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Optimal Distributed Generation Planning in Radial Distribution Networks Considering Protection Coordination Limits

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Abstract: Distributed generation (DG) has been widely used in distribution network to reduce the energy losses, improve voltage profile and system reliability, etc. The location and capacity of DG units can influence on probability of protection mal-operation in distribution networks. In this paper, a novel model for DG planning is proposed to find the optimum DG location and sizing in radial distribution networks. The main purpose of the suggested model is to minimize the total cost including DG investment and operation costs. The operation costs include the cost of energy loss, the cost of protection coordination and also the mal-operation cost. The proposed DG planning model is implemented in MATLAB programming environment integrated with Digsilent software. The simulation results conducted on the standard 38-bus radial distribution network confirm the necessity of incorporating the protection coordination limits in the DG planning problem. Additionally, a sensitivity analysis has been carried out to illustrate the significance of considering these limits.

Keywords: Distributed Generation, Optimal Placement and Sizing, Protection System Coordination, Radial Distribution System.

Nomenclature

A. Indices

i	Index of feeder sections.
j	Index of protective devices.
k	Index of fault types.
l	Index of load levels.
n	Index of DG units.
b	Index of buses.
p	Index of sections associated with the protection zone.

B. Constants

N_{DG}	Total number of DG units.
U_{DG}	Unavailability of DG units.
m	Life cycle of DG units [yr].

IR	Rate of interest.
N_S	Number of feeder sections (i.e. main + lateral parts) of distribution system.
N_{CL}	Numbers of main protective devices operate for near bus fault.
N_{Far}	Numbers of main protective devices operate for far bus fault.
N_{ll}	Number of load levels.
$\lambda_{j,p}$	Failure rate of distribution feeder located in p th part of the main protection zone pertaining to the j th protective device [f/yr/km].
r_p	Repair time [hrs].
p_k^{SC}	Probability of occurrence of k th fault type.
$C_{inv.}$	DG investment cost [\$/MW].
C_{OM}	DG O&M cost [\$/MWh].
$C_{prot.}$	Replacement/resetting cost of each protective devices [\$/].
K_{EENS}	Value of lost load (VOLL) [\$/MWh].

C. Variables

V_b	Voltage of b th buses.
V_b^{max}	Maximum allowable voltage of the buses.
V_b^{min}	Minimum allowable voltage of the buses.

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P_{DG}	Installed capacity of all DG units.
$P_{substation}$	Maximum injected power to the network from upstream substation.
gp	DG penetration coefficient.
C_{EL}	Cost of energy losses [\$].
C_{DG}	Total DG costs including investment and O&M costs.
C_{DG}^{inv}	Total DG investment cost at the first year [\$].
C_{DG}^{OM}	Total DG operation and maintenance (O&M) cost [\$].
IC_n	Installation capacity of n^{th} DG unit [MW].
E_{DG}^n	Annual energy generated by of n^{th} DG unit [MWh].
P_{ll}^{loss}	Power loss in load level ll [MW].
C_{EENS}	Cost of unsupplied energy occurred due to the mal-operation of protective devices [\$].
$I_{i,ll}$	Current flow passing through the i^{th} feeder section at load level ll [kA].
I_i^{max}	Maximum allowable current of the i^{th} feeder section
R_i	Resistance of the i^{th} feeder section [Ω].
EEL	Annual expected energy losses [MWh].
T_{ll}	Time duration of the load level ll [hrs].
K_{ll}^E	Electrical energy price in load level ll [\$/MWh].
T_j^{Close}	Breaking time of the j^{th} main protective device for the case of near bus fault [sec].
T_j^{Far}	Breaking time of the j^{th} main protective device for the case of far bus fault [sec].
$ENS_{j,p}$	Energy not supplied in case of fault occurrence at the end of p^{th} part of the main protection zone pertaining to the j^{th} protective device [MWh].
$L_{j,p}$	Lost load in the case of fault occurrence at the end of p^{th} part of the main protection zone pertaining to the j^{th} protective device [MW].
$P_{j,p}^{sc}$	Probability of fault occurrence in p^{th} part of the main protection zone pertaining to the j^{th} protective device.
$l_{j,p}$	Length of p^{th} part of the main protection zone pertaining to the j^{th} protective device [km].

1 Introduction

UTILIZATION of distributed generation (DG) brings economic, environmental and technical advantages for distribution networks [1,2]. However, all the mentioned advantages mainly depend on DG location and sizing in the distribution network. In recent research works, the numerous studies including diverse optimization models and constraints have been proposed for optimal DG planning (i.e. location and sizing) in distribution networks. In [3,4], power loss reduction and voltage profile improvement are taken into account as the objectives of DG placement. The presented problems of [3,4] are solved via genetic algorithm (GA). At the same context, in [5], the optimal DG placement is formulated as a non-linear optimization problem with

the purpose of reduction in network losses as well as increasing the voltage stability margin. Reliability improvement and power loss reduction are taken into account as the objectives of DG allocation problem in [6], which is solved by particle swarm optimization (PSO) algorithm. Additionally, the optimal placement and sizing of DG is accomplished in [7] to minimize the network power loss.

A modified shuffled frog leaping algorithm is utilized in [8] for solving the optimal DG placement considering the objectives of loss reduction and voltage profile improvement. Also, a DG planning model with the aim of reduction in network losses is proposed in [9], which is solved by artificial bee colony (ABC) algorithm. Furthermore, a new optimization model and solution approach for optimal DG placement based on cost/benefit analysis is presented in [10]. The proposed planning model of [10] considers the technical and economical issues such as energy losses, reliability indices of load points, DG costs and portability. Moreover, loss reduction, voltage profile improvement, environmental issues, DG installation and operation costs are among the heterogeneous objectives considered in the DG allocation problem of [11,12]. In [13], an optimization model for placement of dispatchable and non-dispatchable renewable DGs is suggested to minimize the annual energy loss.

Despite the potential benefits of DG, the location and capacity of DG units may bring serious challenges for mal-operation of the protective devices in distribution networks. The setting of the protection devices is generally performed based on the maximum and minimum currents passing through them in both normal and short circuit conditions. Accordingly, the DG operation in distribution network can make severe changes in both of mentioned currents leading to mal-operation of protection devices namely blinding, missing the coordination and so on.

Generally speaking, from mathematical viewpoint, the coordination of protective devices can be regarded as an optimization problem. The associated constraints of such problem include several equality and inequality equations based on the main and backup protective devices. Therefore, the chief objective associated with the coordination of the protective devices is minimizing the summation of operating time pertaining to all main and backup protective devices for all fault locations. As the proposed optimization model considers the entire protective devices simultaneously, the occurrence of mal-operation of protective devices for some types of fault and/or some fault locations is potentially possible. These mal-operations cause unnecessary load shedding leading to increase the system's energy-not-supplied (ENS) and so escalating the reliability cost based on value of lost load (VOLL) [14].

The probability of protection mal-operation depends on DG location and its capacity. In previous studies concerning the DG placement, the impact of DG on

mal-operation of protective devices is not taken into account. In this paper, a novel optimization model for DG planning problem is proposed. The objective function of the presented model consist of DG investment cost and associated operation costs including protection coordination and mal-operation costs as well as the cost of energy losses. To best of authors' knowledge, the protection coordination and mal-operation costs have not been taken into consideration in the previous research works in the area of DG planning problems, and it is specific to this paper.

The rest of this paper is organized as follows: Section 2 presents a brief review of protection problems raised due to operation of DG in distribution networks. The mathematical formulation of the proposed DG planning model and its solution approach are presented in section 3. Section 4 encompasses the numerical results obtained by application of the suggested model on a standard radial distribution network. Sensitivity analysis is performed in section 5 to demonstrate the impacts of variation in effective parameters on the cost of DG planning problem. Finally, section 6 concludes the paper.

2 Protection Issues in Presence of DG

Accurate operation of protective devices has a great role in reliable electricity service in distribution system. However, despite the elegant benefits of DG, it can cause some problems such as harmonics, voltage flicker, voltage profile distortion and increase in short circuit level [15]. Also, high penetration of DG in distribution networks may raise some difficulties for appropriate operation of the protective devices.

DG installation in distribution networks mainly changes the radial configuration of distribution network leading to alteration in short circuit capacity of DG-equipped buses. Thus, the mentioned issues should be significantly taken into account in setting and coordination of protective devices [16]. The most common problems created for correct operation of protective devices caused by DG, can be classified to protection blinding, incorrect tripping, improper reclosing, islanding and increase in short circuit level [17].

3 Mathematical Formulation

The objective function of the proposed DG planning problem, denoted by OF, is presented as follows:

$$\text{Min } OF = [C_{EL} + C_{DG} + C_{Prot.} + C_{EENS}] \quad (1)$$

3.1 Cost of Energy Loss

Three-level load duration curve (LDC) is extensively used in recent papers in the area of distribution system planning [18-20]. In this paper, three-level LDC, as depicted in Fig. 1, is used for simulation.

To calculate the annual expected energy loss for each candidate configuration of DG units, the power loss should be calculated for each load level of LDC as below:

$$P_{ll}^{loss} = \sum_{i=1}^{N_s} |I_{i,ll}|^2 \times R_i \quad (2)$$

On the other hand, the annual expected energy loss of the network is calculated based on (3):

$$EEL = \sum_{ll=1}^{N_{ll}} \left[P_{ll}^{loss} \times \frac{T_{ll}}{8760} \right] \quad (3)$$

Accordingly, the annual cost of energy loss for the distribution system can be represented as below:

$$C_{EL} = \sum_{ll=1}^{N_{ll}} \left[P_{ll}^{loss} \times \frac{T_{ll}}{8760} \times K_{ll}^E \right] \quad (4)$$

3.2 Cost of DG Units

The total costs associated with DG units can be represented as follows:

$$C_{DG} = C_{DG}^{inv} + C_{DG}^{OM} \quad (5)$$

It is noted that although the investment cost of each DG unit is spent at the beginning of the planning horizon (one year in this paper), this cost should be amortized throughout the life cycle of DG unit regarding to the interest rate. Thus, according to one year planning horizon, only a portion of the total investment cost should be taken into account as follows [20]:

$$C_{DG}^{inv} = \frac{IR \times (1 + IR)^m}{(1 + IR)^m - 1} \left[\sum_{n=1}^{N_{DG}} (C_{inv} \times IC_n) \right] \quad (6)$$

DG Operation and maintenance (O&M) cost, i.e. the cost paid for fuel, labor costs, cost of spare parts and etc., is commonly taken as a function of electric energy generated by DG unit, as mathematically shown by (7):

$$C_{DG}^{OM} = \sum_{n=1}^{N_{DG}} (C_{OM} \times E_{DG}^n) \quad (7)$$

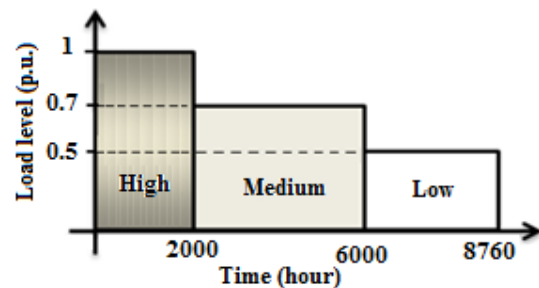


Fig. 1 Annual load duration curve.

3.3 Cost of Protective Devices Replacement/Resetting

At first, the coordination program should be carried out for the network without DG to find the rated current and also settings of the protective devices in the base case. The objective function for optimal coordination is formulated as below [21]:

$$\text{Min} \left\{ T = \sum_{j=1}^{N_{CL}} T_j^{Close} + \sum_{j=1}^{N_{Far}} T_j^{Far} \right\} \quad (8)$$

For each configuration of DG units in distribution network, the coordination program is separately executed to find the proper rated current and settings of protective devices. Regarding to the base case, if replace/reset of a protective device within the coordination program execution is required, an extra cost is added to the objective function value (i.e. OF). This extra cost comprises the cost of purchasing and installing the new protective devices, cost of scheduled load shedding, and the associated labor cost.

3.4 Cost of Energy Interruption

As previously described, it is needed to coordinate the protective devices after installing DG units in distribution network. However, the mal-operation of protection system is still probable leading to unnecessary load shedding. Furthermore, as the setting of the protective devices is not changed for the outage of one or more DG units, the probability of protection mal-operation would be increased in this case.

The mal-operation of protection system, resulting unnecessary load shedding, increases the ENS (energy not supplied) value of the system and consequently decreases the profit of distribution companies (DISCOs).

In this work, to calculate the cost of energy interruption, single-contingency criterion is taken into consideration. In other words, for each proposed DG configuration including NDG units installed in distribution network, (NDG+1) different cases should be studied; one case when all DG units are in service and NDG other cases are when one DG unit is out of service and other (NDG - 1) DG units are in service.

The short circuit study should be distinctly carried out for every above-mentioned case to obtain the probable area of missing the protection coordination. To do so, the main protection zone of each protective device is divided into 10 sub-sections. If the protection area includes a section of the main feeder together with some lateral branches, both main and lateral parts are divided into 10 sections. At the end of each sub-section, the short circuit analysis is performed for all fault types to calculate the ENS value for each part of the feeder as follows:

$$ENS_{j,p} = L_{j,p} \times r_p \quad (9)$$

In this study, the average load of each load point is utilized for ENS calculation. For each load point, this value is assumed to be 0.705 of the peak load pertaining to that load point, based on the Fig. 1.

The probability of each kind of fault is calculated as below:

$$P_{j,p}^{sc} = \lambda_p^{sec} \times I_{j,p} \times P_k^{sc} \quad (10)$$

Based on (10), the expected energy not supplied (EENS) can be mathematically expressed as below:

$$EENS = \sum_j \sum_p ENS_{j,p} \times P_{j,p}^{sc} \quad (11)$$

The EENS calculation method of (11) is separately used for ($N_{DG}+1$) different mentioned cases pertaining to each candidate allocation of DG units'. Accordingly, regarding the unavailability of DG units, the annual EENS can be calculated as follows:

$$EENS_{total} = (1 - U_{DG})^{N_{DG}} \times EENS_{N_{DG}} + U_{DG} \times (1 - U_{DG})^{(N_{DG}-1)} \times \sum_{N_{DG}} EENS_{(N_{DG}-1)} \quad (12)$$

$EENS_{N_{DG}}$ stands for the EENS value when all DG units are in service. Furthermore, $EENS_{(N_{DG}-1)}$ represents the EENS when one DG unit is out of service and the other ($N_{DG}-1$) DG units are in service.

Therefore, the energy interruption cost can be calculated based on (12):

$$C_{EENS} = EENS_{total} \times K_{EENS} \quad (13)$$

3.5 Constraints

The constraints of the suggested model are as below:

$$V_b^{\min} \leq |V_b| \leq V_b^{\max} \quad (14)$$

$$I_{i,ll} \leq I_i^{\max} \quad (15)$$

$$P_{DG} \leq gp \times P_{substation} \quad (16)$$

Constraint (14) confines the voltage magnitudes which should be retained within their secure permissible ranges. Additionally, constraint (15) ensures the power flow passing through every distribution feeder is kept under its own thermal rating (i.e. maximum allowable capacity). Constraint (16) limits the total DG installed capacity, i.e. DG penetration, which should be lower than a predefined (say, gp) percentage of power injected to the network by upstream substation.

If a constraint is violated, the associated penalty is applied. The details of penalty calculation method are reported in [22].

3.6 The Proposed Solution Approach

To solve the proposed DG planning problem, the standard GA is utilized. Different implementation steps of GA can be summarily described through the following step-by-step procedure:

Step 1- Randomly generate the initial population based on input data (i.e. candidate buses for DG placement).

Step 2- Evaluate the fitness value of each individual member based on (1) and then sort them in descending order.

Step 3- Select a set of high-performance members (i.e. members with higher fitness value) and creating new generation using GA crossover operator.

Step 4- Randomly select a set of members and creating a mutant generation using GA mutation operator.

Step 5- Combine the three above generations, i.e. generation of *Steps 2-4*, based on their performance.

Step 6- Eliminate the low-performance members and create the next generation.

Step 7- Check the stopping criterion. If it is not reached, go to *Step 3*; otherwise, report the final result.

The flowchart of the proposed solution approach is shown in Fig. 2.

As shown in Fig. 2, the flowchart is divided into two parts. The upper part surrounded by a solid rectangle is a part of the program that is performed in MATLAB programming environment. In this part, construction of the initial and next generations of GA, sorting the individual members regarding their fitness value and checking the stopping criterion is performed. Additionally, the lower part surrounded by a dotted line rectangle is another part of the program that is executed within the DigSilent software. In this part, the operational procedure related to the planning framework including load flow, protective devices coordination, checking the technical limits as well as calculation of objective function value (*OF*) is performed.

4 Numerical Study

In this section, to illustrate the necessity of incorporating the protection coordination limits into the DG allocation problem, the proposed model is applied on a distribution test system and the obtained results are discussed.

4.1 38-Bus Distribution Test System

The test system considered for simulation of proposed DG allocation problem is a standard 38-bus radial distribution network, depicted in Fig. 3 [23].

For the sake of simplicity, it is assumed that the DG installation in six buses (buses 5 and 34-38) is feasible, as shown in Fig. 2. Without loss of the generality, it is noted that this assumption does not restrict the

capability of the suggested DG planning model.

The protective devices of the 38-bus test system consist of one circuit breaker equipped with over current (O/C) relay, one recloser and four fuses, as schematically demonstrated in Fig. 3. The O/C relay is a normally inverse type, and its pick up current is set to 1.5 times of the maximum load current. Very inverse and normally inverse curves are used as the instantaneous and delayed characteristic of the recloser, respectively. Finally, the DG units are assumed to be synchronous-type generators operating under unity power factor [24].

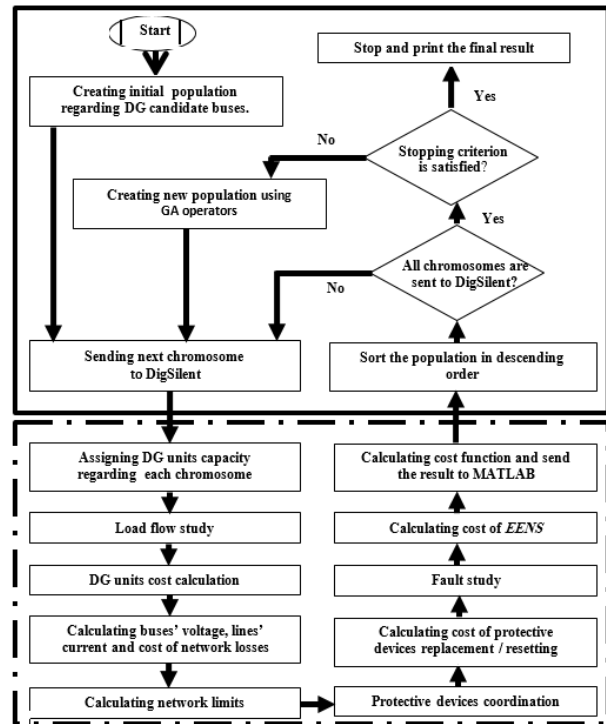


Fig. 2 Flowchart of proposed algorithm.

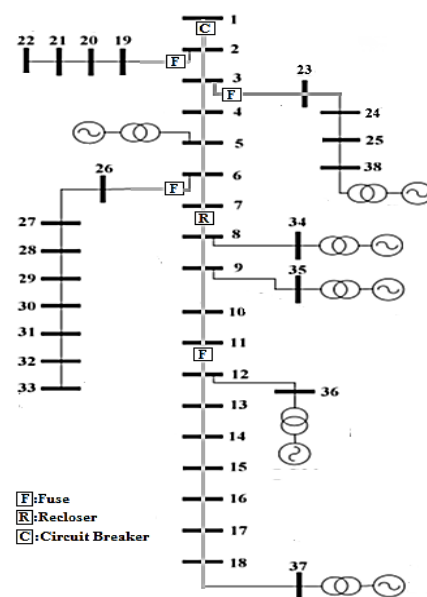


Fig. 3 Single line diagram of the 38-bus distribution network.

4.2 Simulation Data

The candidate capacities of DG are selected between 0 to 2 MVA with the discrete step of 100 kVA. The unavailability of DG units is considered to be 0.12.

The failure rate of every section pertaining to the main feeder and lateral branches is selected as 0.2 and 0.4 f/yr/km, respectively. Also, the repair time for all sections of both main and lateral branches is assumed to be 4 hours. The costs and GA data are presented in Table 1. The associated data pertaining to the protection devices (i.e. rows 5 to 7 of Table 1) are taken from technical documents of Mazandaran Regional Electrical Company's (MAZREC).

Moreover, the occurrence probability of each fault type is presented in Table 2.

The interest rate is considered 3%. Additionally, the stopping criterion is assumed to be satisfied if there is no improvement (i.e. better result with lower OF value) achieved after 50 iterations.

The optimization constraints are presented in Table 3.

4.3 Simulation Results

To show the impact of protection coordination limits on DG placement problem, the simulation results of the two cases, i.e. with and without considering protection coordination limits, are presented in Table 4.

In the case of not considering the protection coordination limits, the replacement/resetting cost of the protective devices and also the cost of energy interruption due to the mal-operation of protective devices, are not included in objective function. Also, the mentioned consideration has not any impact on the decision-making strategy of DG allocation.

The voltage profiles for the base case, i.e. without DG units, and for the best solutions of two simulation cases in the presence of DG units, i.e. with and without considering the protection coordination limits, are depicted in Fig. 4.

As shown in Fig. 4, the voltage magnitude of buses 31-33 is less than 0.95 p.u. in the case of no DG. This event means that the constraint of voltage limit is violated. Additionally, despite the better voltage profile in the case of not considering the protection coordination limits, the voltage magnitudes of network have no violation in none of these two cases.

The numerical value of each component of the total cost, formulated in (1), for the best solution of the proposed DG planning model for two mentioned simulation studies, are presented and compared in Table 5.

The results of Table 5 indicate that considering the protection coordination limits lead to increase in cost of energy losses by 8.19%. Additionally, in this case, the other cost items, i.e. DG costs, replacement/resetting cost of protective devices and EENS cost are decreased by 8.23%, 66.67% and 8.04%, respectively. Moreover, despite the consideration of protection coordination

limits leads to increase in cost of energy loss by 1595.09\$, reduction in other cost items are so impressive that the total cost in the case of considering the protection coordination is obtained 52,386.27 \$. The mentioned total cost is 7.76% less than the total cost in the case of not considering the protection coordination limits. This cost reduction is mainly due to decrease in DG costs and in EENS cost.

Table 1 Data utilized in the simulation [18].

Parameter	Value
K_i^E	70,50,35 [\$/MWh] for $i = 1, 2, 3$
DG Investment cost (C_{inv})	700000 [\$/MW]
DG O&M cost (C_{OM})	40 [\$/MWh]
$VOLL$	1000 [\$/MWh]
Replacement/resetting cost of protective device	120 [\$/device]
Fuse price	150 [\$]
Recloser price	15000 [\$]
Number of GA initial population	100
Crossover probability	0.8
Mutation probability	0.1
Maximum iteration	1000

Table 2 Occurrence probability of each fault type.

Fault type	Occurrence probability
Single line to ground	0.7
Double line	0.15
Double line to ground	0.1
Three phases	0.05

Table 3 Optimization constraints.

Constraint	Limits
Current of feeder section	$ I_{i,l} \leq I_l^{max} $
Bus voltage	$0.95 \text{ pu} \leq V_b \leq 1.05 \text{ pu}$
DG penetration coefficient	$gp = 0.65$

Table 4 Coefficient of cost.

Without considering protection coordination limits		With considering protection coordination limits	
Bus number	DG capacity	Bus number	DG capacity
5	1.3 MW	5	1.6 MW
37	0.4 MW	--	--

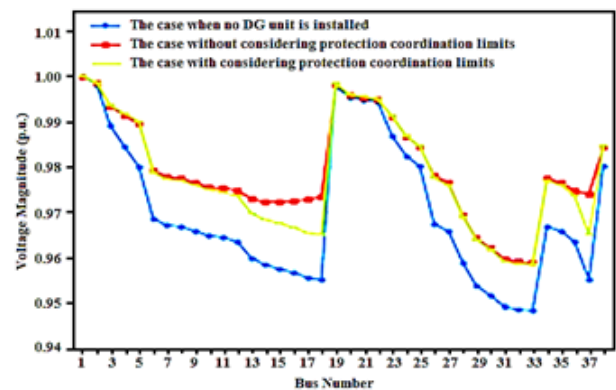


Fig. 4 Voltage profile for three different states.

There are some basic factors which can influence on *EENS* cost such as failure rate of distribution feeders, unavailability of DG units, load level of the network and also *VOLL* value. In the following section, the impact of variation of all the mentioned factors on outcomes of proposed DG placement model is analyzed.

5 Sensitivity Analysis

As another numerical experiment of this paper based on consideration of the protection coordination limits, a sensitivity analysis is performed. In this analysis, the impact of change in each key optimization parameter on the trend of cost saving is studied.

5.1 Variation of Failure Rate

It can be shown that the variation of distribution feeders' failure rate can potentially affect the expected frequency of faults and also the network's *EENS*. The variation of cost difference between the two cases of this study, i.e. the case with consideration of protection coordination limits and the case without it, versus changes in failure rate of distribution feeders are numerically represented in Table 6. In this work, it is assumed that the failure rate for main part of the distribution feeder is half of the failure rate of lateral parts.

The results of Table 6 evidently show that increase in failure rate of feeders brings about the increase of total cost difference between two cases. Thus, the consideration of protection coordination limits in weak distribution systems with high failure rate is so obligatory.

5.2 Variation of DG Units' Unavailability

Increase in unavailability of DG units can make molesting problems in coordination of protective devices leading to increase in network's *EENS*. To assess the impact of DG units' unavailability on the total cost difference of two mentioned cases, the obtained results arising from the variation of DG units' unavailability from 0.06 to 0.12 with 0.02 step length are presented in Table 7.

As clearly shown in Table 7, increase in unavailability of DG units raises the total cost difference between two cases. Therefore, it is demonstrated that the operation of DG units with high value of unavailability confirms the necessity of taking the protection coordination limits into consideration.

5.3 Variation of Load Factor of the System

Increase in load level of the system raises the system *ENS* for each fault occurrence and also the associated *EENS* cost based on (11). Based on Fig. 1, the load factor of distribution network is obtained 0.705. To illustrate the impact of network's load factor on the total cost difference of two simulation cases, the suggested

DG planning model is solved for two other load factors of 0.605 and 0.805 (created by changing the time duration of load levels pertaining to the annual LDC). Table 8 presents the corresponding results obtained by consideration of various load factors.

As depicted in Table 8, increase in system load factor leads to increase in total cost difference of two simulation cases. Therefore, considering the protection coordination limits in case of heavy loads is an essential issue.

Table 5 Details of the best chromosomes for two cases.

Cost item	Costs Without considering protection coordination limits (\$)	Costs With considering protection coordination limits (\$)	Variation
C_{EL}	19480.65	21075.74	+ 8.19 %
C_{DG}	553625.35	508076.68	- 8.23 %
$C_{prot.}$	360	120	- 66.67 %
C_{EENS}	101870.2	93677.51	- 8.04 %
Total cost	675336.2	622949.93	- 7.76 %

Last column shows the increase in cost with considering protection coordination (presented in 3rd column) in comparison with the cost without considering protection coordination (presented in 2nd column).

Table 6 Cost difference of two cases versus feeders' failure rate.

Feeder's failure rate (f/Km.yr)		Cost difference (\$)
Main	Lateral	
0.2	0.4	52386.27
0.4	0.8	65067.22
0.6	1.2	97332.38
0.8	1.6	130970.56
1	2	151151.27

Last column shows the extra total cost of the case without considering the protection coordination in compare with the case where the protection coordination is considered.

Table 7 Cost difference of two cases versus DG units' unavailability.

DG units' unavailability	Cost difference (\$)
0.06	30705.78
0.08	31436.73
0.10	51216.54
0.12	52386.27

Last column shows the extra total cost of the case without considering protection coordination in compare to the case with considering protection coordination.

Table 8 Cost difference of two cases versus system load factor.

Load factor	Cost difference (\$)
0.605	29953.48
0.705	52386.27
0.805	61508.12

The last column shows the extra total cost of the case without considering protection coordination compared to the case in which the protection coordination is considered.

5.4 Variation of VOLL

The *VOLL* represents the economic value of the lost electric energy in case of failure occurrence in distribution network. Variation of *VOLL* changes the cost of *EENS*. Thus, the more *VOLL* the more *EENS* cost. Table 9 presents the impact of *VOLL* variation on the total cost difference between two simulation cases.

Increase in *VOLL* means each MWh lost energy is more expensive. Since the improper operation of protective devices leads to increment of system's *ENS*, the contribution of C_{EENS} in *OF* value extremely increases for the cases of higher *VOLL*. Based on this issue, the cost difference between two cases increases more.

In Table 9, the system *VOLL* is changed from 250 \$/MWh to 2000 \$/MWh and the achieved results are reported. It can be observed that the more *VOLL* value, the more cost difference between two simulation cases. As a result, considering the protection coordination limits in distribution networks encompassing loads with higher priority of continuous service is so crucial.

5.5 Simultaneous Changes in Failure Rate and VOLL

In this case, the *VOLL* and feeders' failure rate are simultaneously changed. To do so, the feeders' failure rate is changed from 0.2 to 1 f/yr/km with the steps of 0.2, for each value of *VOLL* reported in Table 9. Additionally, the impact of simultaneous changes in *VOLL* and feeders' failure rate on the total cost difference of both simulation cases is graphically depicted in Fig. 5.

As shown in Fig. 5, when the failure rate is kept unchanged, increasing the *VOLL* leads to increase in cost difference of the two cases. On the other hand, when the *VOLL* is retained constant, increasing of failure rates has the same effect. Thus, it is expected that the simultaneous increase in both of *VOLL* and failure rate causes extra growth in cost difference. It is remarkable that the maximum cost difference occurs when both of *VOLL* and feeders' failure rates adhere to their own maximum values.

At the whole, it can be concluded from Fig. 5 that in weak distribution network including loads with high priority of continuous service, considering the protection coordination limits is essential due to reduction in associated operation costs.

6 Conclusion

In this paper, a novel optimization model for DG placement is proposed. In the presented model, two new cost items namely protection coordination and protection mal-operation costs are taken into consideration as the objectives beside other widely-used costs, i.e. DG investment and energy losses costs.

Table 9 Cost difference of two cases versus system *VOLL*.

System <i>VOLL</i> [\$/MWh]	Cost difference [€]
250	27518.63
500	30830.82
1000	52386.27
1500	60074.02
2000	69988.12

Last column shows the extra total cost of the case without considering the protection coordination compared with the case with considering protection coordination.

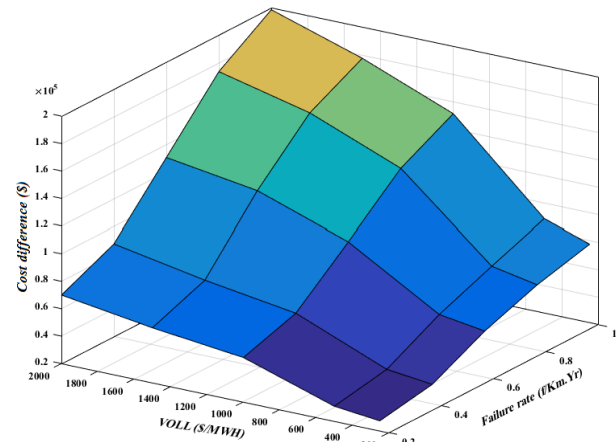


Fig. 5 Impact of simultaneous changes in *VOLL* and failure rate on cost difference of two simulation cases.

Simulation studies are conducted on the standard 38-bus radial distribution system. The obtained results indicate that in spite of increase in cost of energy losses in the case of considering the protection coordination limits, reduction in other cost items are so substantial that leads to the lower total cost compared with the case of not considering it. Hence, the simulation results prove the necessity of considering protection costs within the DG planning problem.

Moreover, the attained results of sensitivity analysis shows that considering the protection coordination limits through the DG planning problem can be so determinative. The significance of this consideration remarkably increases in the cases of heavy-loaded distribution networks, presence of DG units with high unavailability, presence of loads requiring high priority of stable service (i.e. the least interruption), and also network devices with high failure rate.

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