Modelling, Measurement and Control A
Vol. 91, No. 2, June, 2018, pp. 83-88
Journal homepage: http://iieta.org/Journals/MMC/MMC_A

An efficient method for sizing and allocation of distributed generation and voltage regulators in a distribution network

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https://doi.org/10.18280/mmc_a.910209

Received: 27 May 2018
Accepted: 30 June 2018

Keywords:
distribution network, voltage regulator, genetic algorithm, voltage drop, distributed generation

ABSTRACT

One of the well-known challenges in designing long distribution lines is to determine the efficient locations of voltage drop compensating devices e.g. Voltage Regulators (VRs) and Distributed Generations (DGs). Determination of optimal locations, results in more economical benefit of these equipments. The majority of the works presented in the literature try to satisfy this goal, using classical load flow methods, such as Newton-Raphson approach or the back-forward method. However, these classical methods may suffer from some serious deficiencies. Namely, the first method is faced to the risk of divergence in distribution systems and the second is time consuming. Moreover, both methods impose quite significant complexity. The method presented in this paper employs a load distribution technique in addition to the genetic algorithm solution, enabling the investigation of simultaneous effects of the distributed generation and voltage regulator on a distribution feeder. In the proposed algorithm, an objective function composed of power losses and voltage deviations is used to obtain an optimal location of the above mentioned equipments (DGs and VRs) and the efficient size of the distributed generation system. The proposed idea has been examined for the IEEE 33-Bus test system and its favorable efficiency is confirmed.

1. INTRODUCTION

Power distribution network is an interface medium between power consumers and transmission systems. The two issues of voltage drop and power losses have been known as the main challenges which cause serious problems in distribution systems, especially when the loads are concentrated at the end of long feeders. The low voltage level used in power distribution networks implies the flow of quite high currents. This significantly increases the value of power losses in the distribution networks compared to the transmission networks.

Various methods are suggested to reduce the power losses in distribution systems. Some of the most prevalent methods included capacitor siting, efficient placement of DGs and reconfiguration of the network and voltage regulators.

Some researches show that application of DGs with unfit capacity or placing them at inappropriate locations within the network may increase the power losses, compared to the state before the installation of DGs [1]. Various optimization methods have been proposed in the literature, which can be classified into analytical methods [2] and heuristic methods [3-9]. Heuristic methods include the evolutionary optimization approaches based on the Genetic Algorithm (GA) [3], Artificial Bee Colony (ABC) algorithm [4], fuzzy research reasoning approach [5], Particle Swarm Optimization (PSO) [6], Ant Colony algorithm [7], Cerebellar Model Articulation Controller (CMAC) [8], Clonal selection algorithm [9] and Leaping Frog algorithm [10].

A combination of genetic algorithm and PSO is used in [11] to determine the optimal sizes and places of DGs in order to reduce the losses and voltage drop over the network. In [12] the genetic algorithm is employed to determine the optimal sizes and locations of DGs, which not only minimize the power losses and voltage drops, but also enhance the system reliability. The genetic algorithm is also applied in [13] to determine the sizes and locations of DGs which minimizes the costs and losses in the distribution network.

In addition to Using the genetic algorithm to simultaneously find the optimal locations of DGs and VRs, this paper also attempts to determine the optimal sizes of DGs, which minimize both power losses and voltage drops in the network. All of [11-12] and [13] employ the genetic algorithm just to find the optimal locations of DGs. However, none of them considers the locations of VRs as variable parameters to be found through the optimization process. However, our proposed method jointly optimizes the sizes and locations of DGs and the locations of VRs, to minimize power losses and voltage drops in the distribution system.

Many papers have investigated the use of capacitor banks in order to minimize the power losses and optimize the voltage levels within the network [14-15]. However, there are very limited papers which have also considering the role of VRs in this problem. Therefore, bringing VRs into consideration may provide some noteworthy opportunities for new models and algorithms. In [16], a computerized algorithm is used for controlling the optimized voltage levels, which is suitable for large radial distribution networks.

In [17] a two-steps algorithm has been proposed for optimal placement of VRs in distribution systems. In the first step, voltage regulators are placed at candidate buses (and the tap position is determined), aiming at minimizing voltage drops and real power losses. In the second step, an attempt to reduce the number of voltage regulators is made, taking into consideration economical aspects. In [18], the placement of VRs is done with help of two different algorithms. These algorithms help to find the location and number of VRs required for the system.

2. DISTRIBUTED GENERATION

A distributed generation (DG) is a power source which installed near the consumers that is directly connected to the distribution network. The DG can be used to provide the network with its whole electrical power demand or a part of it, or it can alternatively be used as stand-by source. Synchronous /asynchronous generators and power electronics convertors are often used in order to connect the DG to the distribution network. Table 1 illustrates different kinds of DGs, as well as the connection type which is used to connect each kind of DG to the distribution network.

Table 1. Types of DG and their connections [19]

Heading1	Heading 2	Heading 3
fuel cell	-	Inverter
Photovoltaic	-	Inverter
Wind	Squirrel cage induction generators Doubly fed induction generation Conventional or permanent magnet synchronous generator	Directly Rectifier + Inverter Rectifier + Inverter
Micro-turbines	Permanent magnet synchronous generates	Rectifier + Inverter or AC/AC Converter
Gas turbines	Synchronous generator	Directly

2.1 Placement of DGs

Consider a distribution network with N load buses as in [20]. The buses are labelled as 1 to N, from the sending end of the feeder towards its receiving end. Since the place of the distributed generation is not already known, an additional bus is added to the system; this bus, labelled as the bus number N+1, and is connected to a load bus of the system through the impedance of the DG. Eq (1) expresses the relationship between the voltages and the currents in the described system.

$$Y_{bus} V_{bus} = I_{bus} \tag{1}$$

where Y_{bus} is the admittance matrix and V and I denote the voltage and current vectors corresponding to bus numbers 1 to N+1, respectively. Eq. (1) can be rewritten as (2).

$$\begin{bmatrix} Y_{1,1} & Y_{1,2} & \cdots & Y_{1,N} & Y_{1,N+1} \\ Y_{2,1} & Y_{2,2} & \cdots & Y_{2,N} & Y_{2,N+1} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ Y_{N,1} & Y_{N,2} & \cdots & Y_{N,N} & Y_{N,N+1} \\ Y_{N+1,1} & Y_{N+1,2} & \cdots & Y_{N+1,N} & Y_{N+1,N+1} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \\ V_{N+1} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \\ I_{N+1} \end{bmatrix} \tag{2}$$

Eq. (2) can be simplified by partitioning into some appropriate submatrices, as shown in Eq. (3).

$$\begin{bmatrix} Y_A & Y_B & Y_C \\ Y_B^T & Y_D & Y_E \\ Y_C^T & Y_E^T & Y_F \end{bmatrix} \begin{bmatrix} V_I \\ V_Y \\ V_{N+1} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_Y \\ I_{N+1} \end{bmatrix} \tag{3}$$

where,

$$Y_A = Y_{1,1}, Y_B = \begin{bmatrix} Y_{1,2} & \cdots & Y_{1,N} \end{bmatrix}, Y_C = Y_{1,N+1}, Y_F = Y_{N+1,N+1}$$

$$I_Y = \begin{bmatrix} I_2 \\ \vdots \\ I_N \end{bmatrix}, V_Y = \begin{bmatrix} V_2 \\ \vdots \\ V_N \end{bmatrix}, Y_D = \begin{bmatrix} Y_{2,2} & \cdots & Y_{2,N} \\ \vdots & \ddots & \vdots \\ Y_{N,2} & \cdots & Y_{N,N} \end{bmatrix}, Y_E = \begin{bmatrix} Y_{2,N+1} \\ \vdots \\ Y_{N,N+1} \end{bmatrix}$$

According to the above mentioned definition, the network is connected to the bus number 1 and the DG is connected to the bus number N+1. Therefore,

$$I_Y = 0, V_1 = V_S, V_{N+1} = V_{DR}, I_{N+1} = I_{DR}$$

Replacing the above Eqs in Eq (3) yields:

$$\begin{bmatrix} Y_A & Y_B & Y_C \\ Y_B^T & Y_D & Y_E \\ Y_C^T & Y_E^T & Y_F \end{bmatrix} \begin{bmatrix} V_S \\ V_Y \\ V_{DR} \end{bmatrix} = \begin{bmatrix} I_S \\ 0 \\ I_{DR} \end{bmatrix} \tag{4}$$

Since utility voltage is fixed at its nominal level, V_s always has the value of 1.0p.u. Putting $V_s=1$ into Eq(4) and rearranging it result in [20].

$$V_Y - Y_D^{-1}\left[Y_B^T + Y_E (Y_F - Y_E^T Y_D^{-1} Y_E)^{-1} (I_{DR} - Y_C^T + Y_E^T Y_D^{-1} Y_B^T)\right] \tag{5}$$

Assuming $I_{DR} = 0$, it follows from the above that:

$$V_Y^{ini} = -Y_D^{-1}\left[Y_B^T + Y_E (Y_F - Y_E^T Y_D^{-1} Y_E)^{-1} (-Y_C^T + Y_E^T Y_D^{-1} Y_B^T)\right] \tag{6}$$

The voltage changes at buses number 2 to N in the system with the DG, are calculated by subtracting (6) from (5), as the following:

$$\Delta V_Y = -Y_D^{-1} Y_E (Y_F - Y_E^T Y_D^{-1} Y_E)^{-1} I_{DR} \tag{7}$$

or, equivalently

$$\Delta V_Y = m I_{DR} \tag{8}$$

In the above equation, m is the coefficient matrix with dimension (N-1) used for calculation of the voltage changes corresponding to buses from 2 to N.

Connection of DG into the system results in new voltages. These new voltages can be obtained either from (6) or by superposition of the initial voltage and the voltage variation of each individual load, as calculated in (8). The latter approach yields:

$$\begin{bmatrix} V_s \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} V_s \\ V_2^{ini} \\ \vdots \\ V_N^{ini} \end{bmatrix} + \begin{bmatrix} 0 \\ m_2 \\ \vdots \\ m_N \end{bmatrix} I_{DR} \tag{9}$$

where V_k^{ini} and V_k are voltages of the system without the DG and with the DG, respectively

2.2 Maximizing loss reduction by DG placement

Losses in power systems depend on the current flow in the lines, as well as the line parameters (resistance r and reactance x). The real and reactive power losses are I^2r and I^2x, respectively. These losses are unwanted due to the fact that they confine system efficiency and increase the total cost of electricity. Although system losses are inevitable, they can be minimized by planning and operating distribution networks in an optimal way. Optimal placement of DGs in the power distribution system can significantly reduce the losses, since DGs that are located appropriately can support the adjacent loads locally and this can reduce the overall current circulating in the network. The active losses can be represented as

$$P_L^{ini} = \sum_{j=1}^{n_{br}} \left| I_j \right|^2 r_j \tag{10}$$

where n_{br} denotes the total number of branches in the system and I_j and r_j denote the values of the current and the resistance corresponding to the branch number j, respectively.

$$I_j = (V_{ja}^{ini} - V_{jb}^{ini})Y_j \tag{11}$$

If the voltages of the sending end point (a) and the receiving end point (b) of the line number of j by are denoted by V_{ja}^{ini} and V_{jb}^{ini}, and the admittance of line j is shown as Y_j, (10) and (11) result in :

$$P_L^{ini} = \sum_{j=1}^{n_{br}} \left| (V_{ja}^{ini} - V_{jb}^{ini})Y_j \right|^2 r_j \tag{12}$$

The bus voltages change due to the DG inclusion in the system. Therefore, the new system power losses will become:

$$P_L = \sum_{j=1}^{n_{br}} \left| (V_{ja} - V_{jb})Y_j \right|^2 r_j \tag{13}$$

Replacing V_{ja} and V_{jb} by $V_{ja}^{ini} + \Delta V_{ja}$ and $V_{jb}^{ini} + \Delta V_{jb}$, results in:

$$P_L = \sum_{j=1}^{n_{br}} \left| \left[(V_{ja}^{ini} + \Delta V_{ja}) - (V_{jb}^{ini} + \Delta V_{jb}) \right] Y_j \right|^2 r_j \tag{14}$$

Substituting ΔV_{ja} and ΔV_{jb} from (8) into (14), leads to:

$$P_L = \sum_{j=1}^{nbr} \left| \left[(V^{ini}_{ja} - V^{ini}_{jb}) + (m_{ja} - m_{jb}) I_{DR} \right] Y_j \right|^2 r_j \tag{15}$$

The active loss reduction of the system due to the inclusion of DGs can be calculated by subtracting (15) from (12). The reduction in the power losses of the system is thus:

$$\Delta P_{Loss} = \sum_{j=1}^{n_{br}} \left\{ \begin{array}{l} \left| (V_{ja}^{ini} - V_{jb}^{ini})Y_j \right|^2 - \\ \left| \left[(V^{ini}_{ja} - V_{jb}^{ini}) + (m_{ja} - m_{jb}) I_{DR} \right] Y_j \right|^2 \end{array} \right\} r_j \tag{16}$$

3. VOLTAGE REGULATOR

Voltage regulator is actually an auto-transformer which is able to adjust the tap, automatically. This device has normally 32 taps which is able to adjust the voltage within a ±10% %10 range. Voltage regulator can be exploited in both single-phase and three-phase configurations. The single-phase types are more usual than the three-phase ones [21]. The connection of single-phase voltage regulators in three-phase systems is usually performed in open-triangle and closed-triangle configurations. For the single-phase voltage regulator, the relations between currents and voltages of the source vs. input currents and voltages can be expressed as [22]:

$$V_L = \frac{1}{a_R}.V_S,\ I_L = a_R.I_S,\ a_R = 1 \mp \frac{N_2}{N_1},\ d = \frac{1}{a} \tag{17}$$

Figure (1) depicts the main three-phase model for the all connections.

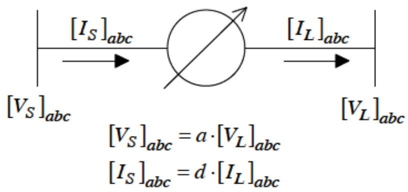

Figure 1. The model of a three-phase voltage regulator

In this paper, a combination of the forward / backward load flow [23] and the genetic algorithm has been proposed in order to place the voltage regulator.

4. THE PROPOSED METHOD

In this paper, the genetic algorithm strategy has been utilized in order to enable the joint realization of two distinct goals, i.e. the effective placement of the DGs and VRs simultaneously, on the one hand, and determination of the optimal size of DGs, on the other hand. A binary code method has been widely exploited in the literature to simulate and implement the genetic algorithm. In contrast, a real value coding method has been used in this paper in order to minimize the running time of the program. The reason for selection of the value coding method is the fact that the use of the binary coding results in considerably long running time and maybe inaccurate results. The main principles of the genetic algorithm and its details have been widely discussed in [24].

5. SIMULATION STUDY

5.1 The test system

The system under study is the IEEE 33 bus system, which its data has been presented in [25]. Figure (2) illustrates this network. The assumed base values for per-unit parameters are V_b = 12.66 kV and S_b = 10MVA.

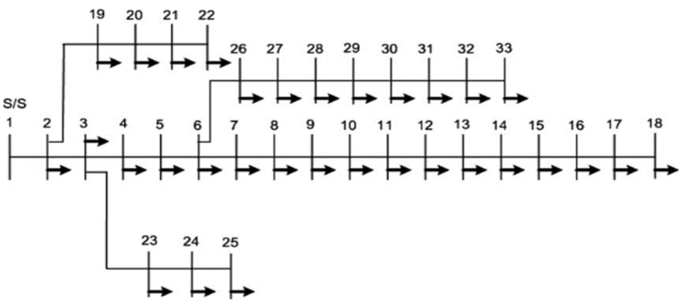

Figure 2. IEEE 33 bus system used in the simulation study

5.2 Placement of DG

Figure (3) shows the buses voltage variation due to inclusion of a DG connected to the load bus number 13 through the impedance of the DG equal to Z_{DG}=0.01+ j 0.01. The adopted approach is to consider the DG as the negative resistor and then combining the forward-backward load flow and the genetic algorithm to find an optimal solution. However, the forward-backward load flow approach - in its ordinary form - is not applicable for high capacity DGs, since it tends to diverge in such scenarios. Moreover, this approach cannot determine the efficient places of DGs precisely, when low capacity DGs are used and has been proved to be useful only in determination of the place of the local compensators.
According to (16), Simulation results show that the power losses of the studied network has been reduced by 0.0033 per-unit after inclusion of the DG. It is worth mentioning that this improvement has been attained in case of a DG with limited capacity.

5.3 Placement of voltage regulator

The framework used to model the voltage regulator is exactly similar to that used for auto-transformer and all of the relations that describe the voltages and currents are the same. The ratio and the impedance used for modelling the voltage regulator within the present simulation are a_r=N_1:N_2=0.9 and Z=0.1+ j 0.01.

As stated before, placement of the voltage regulator in this paper has been carried out by performing the forward-backward load flow algorithm. Figure 4 illustrates the voltage variations of the network busses after placement of the voltage regulator on the branch between the busses number 4 and 5, as a sample scenario. Simulating results also illustrate that the placement of the voltage-regulator on the branch between the busses number 4 and 5 reduces the real losses by 0.0022 pu.

5.4 Coordinated placement of VR and the DG

The flowchart of figure (5) shows the process used to jointly determine the optimal place of both DG and VR as well as the optimum size of the DG. To combine these three methods one should firstly determine the objective function, and run the genetic algorithm over the network according to the determined objective function in the next step.

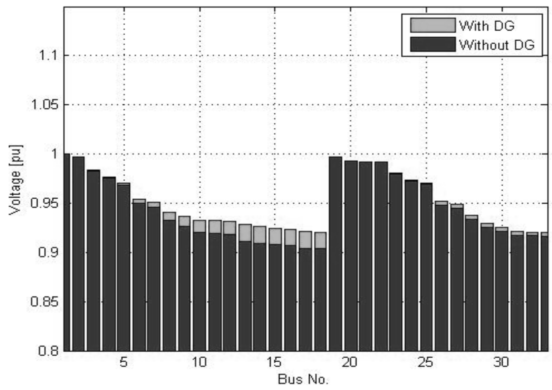

Figure 3. Voltage regulation of the system in the presence of DG

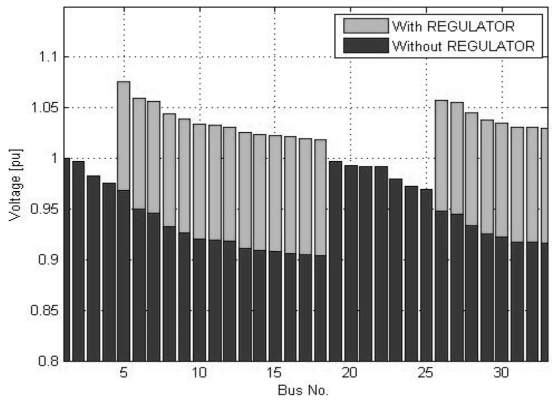

Figure 4. Voltage variation in the network in the presence of the voltage regulator between buses 4 and 5

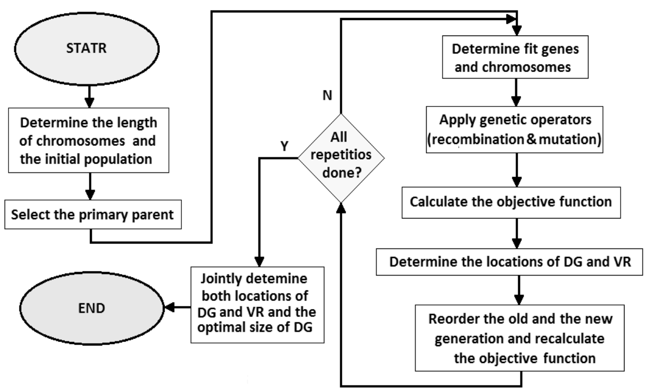

Figure 5. The flow chart of the overall process of simulations in the proposed algorithm

In the implementation of the genetic algorithm in this paper, 12 chromosomes are considered, where the length of each chromosome is equal to 2. Therefore, there are 12 couples of genes. The process of Figure 5 has been performed for 5 standard sizes of DG over the distribution network in the city of Esfahan, Iran. The 5 standard sizes considered for the DG are shown in table 2. For each DG size, the best place of both DG and VR are obtained by minimizing the following objective function.

$$f\ (\Delta V_{\text{tot}}, \Delta P_{\text{tot}}) = \frac{\gamma_1 \alpha}{\Delta V_{\text{tot}}} + \frac{\gamma_2 \beta}{\Delta P_{\text{tot}}} \qquad (18)$$

$$\gamma_1 = 2\ ,\ \gamma_2 = 5,\ \alpha = \left[\sum |V_i - 1|\right]^{-1},\ \beta = 0.001$$

Table 2. The different sizes of DGs considered in simulations

IDR (pu)	DG size (KW)
0.02-0.02i	50
0.04-0.04i	100
0.08-0.08i	200
0.12-0.12i	300

In (18), V_i is the voltage of the bus number i (i = 1, 2, … 33) and α and β are the scaling factors used to convert the variations in voltages and power losses into per-units, respectively. γ_1 and γ_2 are the coefficients used to make relative prioritization between the voltage variation and the power losses in the objective function, values of which should be determined by the policy of utility. In this paper, these values have been selected as γ_1=2 and γ_2=5. The number of chromosomes for the recombination phase (N_c) and mutation phase (N_m) during the operation of the genetic algorithm are yielded from equations of (19) and (20).

$$N_C = 2.\text{round}\ (P_c n_{po} / 2) \qquad (19)$$

$$N_m = \text{round}\ \left(p_m n_{po}\right) \qquad (20)$$

where n_{po} is the initial chromosome population, p_c is the recombination coefficient (which is normally between 0.6 and 0.95 and is set to 0.6 in the present simulation) and p_m is the mutation coefficient (which is normally between 0.1 and 0.3 and is set to 0.3 in this simulation). The values of N_c and N_m obtained from the above equations in the present simulation are equal to 10 and 4, respectively.

Table 3 shows the optimum values of the objective function (obtained at the optimal location of DG and VR). The results are calculated using 25 iterations of the proposed algorithm, for each size. The best result (i.e. the smallest value of the objective function) is achieved for the 500KW DG, by placement of the VR between the busses number 6 and 7.

Table 3. The optimal locations of DG and VR and the value of the objective function for five DG sizes

Size of DG	Location of DG	Location of VR	The value of the objective function
50	19	6-7	3.1309
100	23	6-7	3.0243
200	23	6-7	2.8978
300	3	6-7	2.6420
500	3	6-7	2.4276

In order to illustrate the convergence trend of the algorithm, diagram of the value of the objective function vs. number of iterations for the 50KW DG is depicted in Figure 6. The result has converged in the fourth iteration and preserves its convergence until the 25th iteration, which confirms the reliability of the response.

Without the DG, the best place for the VR is between buses number 3 and number 4. However, when the DG is present, the convenient location of the VR, which optimizes the objective function, is between buses number 6 and number 7. Since the considered DG sizes are quite close to each other, the difference between the optimal values of the objective function in the five scenarios are also quite small. This observation confirms the validity of the process, since the small difference between voltages and power losses in different scenarios results in s a slight discrepancy in the objective functions corresponding to the five scenarios.

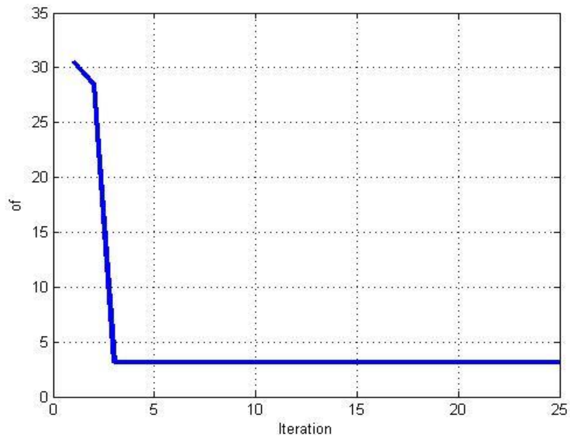

Figure 6. The value of the objective function vs. iteration number for the 50KW DG

6. CONCLUSION

In this paper, the optimal coordinated placement of DGs and VRs using the genetic algorithm is considered for different sizes of the DGs. Appropriate simulations have been carried out over the IEEE 33 bus system to support the method proposed in this paper. The results show that placement of DGs and VRs according to the proposed method will lead to significant reductions in the voltage drops and power losses of the whole system. The proposed method is also easily applicable to large networks. Due to limitations on the DG size available in the market, the DG capacity would not be determined by the genetic algorithm, during the optimization process.

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NOMENCLATURE

V_l	The secondary voltage,
V_s	The source voltage,
a_r	The ratio of voltage regulator,
I_s	The primary side current (source),
I_L	The secondary side current (output).
Y_{bus}	The admittance matrix
I_{DR}	The current injected by DG