie Switch	37 – 7 – 9 – 32 – 14	9 – 33 – 35 – 36 – 37

Active Power Losses	139.51 kW	8.683 kW
DERs Size	--	(#6, 1100) (#25, 795) (#16, 500) (#31, 650)
C-Bs Size	---	(#30, 1050) (#13, 300) (#25, 150) (#23, 300)
Vmin @ Bus no	0.9378 p.u @ B18	0. 9575 p.u @ B10
Case 2: Trip line No.17	DNR only	DNR and (DERs with C-Bs)
VSImin @ Bus no	0.7392 @ B18	0.9763 @ B22
Opened Tie Switch	37 – 7 – 9 – 17 – 14	17 – 33 – 35 – 34 – 37
Active Power Losses	147.55 kW	7.3416 kW
DERs Size	--	(#6, 1100) (#25, 750) (#16, 450) (#31, 750)
C-Bs Size	---	(#30, 1050) (#13, 300) (#25, 300) (#23, 300)
Vmin @ Bus no	0.9275 p.u @ B18	0. 9941 p.u @ B22
Case 3: Trip line No.1	DNR only	DNR and (DERs with C-Bs)
VSImin @ Bus no	0	0.9503 @ B22
Opened Tie Switch	Fail	36 – 33 – 35 – 34 – 37
Active Power Losses	***	7.3416 kW
DERs Size	--	(#6, 1600) (#25, 110) (#16, 400) (#31, 750)
C-Bs Size	---	(#30, 1050) (#13, 300) (#25, 300) (#23, 450)
Vmin @ Bus no	0	0. 9874 p.u @ B22

Table 11. Comparison of the contingency cases in case of DNR only and DNR with (DERs and C-Bs) for IEEE 69-bus system (*strategy #2* of *scenario II*)

Case 1: Trip line No.58	DNR only	DNR and (DERs with C-Bs)
VSImin @ Bus no	0.7895 @ B61	0.9879 @ B65
Opened Tie Switch	61 – 14 – 58 – 69 – 70	71 – 73 – 58 – 69 – 70
Active Power Losses	99.59 kW	2.614 kw
DERs Size	---	(#61, 1680) (#17, 500) (#50, 700) (#11, 360)
C-Bs Size	---	(#61, 1200) (#17, 300) (#50, 300) (#11, 150)
Vmin @ Bus no	0.9428 @ B61	0. 9970 p.u @ B65
Case 2: Trip line No.62	DNR only	DNR and (DERs with C-Bs)
VSImin @ Bus no	0.7851 @ Bus 61	0.9165 @ B64
Opened Tie Switch	62 – 14 – 58 – 69 – 70	71 – 62 – 72 – 69 – 70
Active Power Losses	100.65 kW	11.925 kW
DERs Size	---	(#61, 1680) (#17, 500) (#50, 700) (#11, 360)
C-Bs Size	---	(#61, 1200) (#17, 300) (#50, 300) (#11, 150)
Vmin @ Bus no	0.9414 p.u @ Bus 62	0. 9785 p.u @ B63
Case 3: Trip line No.1	DNR only	DNR and (DERs with C-Bs)
VSImin @ Bus no	0	0.9892 @ B65
Opened Tie Switch	Fail	71 – 73 – 72 – 69 – 70
Active Power Losses	***	2.5835 kW
DERs Size	--	(#61, 1680) (#17, 500) (#50, 700) (#11, 360)
C-Bs Size	---	(#61, 1200) (#17, 300) (#50, 300) (#11, 150)
Vmin @ Bus no	0	0. 9892 p.u @ B65

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