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A novel approach for optimal DG allocation in distribution network for minimizing voltage sag

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Abstract. The cost incurred by voltage sag effect in power networks has always been of important concern for discussions. Due to the environmental constraints, fossil fuel shortage crisis and low efficiency of conventional power plants, decentralized generation and renewable based DG have become trends in recent decades; because DGs can reduce the voltage sag effect in distribution networks noticeably; therefore, optimum allocation of DGs in order to maximize their effectiveness is highly important in order to maximize their effectiveness. In this paper, a new method is proposed for calculating the cost incurred by voltage sag effect in power networks. Thus, a new objective function is provided that comprehends technical standards as minimization of the cost incurred by voltage sag effect, active power losses and economic criterion as the installation and maintenance costs of DGs. Considering operational constraints of the system, the optimum allocation of DGs is a constrained optimization problem in which Lightning Attachment procedure optimization (LAPO) is used to resolve it and is the optimum number, size and location of DGs are determined in IEEE 33 bus test system and IEEE 34 bus test system. The results show that optimum allocation of DGs not only reduces the cost incurred by voltage sag effect, but also improves the other characteristics of the system.

Keywords: distributed generation (DG); voltage sag; lightning attachment procedure optimization (LAPO); expected sag frequency (ESF); exposure length

1. Introduction

Distribution network planners have become interested in renewable energy resources due to the destructive effects of fossil fuels on the environment. Advances in technology of connecting renewable energy resources to the networks and deregulation of the power market have made these units more prevalent (Alsayegh *et al.* 2010, Hamzeh *et al.* 2018, Rahiminejad *et al.* 2014, Rahiminejad *et al.* 2016, Moosavi *et al.* 2017). Installing a DG in the appropriate location with an appropriate size can have many economic and technical benefits among which reducing the power losses, improving power quality and reliability, eliminating congestion and improving voltage profile can be mentioned (Das *et al.* 2018, Sirjani and Jordehi 2017, Li *et al.* 2018, Ha *et al.* 2017,

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Mirzaei *et al.* 2017, Ehyaei and Farshin 2017). Several studies have been done on the optimum allocation of DGs in distribution networks so as to achieve more technical and economic benefits (Mostafaeipour *et al.* 2017a, b). In (Ettehadi *et al.* 2013), the optimum allocation of the DG has been done in order to improve the voltage stability and compensate reactive power. In (Ameli *et al.* 2014), the optimum location and size of the DG have been defined using PSO algorithm to improve the technical and economic characteristics. In (Aman *et al.* 2014), the optimum location and size of multiple DGs have been defined together using HPSO in order to maximize load ability, minimize power losses and improve the voltage. In (Karimyan *et al.* 2014, Foroughi Nematollahi *et al.* 2018, 2016), a modern approach for DG allocation has been suggested for long-term DG planning to minimize the power losses. In (Kansal *et al.* 2013), PSO has been used to define the optimum active and reactive power generated by the DGs.

On the other hand, studies show that DG installation can reduce the voltage sag effect which will obviously improve the power quality and reliability (Pipattanasomporn *et al.* 2005). Reducing damages imposed on the equipment and the financial losses incurred by voltage sag effect will result in sensitive industrial consumers' satisfaction. Thus, due to the importance of this issue, voltage sag elimination techniques using DGs have been reviewed in (Ipinnimo *et al.* 2013). In (Freitas *et al.* 2006; Renders *et al.* 2008), the effectiveness of inverter based DG, synchronous based DG and asynchronous based DG in reducing voltage sag effect in LV distribution network has been compared. In (Bozalakov *et al.* 2015), damping control strategy and positive-sequence control strategy of the DGs have been presented in order to support the network during the voltage dip. In this paper, a LAPO-based approach is proposed for the optimum allocation of DGs considering power losses, voltage profile, voltage sag, installation and maintenance costs of DGs. Therefore, a voltage sag function is also added to the optimization problem. In other words, in this paper, it is tried to include the technical criteria like voltage sag reduction, voltage profile improvement and power losses reduction as well as the economic criteria like installation and maintenance costs of DGs in an objective function in to improve the system effectiveness. Thus, a new formula is provided for calculating the cost incurred by voltage sag effect. It should be noted that operational constraints are also considered for resolving the optimization problem. Optimization of a radial network and a meshed network are done through using the LAPO. The rest of this paper is organized as follows: in section 2, flaws of the current approaches in voltage sag analysis are discussed and the recommended approach is explained. In section 3, the new objective function for resolving the optimization problem is provided for resolving the optimization problem. In section 4, solving optimization problem using LAPO is explained. In section 5, the recommended method is implemented on a 34-bus radial distribution network and a meshed distribution network. Finally, the paper is concluded in section 6.

2. Voltage sag analysis

In power networks, voltage dip often occurs due to the faults like short circuit or running large motors. According to IEEE 1159-2009 standard, voltage reduction ranges from 10% to 90% and the defined time from half a cycle to 1 minute(Anon 1998, 1997 n.d., Biswas *et al.* 2012). Studies show that 92% of power quality-related problems which industrial consumers have to deal with are the voltage dip faults (Cheng *et al.* 2003). This phenomenon causes protection devices to trip as a result of which industrial equipment shut down and the whole production process is interrupted in factories. The amount of economic losses depends on the activity of the factory and extension range of this phenomenon. The first level of losses includes production loss, equipment damages, recovery operations and the second level, known as the hidden loss, includes the commercial performance of factories as factory reputation, consumer satisfaction and consumer retention (Di Fazio *et al.* 2014). Most of the studies done so far have focused on the voltage dip caused by short circuit faults in the power networks (Becker *et al.* 1994). On the other hand, sensitive industrial, residential and commercial loads in distribution networks are increasingly growing. These loads are extremely vulnerable against the voltage dip phenomenon; thus, solutions should be thought in order to reduce the dip effect around the sensitive loads. The range and duration of a dip are its two main characteristics; its range depends on the type and location of the fault as well as the network topology, and its duration depends on the protection devices and the way the fault is dealt with (Bollen and Bollen 2000). ESF is another significant parameter in voltage sag analysis that is the result of multiplying fault rate of the buses and lines of the system by the total length of the lines and number of buses in the AOS (AOS is the area in which the sheen voltage with sensitive load goes lower than a specific value (Vcrit) in case a fault occurs(Qader *et al.* 1999). Moreover, in order to the calculate amount of trips of the equipment which occurs due to the voltage sag, voltage tolerance characteristics of the equipment have to be provided based on both common tolerance curves which are (a) the ITIC curve and (b) the SEMI F47 curve (Wang *et al.* 2005).

ESF, range characteristics and its relevant duration in the bus under study (PCC) can be calculated using stochastic methods. Stochastic prediction is often done based on the historical fault statistics data and the vulnerability area method (McGranaghan *et al.* 1993, Oyj and Oyj 1999). The most common methods used for stochastic evaluation of voltage sags are critical distance (Bollen 1995) and fault position (Qader *et al.* 1999, Becker *et al.* 1994, 1997 n.d., Oyj and Oyj 1999, Di Fazio *et al.* 2014, Cheng *et al.* 2003; Bollen and Bollen 2000). Critical distance method is not applicable for the circular networks; only it can be used for the precise prediction of voltage sags in radial networks. The major problem of the fault position method is that its accuracy depends on the location and number of faults simulated in the network (Park and Jang 2007, Park *et al.* 2010, Goswami *et al.* 2009). Several factors may be considered to get a more precise evaluation of the voltage sags. For example, in (Goswami *et al.* 2009, Milanovic *et al.* 2005, Aung *et al.* 2004), the effects of different distributions of faults such as constant, exponential and normal distributions on voltage sag prediction have been examined. Furthermore, a method has been recommended in (Aung and Milanovic 2006) with respect to the failure of protection devices. In this section, using the method recommended in (Park *et al.* 2010) for stochastic prediction of voltage sags and determining ESF, a new method is offered for calculating the cost incurred by voltage sag effect in a power network which may be utilized in the optimization problem explained.

As seen above, ESF of the bus (PCC) is determined by multiplying the fault rate of the lines and the buses by the total length of the lines and number of buses in the AOS (Park *et al.* 2010). Hence, in this paper, ESF is determined using the method presented in (Park *et al.* 2010) and the assumptions below are considered to calculate the cost incurred by the voltage sag effect. Eventually, as it will be explained in section 4, the cost incurred by voltage sag effect will be comprehended in the objective function of the optimization problem.

3. Problem formulation

In this section, assumptions of the mathematical model of the objective function and the constraints are explained.

Table 1 System fault statistics for buses and lines

Type of fault	Bus fault rate(events/year)	Line fault rate (events/100 km/year)
SLGF	0.08	3.36
LLF	0.005	0.21
DLGF	0.011	0.462
3PH	0.004	0.168

Assumptions

- Since there is usually no reliable information on the fault impedance, the worst-case scenario, that is, zero fault impedance, is assumed in voltage sag analysis.
- When determining the number of voltage sags (ESF), the AOS of unbalanced faults is calculated only for the phase with the lowest voltage during short circuits.
- Fault rate of lines and buses of the system is assumed as in (Goswami *et al.* 2009), the values of which are listed in Table 1.
- The critical voltage (Vcrit) is assumed 0.7 p.u.
- The component failure rate only indicates the permanent failures and they are the primary causes of most voltage sags encountered in the power system. Hence, the permanent, active and temporary failure rates are all merged into a single index to present the failure rate.

By taking the first two assumptions into account, we will consider the worst situation for voltage sag evaluation and thus will care more about the minimization of the cost incurred by voltage sag effect comparing to the rest of the objective functions of the problem (minimization of power losses and voltage profile improvement) which will then result in reducing the voltage sag effect as much as possible. From the definition of ESF in (Park *et al.* 2010) and the assumptions above, the equations below can be deduced for ESF which is the basis for calculating the cost incurred by voltage sag effect. For unbalanced and balanced three-phase faults, ESF is calculated through using Eqs. (1) and (2) respectively.

$$ESF_{UF} = \sum_{i=1}^{3} \left[\sum_{B \in AOS_{ip}} BFR_i + \sum_{L \in AOS_{ip}} l_L \times LFR_i \right] \tag{1}$$

$$ESF_{BF} = \sum_{B \in AOS_{41}} BFR_i + \sum_{L \in AOS_{41}} l_L \times LFR_i \tag{2}$$

The AOS in Eq (1) consists of the phase with the lowest voltage range during short circuits which is shown with “p”. Voltage is equal in all three phases while balanced faults occur, thus, the AOS is respected for only one of the three phases (for example, phase 1) in Eq. (2). Therefore, ESF is calculated through using the equation below

$$ESF = ESF_{UF} + ESF_{BF} \tag{3}$$

3.1 Objective function

Optimum allocation of DGs is a multi-objective constrained optimization problem that has active power losses, the cost incurred by voltage sag effect and total cost of the DGs as its objects, power flow limits, bus voltage and DG capacity as its constraints which will be explained.

3.1.1 Minimization of active power losses

$$P_L = \sum_{i=1}^{N_b} \sum_{j=1}^{N_b} A_{ij} (P_i P_j + Q_i Q_j) + B_{ij} (Q_i P_j - P_i Q_j) \tag{4}$$

where

$$A_{ij} = \frac{R_{ij} \cos(\delta_i - \delta_j)}{V_i V_j} B_{ij} = \frac{R_{ij} \sin(\delta_i - \delta_j)}{V_i V_j} \tag{5}$$

3.1.2 Minimization of the cost incurred by voltage sag effect

As explained before, ESF can be calculated using Eq. (3) for each of the buses of the system and the cost incurred by voltage sag effect in power networks can be further calculated through using the formula provided below.

$$C_s = \sum_{i=1}^{N_b} ESF_i \times \left(A_i + B_i t_i\right) \times P_{Load\,(i)} = \sum_{i=1}^{N_b} \left(A_i + B_i t_i\right) \times load\ \ outage\ \ year_i \tag{6}$$

Using *ESFi×PLoad (i),* annual load outage can be calculated for each bus and by adding them all, one would be able to determine the amount of load that disturbs the network per year. Multiplying this value by the cost of industrial loads outage gives the cost incurred by the voltage sag effect in the power networks.

3.1.3 Minimization of the DG costs

$$C_{DG} = k_c \sum_{i=1}^{N_{DG}} P_{DG_i} \tag{7}$$

3.2 Operational constraint

In this paper, the generation and location of the DGs must be determined so that the network constraints are satisfied. These constraints are as follows

- Thermal limits of the lines: The maximum power flowing at each line must be less than its thermal limit

$$S_i \le S_{i\,\max} \tag{8}$$

- Bus voltage limit: Voltage magnitude of each bus must be held in a specific range as follows

$$V_{i\,\min} \le V_i \le V_{i\,\max} \tag{9}$$

- Capacity of DGs: Power generation of DGs must not be violated from their generation ability.

$$P_{DG\,\min} \le P_{DG} \le P_{DG\,\max} \tag{10}$$

4. Problem solution using the LAPO algorithm

4.1 Lightning attachment procedure optimization (LAPO) algorithm

Recently, a novel meta heuristic optimization known as the optimization algorithm was introduced by Foroughi *et al.* in (Foroughi and Rahiminejad 2017, Nematollahi *et al.* 2017). The method mimics the nature of lightning moving down to the ground. This method consists of 4 steps to find the best solution.

In the first step, test points on the cloud surface and ground are randomly initialized in the predefined rang as follows

$$X^{i}_{testpoint}=X^{i}_{min}+(X^{i}_{max}-X^{i}_{min})\times rand \qquad (11)$$

The objective function value of each test point is obtained through putting the test point in the objective function

$$F^{i}_{testpoint}=obj(X^{i}_{testpoint}) \qquad (12)$$

In the second step, in order to update the test points average of the all test points are required.

$$X_{ave}=mean(X_{testpoint}) \qquad (13)$$

$$F_{ave}=obj(X_{ave}) \qquad (14)$$

In order to update the test point i, a random test point j is chosen so that i≠j. the objective value of solution j (Fj) is compared to Fave.

$$\begin{cases} X^{i}_{testpoint\_new}=X^{i}_{testpoint}+\xi \quad if \quad F^{i}_{testpoint}<F_{ave} \\ X^{i}_{testpoint\_new}=X^{i}_{testpoint}-\xi \quad if \quad F^{i}_{testpoint}<F_{ave} \end{cases} \qquad (15)$$

where

$$\xi=rand\times(X_{ave}+rand\times(X^{j}_{potential\,point})) \qquad (16)$$

For the new test points, the objective function is obtained and the new solutions are replaced with the old ones if the objective function is better than the previous point as follows

$$\begin{array}{ll} X^{i}_{tetpoint}=X^{i}_{testpoint\_new} & \text{if } F^{i}_{testpoint\_new}<F^{i}_{tetpoint} \\ X^{i}_{testpoint\_new}=X^{i}_{tetpoint} & \text{otherwise} \end{array} \qquad (17)$$

In the third step, an exponent factor is defined as follows

$$S^{it}=1-\left(\frac{It}{It_{max}}\right)\times\exp\left(-\frac{It}{It_{max}}\right) \qquad (18)$$

The solutions are also updated by the following equation

$$X_{testpoint\_new}=X_{testpoint\_new}+rand\times S^{it}\times(X_{min}-X_{max}) \qquad (19)$$

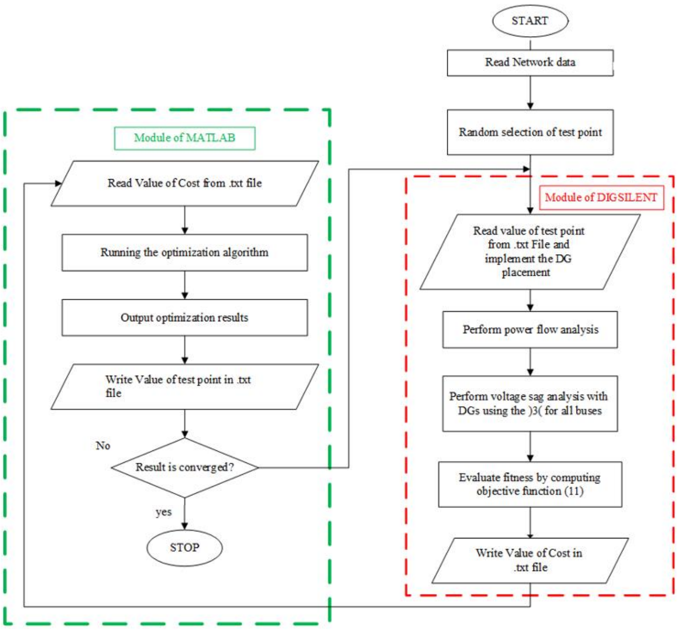


Fig. 1 Flowchart of proposed DG placement optimization algorithm

In the fourth step, for the new test points, the objective function is obtained and the new solutions are replaced with the old ones, if the objective function is better than the previous point as follows:

In (Foroughi and Rahiminejad 2017, Nematollahi *et al.* 2017, 2019) LAPO was applied to a lot of mathematical and engineering optimization problems and the results show superiority of this method compared to the other methods. Thus, this method is used in this paper.

LAPO has been used in this paper for the optimum allocation of DGs. The calculation process can be observed in the flowchart shown in Fig. 1. DPL programming language has been used to work out the objective function and LAPO is implemented using MATLAB on a personal computer with a 2.5GHz CPU.

5. Simulation result

5.1 Utilizing the proposed method on a radial distribution network

The IEEE 34-bus radial network (Chis *et al.* 1997) shown in Fig. 2 is used in order to show the effectiveness of the recommended method. Network loading information and sequence impedances for short circuit analysis are given in(Biswas *et al.* 2012).

Maximum DG capacity is set equal to 50% of annual peak load and the DGs are modeled as PQ bus in load flow analysis. Maximum number of installable DGs is 10. ω_e, ω_c and ω_s are 0.33; K_{th} and K_v are 10^{10} and 10^6, respectively (Biswas *et al.* 2012). In this study, A_i, B_i and t_i are considered with identical values for all the network loads which can be calculated according to (Antikainen *et al.* 2009) that is 3.52, 24.45 and 3, respectively.

Installing DGs in a distribution network will cause losses and bus voltage to change and this

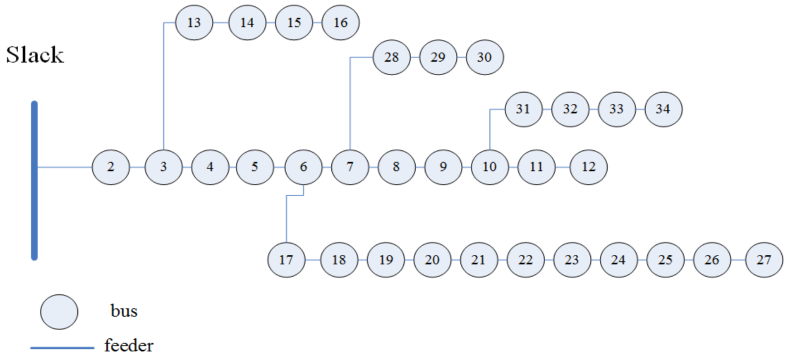


Fig. 2 Radial distribution network configuration

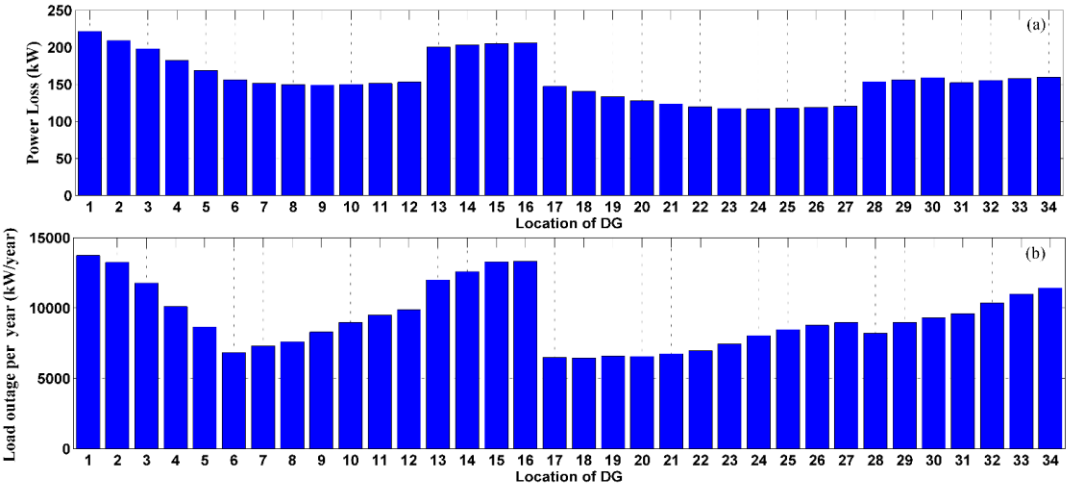


Fig. 3 (a) variation of the ((a) load outage per year/ (b) losses) with location of the single DG

change depends on the number, size and location of the DGs used in the network. For a fixed rating for all the DGs, voltage sag performance depends mainly on their location and less on their injected power to each bus. The closer is the location of the DGs to the buses with higher sensitivity to voltage sag; the less intense would be voltage sag effect in the network. On the other hand, the closer is the center of the load the DGs, voltage sag effect is reduced more [12]. To clarify this, a DG with a fixed capacity of 1.5MW is placed in each bus of the system and the amount of annual losses and outage load of the network related to short circuits are then drawn for shifting the DGs in Fig. 3.

As seen in this figure, power loss is at its minimum for placing the DG at bus 24 which is equal to 116.32 kW; whereas the minimum outage load per year is for placing the DG at the bus 17 which is 6500kW/year (i.e., 6500kW of power disturbs the network per year due to short circuits). Hence, there is no equal minimum value for the power losses and the cost incurred by voltage sag effect. Consequently, it can be concluded that even with a simple relocation of a DG with its size being fixed, the optimum allocation of DGs cannot be performed directly. Now, if one wants to determine the optimum number and size of the DGs, direct solution of the problem would be

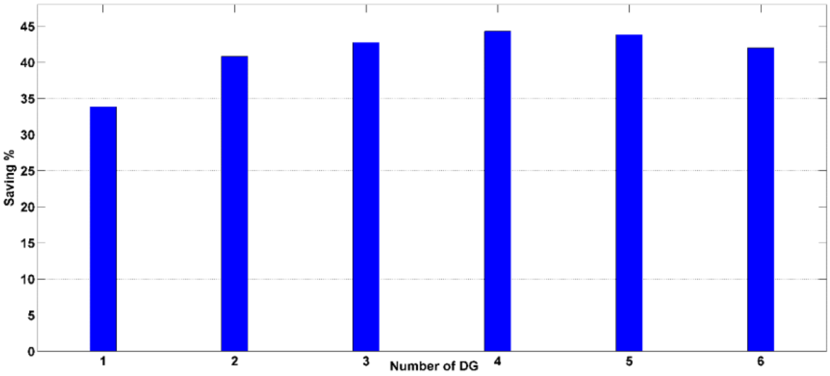


Fig. 4 The variation in percentage savings from the “no DG” condition with variation in the number of DGs

Table 2 Performance of the optimum DG placement problem

No. of DGs	Loss(kW)	Load outage per (kW/year)	Total cost (million $)	Percentage saving (%)	Location (bus number)	DG size(MW)
No DG	221.18	15747.54	2.737	0	-	-
1	123.87	6964.334	1.810	33.85	22	1.4
2	107.67	4768.95	1.619	40.83	24 8	1.2 0.5
3	104.296	3988.837	1.566	42.77	24 10 20	0.6 0.6 0.6
4	95.02	3498.04	1.524	44.31	23 25 9 19	0.5 0.5 0.5 0.5
5	80.443	3018.419	1.537	43.84	23 19 25 8 11	0.5 0.5 0.5 0.5 0.5
6	69.429	2714.071	1.587	42.01	8 23 18 10 21 24	0.5 0.5 0.5 0.5 0.5 0.5

impossible. According to the method presented in Fig. 1, LAPO will be implemented on the 34-bus network and the objective function is considered as in Eq. (12).

Case1: Optimal sizing and siting of DGs

In this situation, number of DGs is defined using a prior method, while LAPO will define only their location and size. Table 2 represents the related results in which the number of DGs is added discretely from 1 to 6.

According to the table, the optimum number of DGs is 4 and the percentage of total cost of the

Table 3 Performance of the optimum DG placement problem

	In this paper				in (Goswami *et al.* 2009)			
No. of DG	Location (bus number)	Each DG size (MW)	Total cost (US million $)	Percentage saving (%)	Location (bus number)	Each DG size (MW)	Total cost (US million $)	Percentage saving (%)
4	23	0.5	1.524	44.31	20	0.5	1.625	40.63
	25	0.5			25	0.5		
	9	0.5			8	0.5		
	19	0.5			17	0.5		

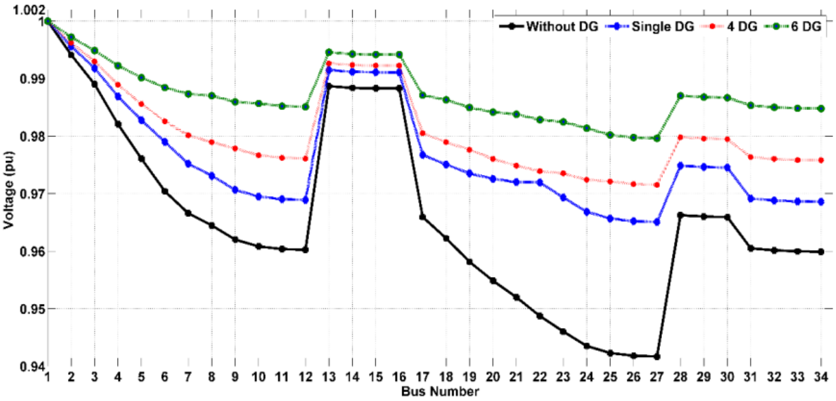


Fig. 5 The bus profile voltage for different number of DG

system compared to the state of using no DGs in the network is 44.31% which is the most economical state. Based on Table 2, it is observed that the higher is the number of DGs, power losses and load outage per year would be less. However, when the number of DGs exceeds 4 any increase in their injected power will overcome the decrease in the power losses and in load outage per year; thus, the total cost of the system will increase and for this reason, 4 DGs will result in minimum cost of the system. Fig. 4 shows that cost saving is at its maximum when having 4 DGs compared to the other states and it will decrease in case the number of the DGs exceeds 4.

Case2: Optimal Number of DGs

In this case, optimal number of DGs and their optimal size and location are determined using LAPO. Location of DGs might vary between 1 to N_{BUS} and their generation might also vary between 0 to maximum generation. After optimization, the optimal number of DGs is equal to the number of buses in which DG generation is not zero; thus, optimal number, size and location are determined simultaneously. Table 3 represents the related calculations and as can be observed, they are similar to results of the previous state (shown in Table 2); that is, the optimum number of DGs is 4 and also the optimum size and location correspond to those of Table 2 which show the effectiveness of the proposed method. Also Likewise, in this table, the total cost calculated using the method presented in (Goswami *et al.* 2009) which seems to be the most complete method among the previous utilized approaches and has the ability to implement in optimum DG placement problem, is compared with the proposed method of this paper. According to this table, by using the proposed method, the total cost amount has been significantly reduced.

Fig. 5 shows voltage profile which implies that as DGs enter the network, voltage profile is

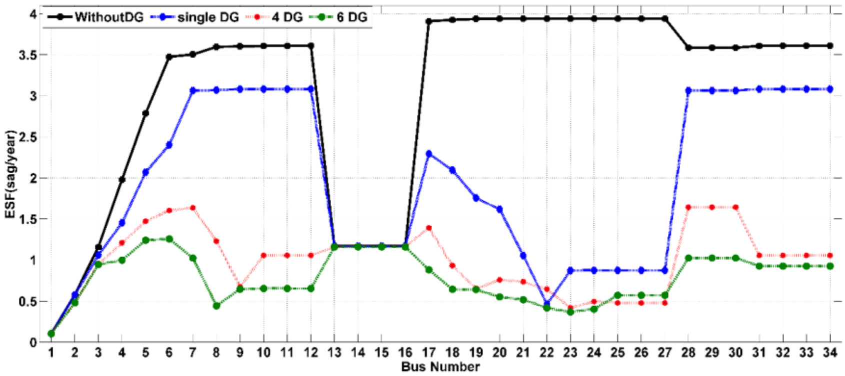
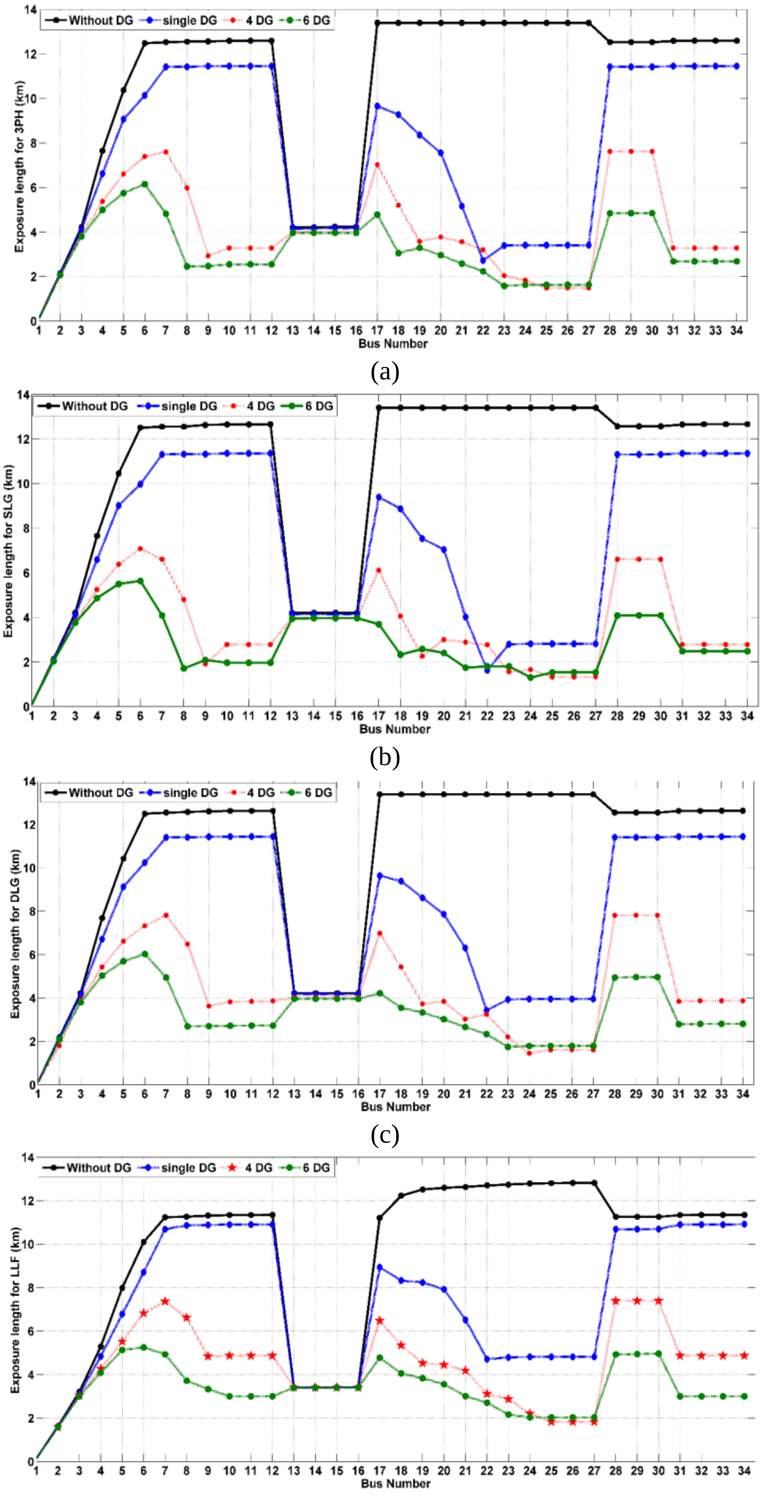


Fig. 6 The estimation sag frequency (ESF) for all busses

improved in a way that as higher numbers of DGs enter the network, the voltage profile is improved more.

Fig. 6 shows ESF for all buses of the system and for different number of DGs. When DGs enter the network, ESF generally decreases for all buses of the network noticeably. Furthermore, as can be seen in the figure, ESF remains almost unchanged for buses 13, 14, 15 and 16 which are in the same branch after changing the number of DGs and the reason to this is that these buses have less active loads compared to the rest of the network first (power of each load is given in [31]) and second, they have rather low ESF; therefore, they have rather insignificant effect on the cost incurred by the voltage sag effect in the whole network; thus, their ESF does not change much at the end of the optimization problem. One more point to consider is that ESF is expected to decrease for all buses by increasing the number of DGs in the network, but it can be inferred from the figure that for example in bus 22, when the number of DGs is increased from 1 to 4, ESF increases; this is because the optimum location for the single DG is bus 22 according to Table 1, but it is a bit far from bus 22 when having 4 DGs; so, ESF has been partly increased at bus 22 (compared to the state 1DG). Hence, it should be noted that total amount of ESF (for all of the buses together) is significantly lower with 4 DGs compared with one DG. Buses 25, 26 and 27 will be also reasoned in the same way and increasing the number of DGs from 4 to 6 causes ESF to increase instead of decrease.

Now, in this section, for greater clarity, the definition of the exposure length is used. Exposure length is equal to length of all the lines located in the AOS for every sensitive load [26]. Figs. 7(a)-7(d). represent the exposure length of each bus load of the network for three-phase, single-phase, two-phase-to-ground and two-phase faults of the network; each diagram is seen to show the same behavior as ESF does when changing the number of DGs. Their value might increase at some buses by increasing the number of DGs, but thoroughly, the exposure length decreases noticeably for all buses by increasing the number of DGs. Moreover, according to these figures, some buses (as buses 17 to 27) have a very large exposure length before placing DGs in the network, which is, for example, 13.4 kilometers for three-phase faults, while the total length of all network lines is 13.5; in other words, as a three-phase short circuit occurs in the network, the voltage of these buses goes lower than V_{crit} (which is 0.7 in this paper) and this does not represent a suitable situation for the network when voltage sag effect occurs. Yet, it can be observed from the figures that installing DGs in the network causes exposure length to decrease significantly and the sensitive buses of the network to be more stable against the voltage sag effect and thus, less power will disturb the



(a)

(b)

(c)

(d)

Fig. 7 The Exposure length during (a) 3PH (b) SLG (c) DLG (d) LLF fault for all busses network per a year due to the short circuits.

5.2 Utilizing the proposed method on a meshed distribution network

To show that the method proposed in this paper is effective enough for networks with a meshed structure, a sample meshed distribution network will be used with a structure of enough complexity which is shown in Fig. 8.

Full information about this network is given in (Hajizadeh & Hajizadeh 2008) and its tie-lines have been tied according to (Kashem *et al.* 2000). The fault rate of lines and buses of this network are assumed as in Table 1. Likewise, the other parameters of the system as Ke, Kc, ωe, ωc, ωs, etc. have been assumed the same as the previous state (the radial network). Table 4 shows the results with different numbers of DGs.

Having 3 DGs in the network is observed in the table in order to give the best performance; total cost of the system is at its minimum in this state, where the cost saving percentage in comparison with the state of having no DGs in the network is 32.38% in comparison with the state of having no DGs in the network. According to the table, the more DGs exist in the network, power loss and load outage per year would be less. Though, increasing the power injected by more than 3 DGs will overcome the decrease in the power losses and load outage per year; therefore, total cost of the system increases. For this reason, using 3 DGs in the network will cost the least for the whole system. Fig.9 shows that cost saving with 3DGs is higher than the other states, but it will decrease if the number of DGs exceeds 3.

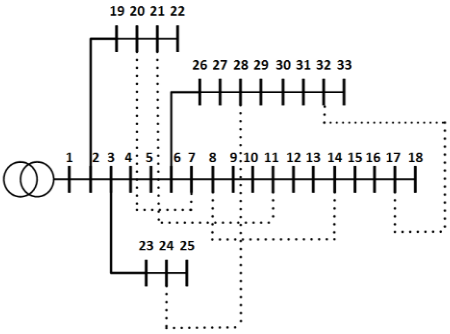


Fig. 8 Loop distribution network configuration

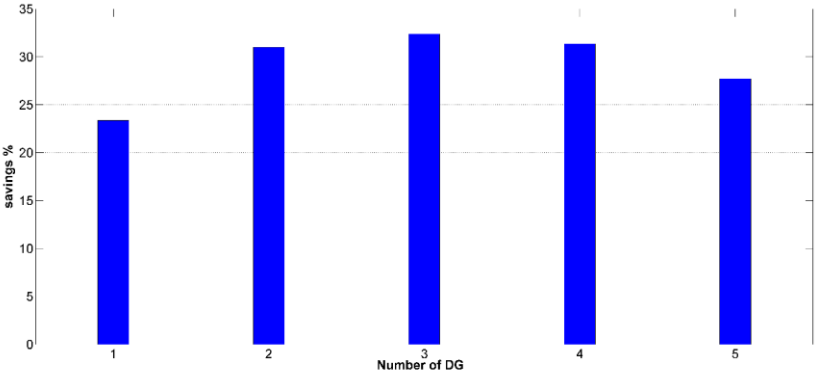


Fig. 9 The variation in percentage savings from the “no DG” condition with variation in the number of DGs

Table 4 Performance of the optimum DG placement problem

No. of DGs	Loss(kW)	Load outage per (kW/year)	Total cost (million $)	Percentage saving (%)	Location (bus number)	DG size (MW)
No DG	154.105	8862.064	1.745	0	-	-
1	96.335	5241.312	1.337	23.38	31	0.9
2	88.096	3458.797	1.204	31.00	30 13	0.6 0.5
3	75.678	2704.399	1.180	32.38	31 24 14	0.5 0.5 0.5
4	64.547	2054.022	1.198	31.35	30 24 14 8	0.5 0.5 0.5 0.5
5	52.816	1905.993	1.261	27.73	32 30 24 14 7	0.5 0.5 0.5 0.5 0.5

Table 5 Performance of the optimum DG placement problem

	In this paper				in (Goswami *et al.* 2009)			
No. of DG	Location (bus number)	Each DG size (MW)	Total cost (US million $)	Percentage saving (%)	Location (bus number)	Each DG size (MW)	Total cost (US million $)	Percentage saving (%)
3	31 24 14	0.5 0.5 0.5	1.180	32.38	29 23 11	0.51 0.51 0.51	1.318	24.46

At the end of this section, the total cost calculated by using the method presented in (Goswami *et al.* 2009) is compared with the proposed method. According to Table 5, by using the proposed method, the total cost amount has been significantly reduced. Also, by comparing Tables 3 and 5, it is also concluded that the proposed method is more efficient for the meshed network, and therefore the amount of its cost reduction is more significant than the radial network.

6. Conclusions

In this paper, a new method is proposed for calculating the financial costs of voltage dip so that shortcomings of existing techniques in assessing voltage dip are resolved. Then, a new objective function is considered for the placement of distribution generation problem that consists of both technical and economic factors e.g., reduction in voltage dip, minimization of line loss and minimization of installation and maintenance costs of DGs. Finally, the placement of distribution generation problem is configured as a single objective, constrained optimization problem where the optimal number of DGs, along with their sizes and bus locations are simultaneously obtained using LAPO algorithm along with their sizes and bus locations. The 34-bus radial distribution system and 33 bus loop distribution system (with closed tie line) are considered as the case studies where the effectiveness of the proposed algorithm is demonstrated. Simulation result illustrates optimal placement of DGs in addition to the significant reduction of financial costs of voltage dip and improves other indicators of the distribution network.

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CC

Nomenclature

Indices

i	The fault type (1: SLGF, 2: LLF, 3: DLGF, 4: 3PH)
p	The phase with lowest amplitude of voltage during the fault

Sets

B	The system buses
L	The system lines
AOS	Area of severity

Variables

P_{DGi}	The size of the ith DG.
$P_{DGi\min}, P_{DGi,\max}$	The minimum and maximum permissible value of each DG capacity.
BFR_i	The bus fault rate for fault type i
LFR_i	The line fault rate for fault type
l_L	The length of line L inside AOS
C_s	The expected annual outage cost ($).
P	The net real power and reactive power injection at respected buses
N_b	The number of buses
N_{line}	The number of lines
N_{DG}	The total number of DG connected
R_{ij}	The line resistance between bus i and bus j
δ	The load angle at corresponding buses
$P_{load(i)}$	The active power at bus i
ESF_i	The estimation sag frequency at bus i
A_i	The constant outage cost parameter of load i ($/kW)
B_i	The dependent outage cost parameter of load i ($/kW).
t_i	The expected outage duration of load I caused by occurrence of fault (h)
S_l	The apparent power that is transmitted through each branch l
$S_{l\max}$	The thermal limit of line or transformer in steady state operation
V_i	The voltage at busses i
$V_{i\min}, V_{i\max}$	The minimum and maximum permissible value of voltage at bus i
K_e	The cost coefficient of power losses ($/kW)
K_c	The DG cost per MW
K_{th}	The penalty multiplayer for power flow limit violation

K_v	The penalty multiplayer for voltage limit violation
δ_{1k}, δ_{2k}	The binary flag that reset to 0 when the constraint is satisfied and set to 1 when the constraint is violated
W_e, W_s, W_c	The relative weights assigned to individual objectives
V_{crit}	The critical voltage
pcc	The point of common coupling
Xmin and Xmax	The lower and upper bound of decision variables
rand	A uniform random variable in the range of [0, 1]
$F^{i}_{testpoint\_new}$	The fitness value of the new test point
It	The current iteration
Itmax	The maximum number of iterations
XSmin	The best solution of the population
X^{S}_{max}	The worst solution of the population

Abbreviations

DG	Distributed Generation
LAPO	Lightning Attachment Procedure Optimization
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
LV	Low Voltage
ESF	Expected Sag Frequency
ITIC	Information Technology Industry Council
PCC	Point of common coupling
SLGF	Single Line to Ground Fault
LLF	Line to Line Fault
DLGF	Double Line to Ground Fault
3PH	3 Phase Fault