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Reliability and Supply Security based Method for Simultaneous Allocation of Sectionalizer Switch and DER Units

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Abstract- *This paper presents a new and useful methodology for simultaneous allocation of sectionalizer switches and distributed energy resources (DERs) considering both reliability and supply security aspects. The proposed algorithm defines the proper locations of sectionalizer switching devices in radial distribution networks considering the effect of DER units in the presented cost function and other optimization constraints such as providing the maximum number of costumers to be supplied by DER units in islanded distribution systems after possible outages. In this paper, the main goal of cost function is to minimize the total cost of expected energy not supplied (EENS) with regard to impacts of load priority and optimum load shedding in the both grid connected and islanding states after possible outages. The proposed method is simulated and tested on a case study system in both cases of with DER and non DER situations. Also, this paper evaluates the number and amount of DER, switch and different DER penetration percentage effects in cost function value. For solving of mentioned problem, this paper uses a new and strong method based on imperialist competitive algorithm (ICA). Simulation and numerical results show the effectiveness of the proposed algorithm for placement of switch and DER units in the radial distribution network simultaneously.*

Keyword: Optimal switch placement, Optimal DER placement, Reliability assessment, Imperialist competitive algorithm, Supply security aspects.

NOMENCLATURE

SL_i	Total amount of load at the downstream side of switch *i*
NSL_i	Number of load points at the downstream side of switch *i*
Ld_{ki}	Amount of load at *k* th load point at the downstream side of switch *i*
SFL_i	Total amount of load in a section between switch *i* and next switches
NSL_i	Number of switches at the downstream side of switch *i*
a_j	*j* th switch at the downstream side of switch *i*
NSL_{aj}	Number of load points at the downstream side of switch a_j
Ld_{maj}	Amount of load at *m* th load point at the downstream side of switch *aj*
SG_i	Total amount of DER at the downstream side of switch *i* in Mw.
NSG_i	Number of DER sources at the downstream side of switch *i*
Dgk_i	Amount of DER at *k* th point of DER sources at the downstream side of switch *i*
SFG_i	Total amount of DER in a section between switch *i* and next switches
NSG_{aj}	Number of DER sources at the downstream side of the switch *a j*
Dgm_{aj}	Amount of DER at *m* th point of DER sources at the downstream side of switch *aj*
P_{CHP}	Power of CHP unit
α	DER penetration percentage in the network
β	DER penetration percentage in switch zone
p_{LOAD}^{Total}	Total load power
P_{PV}	Power of PV unit
P_{WIND}	Power of Wind unit
p	Number of CHP units
k	Number of PV units
n	Number of Wind units
EENS	Expected Energy not supplied
NC	Number of contingencies
NL	Number of load points that are isolated due to contingency j
L_{kj}	Load at load point k due to contingency j

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$P_{DER_{kj}}$ Amount of DER at load point k

pr_{kj} Priority factor at load point k

rj Average outage time of contingency j

λ_j Average failure rate of contingency j

$Cost_{jk}(rj)$ Outage cost ($/MW) of load point k due to outage j with an outage duration of rj

1. INTRODUCTION

Electric power system engineers are facing new challenges for planning and operation of the system due to the recent changes in the distribution networks configuration [1]. The system upgrade deferral, energy and active power loss reduction, distributed energy resources and system reliability improvements are some examples that have motivated utility companies for local connection of renewable energy resources at the distribution level.

The operation and control of distributed energy resources (DER) could also decrees the transferred power on a power system. From viewpoint of generation DER in power system could include combined heat and power (CHP), photovoltaic (PV) and small wind turbines (WT). DER applications could result in high efficiency of energy supply and reduced electricity delivery cost and carbon footprint in a microgrid (MG) [2]. The main issue in determining the site and size of energy resources in optimization problem is about the sitting which plays the main role of economic issues [3-4] and sizing [5-8] of distributed generators.

The improvement of network reliability is the other important effect of DERs on distribution networks. They can reduce and manage the amount of required load shedding, restoration time and amount of interrupted load during and after possible faults [9].

As it is clear, the reliability assessment of distribution system is one of the most important issues of power system planners. Various and flexible operation modes of power system, different output characteristics of DER units, and the various recovery choices of the loads in the local areas, after interruption also complicate the reliability evaluation process.

Implementation of protection and isolation devices such as circuit breakers, reclosers, and remote controlled switches could result in reliability improvement in distribution systems. Sectionalizing switches play an important role in the future of modern distribution networks so that one their application is in the isolation process of the faulted areas when possible faults occur in the system, which results in reduction of customers outages and improved network reliability. It is necessary for system planners to optimize the place of these protection devices according to possible investment and reliability indices [10].

The authors in Ref. [11] considered the impact of uncertainty in generation and load in the reliability analysis of distribution system. Also, Ref. [12] proposed a multi objective cost function that fault cost is modeled as reliability cost. Funds of energy suppliers constrain the possible investment cost of switches in the system and it is not possible to spend more money in the specified fields.

In the real distribution system, the money that will be spent in installing new switches is limited, therefore, the number of installed switches in the network can be found easily. The presented algorithm finds the best locations of the switches and DERs in the network for a specified number of switches and DERs according to the reliability assessment and other cost function constraints. Reference [13] reported a multi objective hybrid firefly algorithm and particle swarm optimization (HFAPSO) based algorithm for optimal allocation of distributed generation (DG), capacitor and protective device in radial distribution network simultaneously.

Optimization technique of simulated annealing based method was presented in Ref. [14], which is proposed to optimal selection the number of installable switches and the locations of these switches in distribution networks. Ref. [15] reported a strong and useful method based on Bellmann's optimality principle in the optimal solution of sectionalizer allocation problem in distribution networks in a short period of time.

In Ref. [16], the immune algorithm (IA) is used to achieve the optimal placement of switching devices by lessening the total cost of customer service interruption and investment cost of line switches. Particle swarm optimization (PSO) based procedure is presented to determine the optimum number and sites of two types of switches (sectionalizers and breakers) in radial distribution systems in Ref. [17]. Optimal allocation of remote-controlled switch devices is also a main challenges which is considered in Ref. [18].

In most researches on distribution systems, the effect of distributed generation sources is not totally considered and only a few studies have discussed the effect of DGs in the problem of switch placement. In Ref. [19] switch placement schemes are proposed for system reliability improvement in radial distribution systems with the presence of DG.

Most of works try to find the suitable number and also optimal location of sectionalizer switches in the radial distribution network, result in a huge search space then obtained results may not be the global optimum as can be seen in the results given in Refs. [14] and [17]. The results of mentioned two papers present different number and structure of switches in a same case study system.

Thus, it is important to consider the impacts of DERs and protection devices such as switching devices in the distribution system reliability assessment simutenosly. Finding simultaneously and appropriate locations of switching devices and DER units in distribution networks is the main objective of this paper. Here, a spanning tree and improved ICA based method is employed to solve the presented optimization problem in the concepts of reliability and supply security improvement. Presented algorithm finds the optimum arrangement of switches in the network and the improved ICA is implemented to find the optimal locations of the switches with considering of DER effects.

2. ICA BASED OPTIMIZATION TOOL

The ICA is a useful and very strong algorithm for the solution of optimization problems. Defining the principle of ICA is out of this papers scope and the complete review is given in several papers for instance in Refs. [20] and [21]. In this paper, because of concurrency and complicity of switch and DER placements, special assimilation and revolution operators are designed and modified to guarantee the proper and feasible solutions in ICA. The coding method for simultaneous solving the sub problem is shown in Fig. 1. Each country or solution is a vector.

According to Fig. 1, the vector contains two main sections. The first section includes the candidate switch locations. The length of the first section is equal to number of switches in the network. The three subsections of the second section, define the types of DER units, capacities and places, respectively. At all stages and operators of simulation process with considering of all constraints, the credit of solution vector is evaluated and if it is necessary the process or part of process will be repeated. The flowchart of solving problem algorithm with modified ICA is illustrated in Fig. 2 graphically.

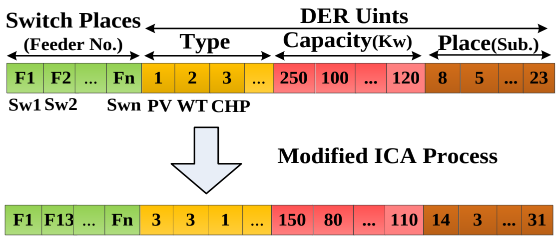

Fig. 1. Design of proposed and modified ICA operators.

3. OPTIMAL SWITCH PLACEMENT

After evaluation process of exist network structure, sectionalizing switches due to security and reliability issues must be placed on the candidate feeders.

The switch graph contains the information as below:

$$SL_i = \sum_{k=1}^{NSL_i} Ld_{ki} \tag{1}$$

$$SFL_i = SL_i - \sum_{j=1}^{NS_i} \sum_{m=1}^{NSL_{a_j}} Ld_{ma_j} \tag{2}$$

$$SG_i = \sum_{k=1}^{NSG_i} Dg_{ki} \tag{3}$$

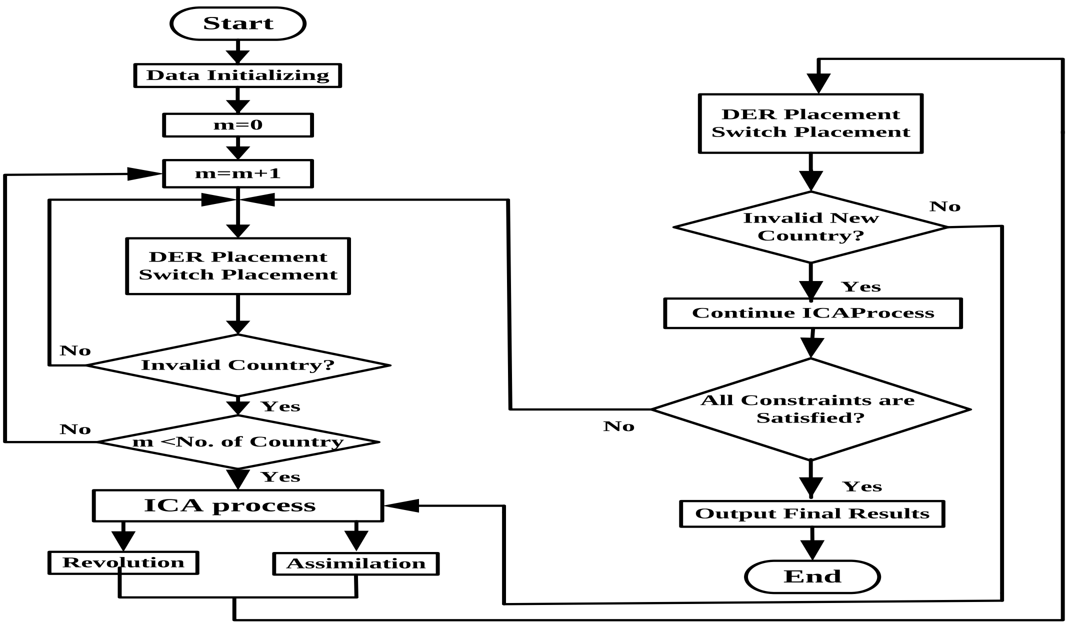

Fig. 2. Flowchart of implementation of modified ICA

Then a very important evaluation step indicates by having DERs in the designed distribution system. For every switch in the population, if amount of DER in zone of specified switch is not zero then $SFG_i \geq \beta SFL$ must be satisfied due to reliability, supply security and islanding aspects, otherwise the solution vector is not valid because in this case DER supported islands in the switch zones cannot be formed in possible faults optimally. If β is one or more than one, the self-healing mode will be performed and this is the ultimate goal of future distribution network. Briefly, the proposed method tries to select the optimal structure of active distribution grid and put the proposed switches in the places with considering of load priorities and network constraints. In this condition, after occurring of possible faults and finding the fault locations, the appropriate switch is opened so that the main feeder or DERs in self-supported islands can supply the maximum amount of loads in each switch zone in the system.

4. OPTIMAL DER PLACEMENT

In this section, depending on size of switch zone, MV substations priority and all constraints, optimal DER placement with the aim of objective function will be performed. Note that the previous analysis is not intended to be used for choosing the best locations for the installation of DER. For this research, a typical combination of three types of DER units is assumed; namely, WT, PV modules and CHP generators. It is assumed that the maximum rated powers of the WT and PV modules are 2.5Mw, whereas the total rated powers of the CHP generators follow from Eq. (5). It is noted, regardless of mentioned issues, in the network there is at least one CHP resource due to the security constraint, urbanity, high efficiency or other aspects of the system under study. Number and amount of all DERs are related to loads of switch zones, DER penetration percentage and MV substations load and priority. In the network, all resources will try to place on the buses with higher priority. Thus the cost function value will be reduced and in the possible events, load shedding can be optimized. It is essential to note that the substation priority is an index which determines the actual priority of each load and is considered in the cost function. All resources are working together to supply the DER penetration percentage that predetermined in the network. In this study DER penetration percentage is assumed α% of total loads of network. Here, priority factors are given to loads where the priority factor is 2 for small user loads, 3 for residential loads, and 4 for commercial load types. The constraints and numbers of DER types in the network are obtained as follows:

$$\sum_{l=1}^{p} P_{CHP} = \left(\frac{\alpha}{100}\right) p_{LOAD}^{Total} - \sum_{i=1}^{k} P_{PV} - \sum_{j=1}^{n} P_{WIND} \tag{5}$$

$$P_{WIND} \leq P_{WIND}^{Max} \tag{6}$$

$$P_{PV} \leq P_{PV}^{Max} \tag{7}$$

$$SFG_i \geq \beta SFL \tag{8}$$

5. PROPOSED COST FUNCTION

Because the mentioned two problems process is simultaneous, hence slight change in one of problems makes a major change in the objective function. So that the objective function for all problems most calculated at the same time. After performing all the problems and their constraints objective function is calculated. If even the solution vector in one step is not valid, all stages will be repeated from the beginning then the related cost can be calculated. The mathematical description of all problems for reliability improvement in smart distribution networks is presented. The yearly cost function with considering proposed EENS index is defined by Eq. (9) which must be minimized and the ICA is applied to minimize the objective function. Noticed that again, the constraints of objective function are the constraints of subproblems that mentioned earlier.

$$EENS = \sum_{j=1}^{NC}\sum_{k=1}^{NL}\left(L_{kj} - P_{DER_{kj}}\right).pr_{kj}.Cost_{kj}\left(rj\right).\lambda_j\left(\frac{\$}{year}\right) \tag{9}$$

6. SIMULATION AND NUMERICAL RESULTS

In this section, proposed algorithm is applied on the test system in its initial condition and simulation results of two subproblems, namely optimal switch placement and optimal DER placement are presented in detail. Average outage cost is assumed 10000($/MW). It should be noted that because of the concurrency of subproblems, the following problem constraints, play a significant role besides the previous problem and cost function constraints. In Table 1 the initial data of system substations is provided. $S_{NO.}$ stands for substation number, S_{Load} is the load value of substations, S_{pr} is the substation priority, S_X and S_y are coordinates of substation in cartesian coordinate. Line data of test system is provided in Table 2 where the start bus, end bus, failure rate and the length of each line section are determined. Bus no. 1 is the main bus which is connected to HV substation and the system has an initial circuit breaker at the start of line no. 1.

In order to demonstrate that the presented algorithm can be suitable method for solving optimal placement of

DERs and switches, a large distribution grid with feeders will be adapted for testing. This is a much more complicated case and requires more computational efforts. There are 30 substations that the first substation is the main HV substation and 29 MV substations from number 2–30 with different standard capacities. Due to achieve the best result of simultaneous allocation of DER and switch, three scenarios are proposed along with an extra reference scenario for comparison, which prepared in Table 3. It is mentioned again that in the all scenarios DER penetration percentage is equal. First, the best locations for switches in test system are determined for the case there is no DER in the system for four installable switches in the network. In this situation, after occurring of possible outages and finding the fault location among all feeders, the situation of proper switches are changed to open so that the maximum number of MV substations can be supplied by the main grid and there is no alternative supply or DER to form self-supported islands in the system.

The algorithm is applied on the system while there are limited numbers of installable sectionalizer switches according to limitation of capital costs and the algorithm is converged to its final state and finds the optimal location of sectionalizer switches in the network to minimize or optimize the system EENS index and increase the reliability aspects.

Then the same scenario is considered while there are 3 DER units. Mentioned DER units are located in the system buses according to Table 3 then the optimal allocation process for switches is achieved in the simultaneous process.

Table 1. Substations Data.

S_{No}	S_x	$S_{y.}$	S_{pr}	S_{load}(Mw)	S_{No}	S_x	$S_{y.}$	S_{pr}	S_{load}(Mw)
1	2400	1200	0	0	16	2875	625	2	0.90
2	2150	1150	1	0.20	17	2980	410	3	0.80
3	1840	912	1	0.11	18	1250	700	1	0.40
4	1450	750	3	0.60	19	625	1225	1	0.20
5	1600	1000	1	0.15	20	1000	1450	3	0.20
6	1250	1050	1	0.20	21	225	1815	1	0.60
7	2400	400	1	0.50	22	800	625	2	0.50
8	2200	750	3	0.55	23	400	725	2	0.80
9	2850	1310	3	0.75	24	825	1725	3	0.50
10	2600	1600	3	0.66	25	1500	1650	1	0.70
11	1330	500	1	0.30	26	1800	1840	2	0.60
12	1000	220	1	0.30	27	1200	1820	4	0.50
13	1825	115	1	0.50	28	2000	1420	1	0.50
14	2550	330	1	0.90	29	2450	1800	1	0.58
15	2825	925	3	0.80	30	2150	1950	4	0.40

Table 2. Line Data

Feeder No.	Line Length(km)	From Bus	To Bus	Failure Rate (per km)	Feeder No.	Line Length(km)	From Bus	To Bus	Failure Rate (per km)
1	0.2800	1	2	0.1000	16	0.2350	16	17	0.1200
2	0.3500	2	3	0.1500	17	0.2000	11	18	0.0500
3	0.4000	3	4	0.2000	18	0.7000	18	19	0.3500
4	0.2700	4	5	0.1000	19	0.4200	19	20	0.2000
5	0.3600	5	6	0.1500	20	0.8200	20	21	0.3500
6	0.9000	5	7	0.2500	21	0.3500	21	22	0.2000
7	0.4300	7	8	0.2500	22	0.4000	22	23	0.1500
8	0.8000	8	9	0.3500	23	0.3900	20	24	0.1500
9	0.4100	9	10	0.3500	24	0.6750	24	25	0.3000
10	1.1000	7	11	0.4500	25	0.3650	25	26	0.1500
11	0.3800	11	12	0.2000	26	0.6000	26	27	0.3000
12	0.5400	11	13	0.3000	27	0.5600	25	28	0.3000
13	0.7800	13	14	0.3000	28	0.5800	28	29	0.3000
14	0.7500	14	15	0.4000	29	0.330	29	30	0.1500
15	0.3500	15	16	0.1600					

Table 3. Allocation scenarios for the case studies.

Scenario No.	Definition
Scenario 1	Switch placement without any DER unit.
Scenario 2	Switch placement with three fixed DER units.
Scenario 3	Simultaneous DER and switch allocation; maximum three DERs can be selected

The routes of MV feeders and structure of test system are illustrated in Fig. 3. Presented algorithm is applied on the mentioned test system while there are 4 switches that can be installed in the network and the result of 1st scenario is illustrated in Fig. 4. The obtained optimal locations of switches in 1st scenario show the effect of load priority, failure rate of feeders and other constraints on the final result. The presented algorithm tries to put the obtained switch places on the feeders where the buses have the higher priority so the isolation of these buses during possible outages at other parts of the system, can be performed by applying switching tactics.

In the second scenario, when a fault occurs in the system and fault location is determined, the proper switches are opened so that the maximum number of MV substations can be supported by the main feeder and the distributed generator in DER supported island of the system. Figure 5 shows the optimal locations for 4 switches based on predetermined DER locations and capacities.

Finally, because of importance of DER locations in optimal solving of switch placement problem, both of mentioned placements have been solved simultaneously. The used method pretends to find the best places of switches in the distribution network so this kind of islands can be formed in the network and the maximum number of MV substations can be supplied by the DER units, considering all constraints such as load priority factor and supply security related aspects.

In this state there are still 4 installable switches in the system and the presented algorithm finds the best locations for installing these switches on the network considering the changes in DER unit locations and amounts. It is noted again that DER penetration percentage in the second and third scenarios is the same and equal to 50% of total network loads (7.35MW) Fig. 6 shows the result of optimal switch and DER placements in the third scenario.

The results of all scenarios are presented in Tables 4 and 5 in more detail. It can be inferred from Table 4 that DERs have a considerable effect on optimal switch placement and cost function value. Locations of switches in the network are dependent to the locations of DERs. The reliability indices such as EENS are also affected while considering DER in distribution systems. Placing the switches in proper places in networks according to the locations of DERs decreases the EENS cost of the system and then reliability and supply security aspects for all load points are improved. It can be seen from Table 5 that the limit of DER penetration percentage is satisfied in all switch zones that DER units are available. Not that because of network structure and other conditions such as supply security aspects, in the zone of 4th switch of scenario 2 self healing or autonomous mode is formed. In this case after any possible faults, DER unit in bus 10 can be supported all of loads in the islanded zone (self healing mode).

It can be inferred from Fig. 5 that considering the impact of DER unit in the solution method has an important effect on finding the best locations for installing switches in radial distribution networks. Because of switch places in this case, system can be formed as an islanded zone after possible outages that happen in all parts of network.

For more explanation, if a fault occurs on line 10 the obtained optimal switch places allow the loads at buses 8-10 to survive in an islanded DER units supported system and this assists to improve the system reliability and supplying maximum number of loads by main feeder or the DER source. In other words, when an outage occurs in the system the fault location is detected and isolated from other parts of network such that maximum number of loads can be provided by the main grid. Besides, the system tries to supply the maximum possible number of substations in three DER supported zones without exceeding the power generation limit of DER units and other constraints. The results of 3rd scenario demonstrate the complexity of problem while there are three DER units in the test system. The presence and allocation of DER units, force the algorithm to configure the switches such that the DER supported zones can be formed after possible faults in the radial distribution network. Based on Fig. 6 the optimal configuration of switches in this network allows the network to form predetermined value of islanded DER supported distribution system after any possible faults in all parts of system. It can be seen from this figure, if any fault occurs in the system, buses 18-23 can create an island which consists of 7 load points and 1 WT in bus no. 27.

In the islanded zones the important loads can be supplied by their DER units. This methodology has a considerable result on distribution system reliability improving and EENS cost, respectively. As shown in Fig. 6, different kinds of DER units are distributed over the system substations and more concentrated close to the larger and higher priority loads (due to constraints, reliability and supply security aspects in the possible outage). This is clearly visible in the Fig. 6 and Table 4, since the 15th, 20th and 27th substations have the highest priority among the related loads in switch zones, in the optimization process DERs are located in these substations. By doing this, cost function can be minimized and optimal load shedding among the substations with a lower priority is performed. The optimal rates of the DER units are presented in Table 4.

According to the results of Table 5, optimal DERs in the all possible islanded zones, supply at least the predetermined minimum value in islanding mode. Rated value of DER units depends on load values of each switch zone, cost function constraints and before mentioned the minimum value of DER penetration percentage. Finally, to show the effectiveness of the proposed algorithm, the trajectory of best solution and convergence of cost function for the test system in 3 scenarios are shown in Fig. 7. It is necessary to guarantee effectiveness of the global optimum solution; therefore, the simulation process is repeated so many times with different probability of ICA operators. In all of the running cases the observed results of the optimization problem are the same considering minimum of 80 iterations. Comparison of results between scenarios 2 and 3 show the worth and feasibility of the proposed method in simultaneous allocation of DERs and switches in the radial distribution network. As it seen from Fig. 8, cost function values after 6 switches are almost the same in the scenario 3. Also this Fig. shows the impact of DER penetration percentage in cost function values with respect to the number of switches. As shown in Fig. 9, the number of DER units after 5^{th} DER is ineffective in the cost function value in the constant DER penetration rate.

7. CONCLUSIONS

In this paper reliability and supply security based optimal and simultaneous allocation of section-alizing switch and DER units are proposed and presented in the presence of possible faults and various constraints. The modified ICA is applied to minimize the proposed EENS based cost function as an optimization algorithm.

Table 4. Result of scenarios.

Scenario	EENS ($/year)	Switch locations (line No.)	DERs			
			Location(Bus)	Sub. Priority	Type	Capacity(Mw)
Scenario 1	69024	1-17-12-7	-	-	-	-
Scenario 2	56195	1-18-12-7	23-10-17	2-3-3	CHP	2.5-2.35-2.5
Scenario 3	53472	1-23-17-12	20-15-27	2-2-2	WT-PV-CHP	2.1-2-3.25

Table 5. Result of scenarios related to each switch zone.

Scenario No.	Switch No.	Switch Location	Sum of Loads(Mw)	DERs(Mw)	DER Penetration (%)
2	1	1	2.76	0	0
	2	18	6.08	2.5	41.1
	3	12	3.9	2.5	64.1
	4	7	1.96	2.35	**Self-Healing**
3	1	1	4.32	0	0
	2	23	3.78	2.1	55.5
	3	17	2.7	2	74.07
	4	12	3.9	3.25	83.33

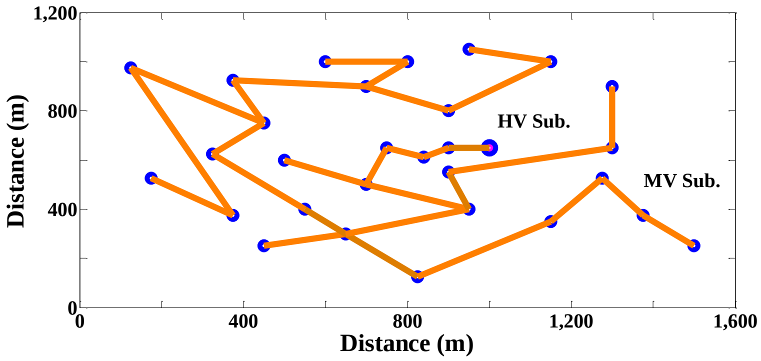

Fig. 3. Case study system structure.

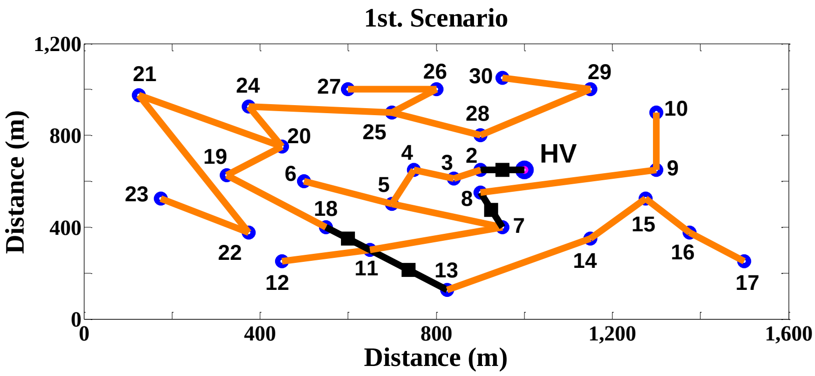

Fig. 4. Optimal switch placement in scenario 1.

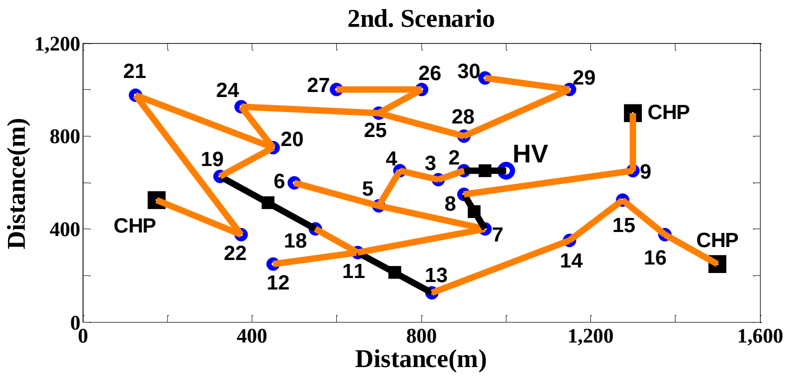

Fig. 5. Optimal configuration of switches in scenario 2.

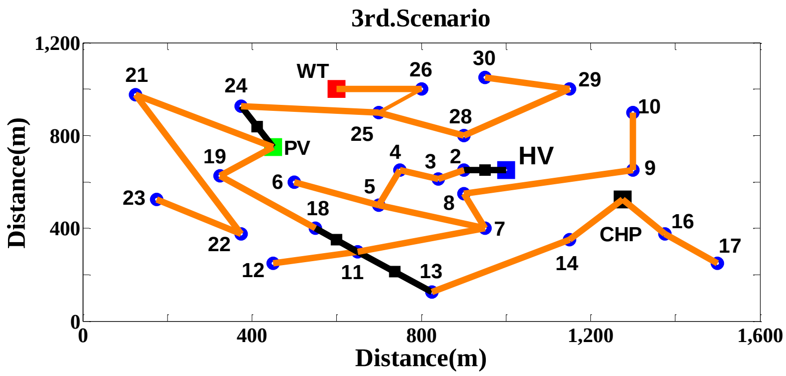

Fig. 6. Optimal places of switches and DERs in scenario 3.

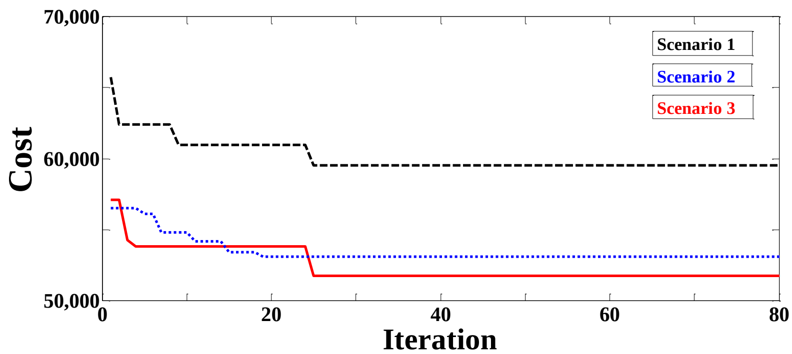

Fig. 7. The convergence of cost function for the test system in 3 scenarios.

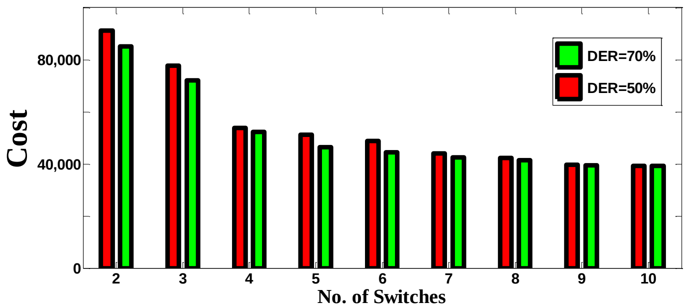

Fig. 8. Cost function values in different number of switches and DER penetration ratio in scenario 3.

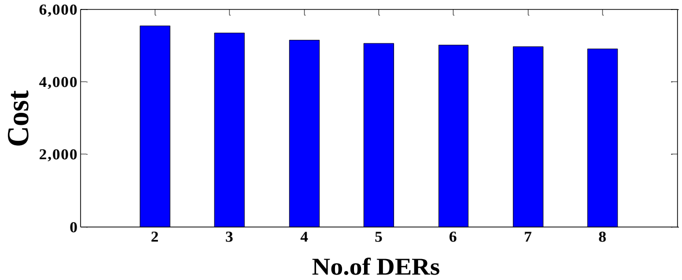

Fig. 9. Cost function values regard to number of DERs in scenario 3.

To avoid infeasible solutions, special assimilation and revolution operators are presented. The proposed new EENS combined with substations priority factor. Results show that simultaneous allocation of switches and DERs is possible to reliability improvement of the power distribution system. This leads to a better manage and operation of system in the presence of faults and other unwanted events.

This leads to a better manage and operation of system in the presence of faults and other unwanted events. Simulation and numerical results show the feasibility of the presented method to improve reliability indices of system. Obtained results show the effects of DER and Switch numbers after specified limit are not especially large in the cost function values.

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