OPTIMAL PLACEMENT OF NON-SITE SPECIFIC DG FOR VOLTAGE PROFILE IMPROVEMENT AND ENERGY SAVINGS IN RADIAL DISTRIBUTION NETWORKS

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Abstract. *This paper proposes a model based on Fuzzy Genetic Algorithm (FGA) to determine the optimal capacity and location of a DG unit in a radial distribution network. In the FGA, a fuzzy controller is integrated into GA to adjust the crossover and mutation rates dynamically to maintain the proper population diversity during GA's operation. This effectively overcomes the premature convergence problem of the simple genetic algorithm (SGA). The main objective functions considered in this study are maximisation of cost savings arising from energy loss, minimisation of voltage drops across all lines, and maximisation of the transfer capability of the system. The model takes into account the peculiarities of radial distribution networks, such as high R/X ratio, voltage dependency and composite nature of loads. The proposed model is evaluated on three radial test distribution systems, and the results obtained are very impressive, with high computational efficiency, when compared with those of the existing approaches cited in the literature.*

Keywords

Distributed generation, fuzzy genetic algorithm, radial distribution systems, voltage profile.

1. Introduction

Generally speaking, the term distributed generation (DG), also known as embedded generation (EG) or decentralised generation (DG) in some quarters is defined as any source of electric energy of limited capacity that is directly connected to the existing power grid distribution network, where it is required by the end-users. Presently, there is no consensus on what exactly the capacity limit of DG as well as the voltage level at the point of common coupling (PCC) to the grid should be. The definitions of these two parameters somewhat vary from country to country [1]. The potential benefits, the drivers responsible for the recent global surge in the interest for DG in the realm of power generation, as well as the issues in connecting DG to the existing grid, have been well reviewed and reported by the authors [2].

To maximise the benefits of DG and/or avoid putting the system operation in jeopardy, we clearly need to optimise DG size and location on the system. Previous research has shown that improper location of DG units on the system could result in more total line loss. To this end, a number of researchers have proposed different approaches in determining the best capacity and placement of DG sources in power distribution networks. A critical review of these approaches has been carried out and reported in [3], and so only a few of them would be referenced in this paper. For example, Acharya, et al. [4] used exact loss formula which involves the calculation of the bus admittance from its impedance to determine the optimal size and location of DG. However, the large size and complexity of distribution networks would render this approach to fall short of the robustness requirements.

Elnashar [5] categorised the impacts of DG on the distribution systems as positive, e.g. voltage profile improvement, and negative, such as increased system loss and short circuit level, and used these to formulate a multi-objective function. This problem formulation is flawed because DG would lead to increase in loss only when it is sited in improper locations, and so its impact cannot be considered negative in all cases. Hedayati et al [6] used continuation power flow to determine the most sensitive buses to voltage collapse. In [7], Tabu search approach was employed, and Kumar et al [8], [9] adopted genetic algorithm (GA) approach, while Haghifam [10] used the concept of Pareto optimality based on non-dominant sorting genetic algorithm (NSGA-II) for the optimisation problem. Two analytical approaches for meshed and radial networks were proposed by Wang and Nehrir [11], even though DG size was not optimised, and Celli et al [12] combined GA with ϵ-constrained technique for the multi-objective problem.

However, a number of these early works [4], [6], [7], [8], [9], [12], [13] did not consider the effect of load modelling in their studies. It is pertinent to mention here that constant power load model is commonly used in the power flow studies of most conventional load flow techniques. Adopting this model alone for distribution systems will not however, give accurate results in view of the voltage dependency nature of most load buses. Therefore, to present a real life scenario, distribution systems require a composite of constant power, constant current and constant impedance load models as adopted in this work.

Similarly, the popular load flow algorithms such as Gauss Siedel, Newton Raphson, and Fast decoupled methods that are usually employed for power flow analysis of transmission networks were adopted by many of these early works [4], [6], [7], [9]. These methods would not work efficiently for radial distribution systems due to the special peculiarities of the latter. Details of this are discussed in Section 3. On the strength of the foregoing, a new power flow technique proposed for radial distribution systems by Eminoglu and Hocaoglu [14] is adopted for the power flow studies carried out in this paper.

The focus of this study is, therefore, to formulate a multi-objective model to determine the optimal capacity and location of a single DG unit in a radial distribution network. A single DG unit is considered on the distribution feeder since connection of a higher number may not be economically viable and could lead to violation of certain system constraints. The objectives considered in the present work are maximisation of energy loss cost savings, minimisation of lines voltage drops, and maximisation of the power transfer capability of the network. These are formulated into a single multi-objective function, and solved using fuzzy genetic algorithm (FGA).

In the proposed approach, weighting factors are allocated to each objective according to the preference of the system planner at any particular time. Also, the composite voltage-dependent load modelling carried out in our previous work, to reflect a real life scenario in the distribution systems, is adopted in this study. The results obtained from the proposed model are compared with those obtained from the existing methods, and they are found to be more accurate (optimal) and computationally faster. The proposed model in this work is suitable for non-site specific DG such as microturbine, diesel generators, fuel cell units, etc.

The present work is suitable for an Independent Power Producer (IPP) in an unbundled deregulated energy market environment, where a generating company's main target is to produce and sell electricity to attain a maximum profit without accurately satisfying system demand/reserve. In this study, a decentralised scheduling, such as that obtainable in Norway, where scheduling is the responsibility of individual generating companies, is assumed. Since the objective of an IPP is to maximise profit, the scheduling is done as if all generation is sold in the spot market. Therefore, generation is assumed at full capacity of the DG unit.

2. Problem Formulation

The aim of the multi-objective function formulated in this study is to maximise the energy loss cost savings, minimise voltage drops across all lines, and to maximise the power transfer capability of the system. Each of these is treated next in the literature.

2.1. Energy Loss Cost Savings (ELCS) Maximisation

The energy loss cost savings for the distribution company (DISCO) could be maximised by installing a DG unit in the system. The mathematical expression given in Eq. (1) is formulated for this objective function. It is the percentage decrease in total energy loss cost when a DG is installed in the network and run for T_d hours in a year. It is desired to have a DG size that maximises this objective function when located at a particular bus.

$$\max(ELCS) = \frac{C_E \sum_{m=1}^{N-1} T_d \left(P_{Lm}^{B} - P_{Lm}^{DG}\right)}{C_E \sum_{m=1}^{N-1} T_d P_{Lm}^{B}}. \quad (1)$$

This expression is subject to Eq. (2).

$$0 \leq \sum_{m=1}^{N-1} P_{Lm}^{DG} < \sum_{m=1}^{N-1} P_{Lm}^{B}, \tag{2}$$

where C_E is unit energy cost [\$/MWh]; P_{Lm}^{B} and P_{Lm}^{DG} are line m active power loss without and with DG installation respectively; N is the number of buses.

2.2. Line Voltage Drop (LVD) Minimisation

To improve the voltage profile of all buses, it is essential to minimise the voltage drop on all lines of the network. Voltage drops are a consequence of increased line loading, as well as line losses. The higher the line loading, the higher the losses incurred and consequently the higher the voltage drop on the line. Given the ever-increasing demand for power, power systems are expected to be more heavily loaded in future. On the strength of this, there is need to minimise voltage drops in anticipation.

The active power loss prior to DG connection to the network on line m is presented in Eq. (3) [15], where line m is between buses i and j. ΔV_m, R_m, and X_m are voltage drop, resistance, and reactance of line m respectively.

$$P_{Lm} = \Delta V_m^2 \frac{R_m}{R_m^2 + X_m^2}. \tag{3}$$

The voltage drop on line m, from the expression in Eq. (3), is as given in Eq. (4).

$$\Delta V_m = \sqrt{\frac{P_{Lm}\left(R_m^2 + X_m^2\right)}{R_m}}. \tag{4}$$

Now the total voltage drops on the system is a sum of the voltage drop on all the lines of the power system, which is formulated as in Eq. (5).

$$\sum_{m}^{N-1} \Delta V_m = \sum_{m}^{N-1} \sqrt{\frac{P_{Lm}\left(R_m^2 + X_m^2\right)}{R_m}}. \tag{5}$$

Minimising the voltage drop on a line is synonymous to maximising the difference between the voltage drop on the line before and after DG connection to the network. This can be formulated in percentage form as in Eq. (6).

$$\min(VLD) = \max\left(\frac{\sum_{m=1}^{N-1} \Delta V_m^B - \sum_{m=1}^{N-1} \Delta V_m^{DG}}{\sum_{m=1}^{N-1} \Delta V_m^B}\right). \tag{6}$$

In other words, the highest value of the expression on the RHS of Eq. (6) minimises the LVD.

2.3. Power Transfer Capability (PTC) Maximisation

The power transfer capability PTC, of a power system is the maximum power that can be transported via a power line from one point to another, without compromising the system security. DG is a viable alternative to distribution system expansion in response to the ever-increasing population growth since environmental and economic constraints prohibit expansion of the existing system. The overall PTC of a distribution system could be computed from Eq. (7), which is the sum of all the power transported on a line m, when P_{DG} size is connected to bus B_k.

$$\begin{aligned} PTC &= \\ &= \frac{\left(\left(P_{DG}^{B_k} + P_{sw}\right) - \sum_{m=1}^{N-1} P_{Lm}^{DG}\right) - \left(P_{sw} - \sum_{m=1}^{N-1} P_{Lm}^{B}\right)}{P_{sw} - \sum_{m=1}^{N-1} P_{Lm}^{B}}. \end{aligned} \tag{7}$$

Simplifying the expression in Eq. (7) leads to Eq. (8).

$$(PTC) = \frac{P_{DG}^{B_k} - \sum_{m=1}^{N-1} P_{Lm}^{DG} + \sum_{m=1}^{N-1} P_{Lm}^{B}}{P_{sw} - \sum_{m=1}^{N-1} P_{Lm}^{B}}. \tag{8}$$

Equation (8) is subject to bus voltage, line thermal limit and DG capacity constraints presented in Eq. (9).

$$\begin{gathered} |V_i|_{\min} \leq |V_i| \leq |V_i|_{\max} \; S_m \leq S_m^{\max} \\ \text{and } P_{DG} \leq 0.4 \sum_{i=1}^{N} P_{Di}. \end{gathered} \tag{9}$$

In fixing the maximum DG capacity constraint, [7] assumed 35 % of the total connected loads. On the other hand, [11] varies DG capacity from 47 to 100 % of the total load demand while [4] and [13] obtained an optimal DG size equal to 47.63 % of the load demand on the test system. However, DG capacity is constrained to 40 % of the total system load demand in this study to avoid any provocation of power quality and protection issues, particularly during the contingency period. This is based on the outcome of our earlier studies on the impact of different penetration levels of DG on the overall network during fault periods.

2.4. The Multi-Objective Function (MOBF)

Combining the three individual objective functions formulated in the previous subsections results in the expression presented in Eq. (10). The bus B_k that maximises MOBF when P_{DG} is sited there is regarded the optimal location in this study. The essence of the percentage in each objective function is to scale them individually so as to have the same magnitude range.

$$MOBF_{Bk} = \max\left(W_1 ELCS + W_3 PTC\right) + \min\left(W_2 LVD\right), \tag{10}$$

where the weighting factors $W_1 + W_2 + W_3 = 1$; (0.4, 0.3 and 0.3 respectively as used in this work). These weights are allocated by the system planner to indicate the relative importance of each objective.

3. Power Flow Method and Static Load Modelling

The popular conventional power flow techniques such as Gauss-Seidel, Newton Raphson, and Fast decoupled methods, usually employed for solving transmission system load flow problems, have been reported to be inefficiently suitable for solving radial distribution systems [13], [14], [16]. In spite of the robustness of Gauss Seidel method, it requires many iterations that consequently slows it down. Newton Raphson (NR) method requires a large computer memory, and worse still the high R/X ratio of distribution systems makes its convergence poor. Actually, fast decoupled approach has the advantage of computational speed and small storage facility when compared to NR. However, the assumptions usually made to simplify the analysis such as: the bus voltage magnitudes are close to 1 p.u, the phase angles are not large in magnitude, and R is far less than X, and therefore ignored [17]; are often invalid in distribution system applications. These are due to the special features of distribution systems which include their radial configuration, wide-ranging resistance and reactance values, unbalanced distributed loads, extremely large numbers of branches and nodes, etc.

On the strength of the foregoing, a power flow technique that would sufficiently take into cognisance, all these special features of distribution systems, and yet with a good convergence performance is required. As a result, the new power flow technique proposed by Eminoglu and Hocaoglu [14] known to offer a better solution for radial distribution networks with voltage-dependent loads, is employed in this study. This method is based on polynomial equations on the forward process and backward ladder equations for each branch of radial distribution systems. Line shunt capacitance and exponents of static load are incorporated in the said power flow method.

In carrying out power flow studies, most conventional techniques assume constant power at load buses, regardless of the voltage magnitude of such buses. This approach is usually employed in transmission networks. However, this assumption would not give accurate results when applied to distribution networks. The reason being that different types of loads such as residential, commercial, as well as industrial loads are commonly found in distribution systems. By the nature of these types of loads, their active and reactive powers are determined by the values of the voltage of the system; hence, they are referred to as voltage-dependent loads.

To reflect this scenario, the steady-state active and reactive load power demand at bus j can be expressed in an exponential form as given in Eq. (11) and Eq. (12) respectively.

$$p_{Dj} = p_{Dj}^{n}\left(\frac{V_j}{V_j^n}\right)^{n_p}, \tag{11}$$

$$Q_{Dj} = Q_{Dj}^{n}\left(\frac{V_j}{V_j^n}\right)^{n_q}, \tag{12}$$

where n_p and n_q are the load power exponents. Values of 0, 1, and 2 are respectively allocated to np and nq for constant power, constant current, and constant impedance loads. Other common exponential values for different static load models could be found in [14]. P_{Dj}^n and Q_{Dj}^n stand for the active and reactive power demand at bus j at the nominal voltage V_j^n; while the j load bus voltage is represented by V_j.

As it is generally known that distribution loads are composite loads that comprise of constant impedance (Z), constant current (I), and constant power (P). This load model in Eq. (11) and Eq. (12) is called ZIP model, which could be modified to reflect the composite nature of the voltage-dependent loads, as presented in Eq. (13) and Eq. (14).

$$P_{Dj} = P_{Dj}^{n}\left(\alpha\left(\frac{V_j}{V_j^n}\right)^2 + \beta\left(\frac{V_j}{V_j^n}\right) + \gamma\right). \tag{13}$$

$$Q_{Dj} = Q_{Dj}^{n}\left(\alpha\left(\frac{V_j}{V_j^n}\right)^2 + \beta\left(\frac{V_j}{V_j^n}\right) + \gamma\right). \tag{14}$$

4. A Brief Overview of Fuzzy Genetic Algorithm

4.1. Genetic Algorithm (GA)

Genetic algorithm (GA) is a stochastic search and optimisation technique based on the mechanism of natural selection and natural genetics [18]. It begins with an initial set of random solutions known as *population*. The population is composed of individual *chromosomes*, each of which represents a possible solution

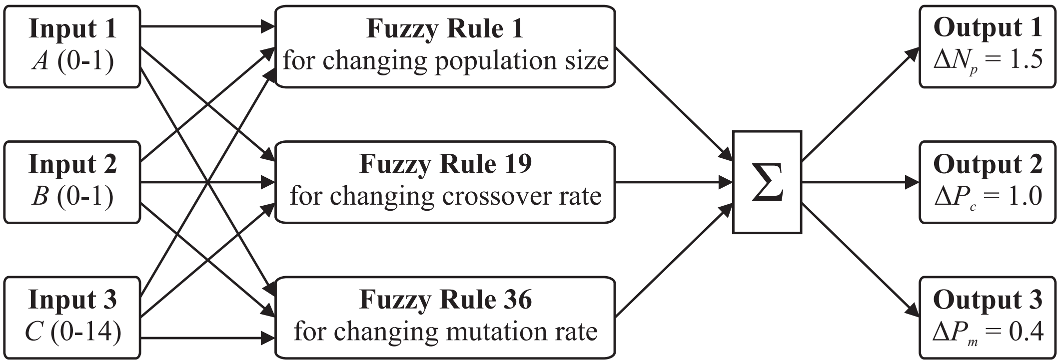


Fig. 1: Fuzzy inference process.

to the optimisation problem at hand. These chromosomes, which are usually binary bit strings, evolve through successive iterations, otherwise known as *generations*.

A common method of encoding GAs is binary encoding; other types include *permutation*, *value*, and *tree* encodings. In binary encoding every chromosome is a string of bits, 0 or 1. The function to be optimised, called the objective function, provides the mechanism to evaluate each string. To maintain uniformity over various problem domains, *fitness function* is used to scale the objective function to a convenient range of 0 to 1. Similar to other optimisation techniques, GAs have certain control parameters which include population size, crossover rate, and mutation rate. The choice of the control parameters, often left to the GA user, itself can be a complex nonlinear optimisation problem [19], [20].

In this study, each DG is represented by a string of 8 binary bits, which depicts the size of DG, P_{DG}. In order to represent the location in the system, a new string B_k, also of 8 binary bits is created. Therefore the solution to the optimisation problem is a concatenation of the two strings. In other words, $P_{DG}B_k$ that is a possible solution to the optimisation problem now contains 16 bits. With an initial population size, N_p of 30, it has a total of $30 \times 16 = 480$ bits.

4.2. Fuzzy Set Theory

Unlike a *classical* set that either wholly includes or wholly excludes any given element, a fuzzy set is a set without a clearly defined boundary. It can contain elements with only a partial degree of membership. In fuzzy logic, the truth of any statement is a matter of degree [21]. Fuzziness measures the degree to which an event occurs, and not whether it occurs or not. The use of fuzzy methods by rule-based systems is applied to solve many types of real life problems. This application becomes necessary most especially when a system is difficult to model using the conventional Boolean models; controlled by a human operator, or when ambiguity or vagueness is common [22].

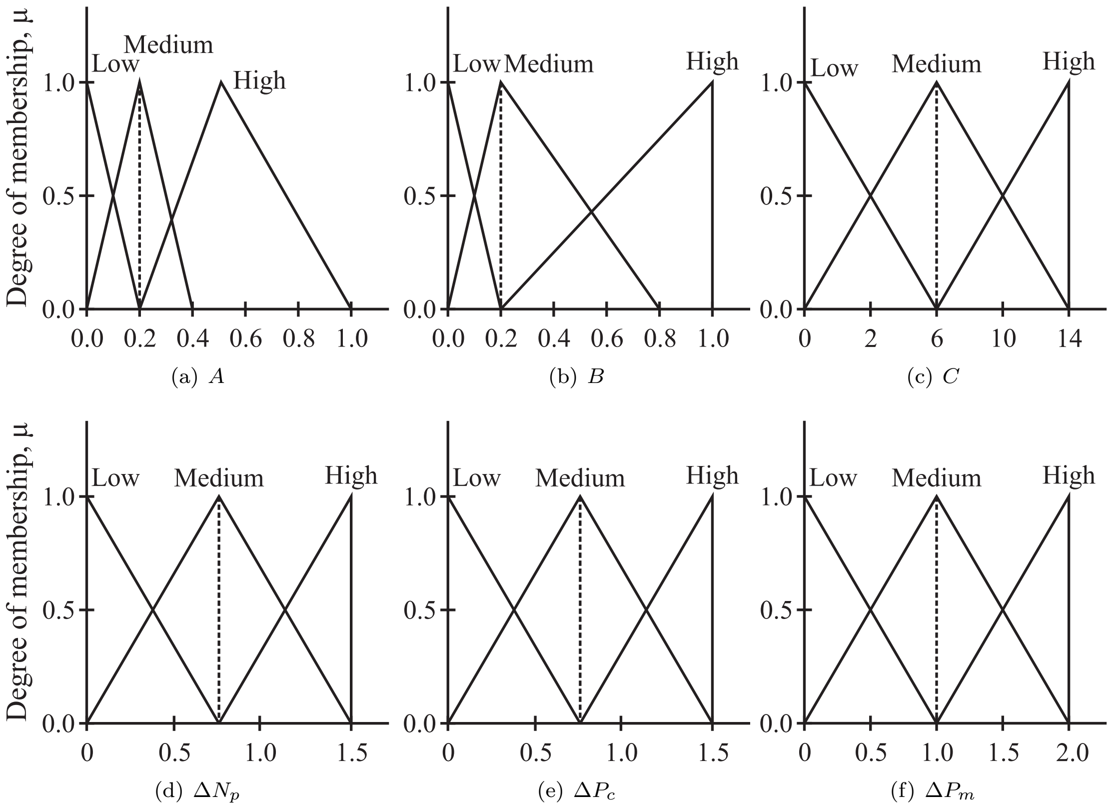
Fuzzy Inference Systems is the process of formulating the mapping from a given input to an output using fuzzy logic. This mapping then provides a basis from which decisions could be made. The most popular type of fuzzy inference is the Mamdani-type proposed in 1975 [23], and the other commonly used is the Sugeno-type. While the two are similar in many respects, the main difference between them is that the latter's output membership functions are either linear or constant, but the former has continuous value output. The process of fuzzy inference system shown in Fig. 1 consists of membership functions, logical operations, and IF-THEN rules.

1) Membership Functions (MFs)

Membership function (MF) is defined as a curve that describes the way each point in the input space is mapped to a membership value of between 0 and 1. A "0" value signifies none membership while 1 means full membership. Other possibilities are in-between these two values. The simplest MFs are built using straight lines to form *triangular* or *trapezoidal* MFs. Other types of MFs include *bell*, *Gaussian*, and *sigmoidal* MFs, etc; details of which could be found in [21]. Generally speaking, MFs are usually given the designation μ. Figure 2 illustrates a triangular type of membership functions for both input and output variables, as adopted in this study. Figure 2(a), Fig. 2(b) and Fig. 2(c) are respectively inputs of outputs in Fig. 2(d), Fig. 2(e) and Fig. 2(f). For our FGA, adjacent MFs are allowed to overlap fully.

2) Logical Operations

The most crucial thing to remember about logical reasoning is the fact that it is a superset of standard Boolean logic. In this context, keeping the fuzzy values at their extremes (0 and 1) would hold true, just as



(a) A (b) B (c) C

(d) ΔN_p (e) ΔP_c (f) ΔP_m

Fig. 2: Fuzzy inference process.

in the standard logical operations. In standard logical operations, logics AND, OR, and NOT are popularly used. To preserve the results of AND truth table, *min* operation could be used in fuzzy logic. In other words, A AND B could be written as *min*(A,B) in fuzzy logic, where A and B are constrained to a range of 0 and 1. Similarly, using the same reasoning, an OR operation can be replaced with the max function, so that A OR B now becomes *max*(A,B). As for the operation NOT A, the equivalent logical reasoning would be operation 1 - A. With these three functions, it is possible to resolve any construction using fuzzy sets and fuzzy logical operation AND, OR and NOT [21].

3) IF-THEN Rules

By using a linguistic approach, fuzzy theory can be integrated into control theory [24]. This could be achieved by using rules of the form IF condition THEN action. The IF part of the rule is called the *antecedent* or premise, while the THEN part is known as the *consequent* or conclusion. From these rules, a functional controller could be created. The maximum number of rules in a system is determined by the number of possible combinations of input sets. In this study for example, three inputs which are composed of three fuzzy sets and three output variables are used. Tab. 3 in the Appendix presents the 51 rules used in this study.

In control applications, the output of a fuzzy knowledge-based system should be a single crisp value. This is achieved by the process of *defuzzification*. In this study, defuzzification of the outputs was performed using the fuzzy centroid [25], which calculates the centre of gravity of the area under the membership function.

5. The Proposed Algorithm

In this study, a fuzzy genetic algorithm (FGA) is created by systematically integrating fuzzy expert systems into GA, to dynamically control the GA parameters during operation. Experiments show that FGA can search faster and more effectively than the simple GA in solving optimisation problems [26]. In achieving this goal, three input variables - $A = (average\ fitness)/(best\ fitness)$, $B = (worst\ fitness)/(average\ fitness)$, and C, which represents the change in the best fitness since the last control action; and three output variables - variations in the current crossover rate P_c, mutation rate P_m, and population size N_p are used in the fuzzy controller. A is defined as a measure of the current population diversity's usefulness. If the value is close to 1 (i.e. high), then convergence has been reached, on the other hand, a low value of close to 0 means the population shows a high level of diversity. These input and output quantities are defined as follows $A \in [0,1]$, $B \in [0,1]$, $C \in [0,14]$, $N_p \in [30,45]$, $P_c \in [0.6,0.9]$, and $P_m \in [0.01,0.015]$ in this study, as implemented in [27].

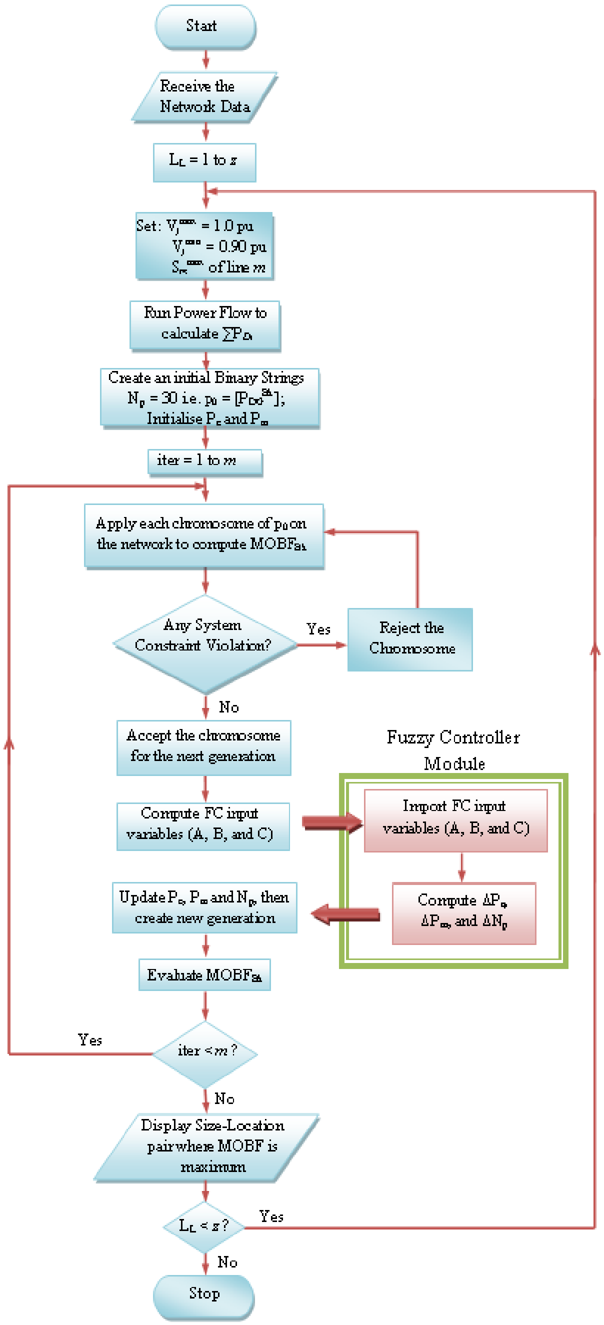


Fig. 3: The proposed algorithm flowchart.

The linguistic value sets of the inputs and outputs are all Low, Medium, High with respect to the lower and upper limit values respectively. The fuzzy IF-THEN rules previously described [22], [28] are adopted to combine fuzzy sets in this paper. The FGA has been executed in this study with an initial population size of 30, and 0.6 and 0.01 as the initial crossover and mutation rates respectively. The maximum generation of 100 is used, using Roulette Wheel selection. The output change ΔP_c, ΔP_m, and ΔN_p are multiplied by the current crossover rate, the mutation rate, and the population size respectively. The results obtained by implementing the 51 fuzzy control rules are presented in Tab. 3 in the Appendix.

The proposed DG placement algorithm for radial distribution systems is summarised in the flowchart presented in Fig. 3. The algorithm is successively implemented in MATLAB. In this work, the best location is determined by selecting the bus with the highest value of MOBF. This is the bus that maximises energy loss cost savings and power transfer capability of the system, and also minimises the sum of voltage drops on all the lines of the network simultaneously.

6. Application to Test Networks

To test the accuracy of the proposed method described in Section 5, three test radial distribution systems are used. A natural gas fired combustion turbine generator is assumed for the DG unit in this study. The results obtained with the approach presented in the literature on the two test systems are very accurate and reliable. This study also assumes there is no forced outage on any of the lines and the substation generator and transformer throughout the period under consideration. In calculating the power loss for the year, three loading levels are adopted; light, normal and heavy loadings.

6.1. Case 1 - 30-Bus Radial Distribution System

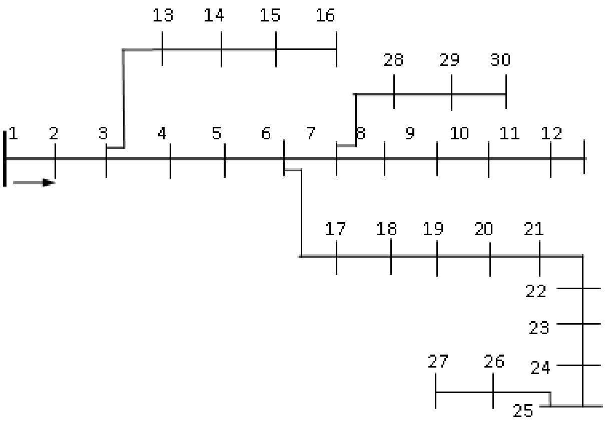


Fig. 4: 30-bus radial distribution system.

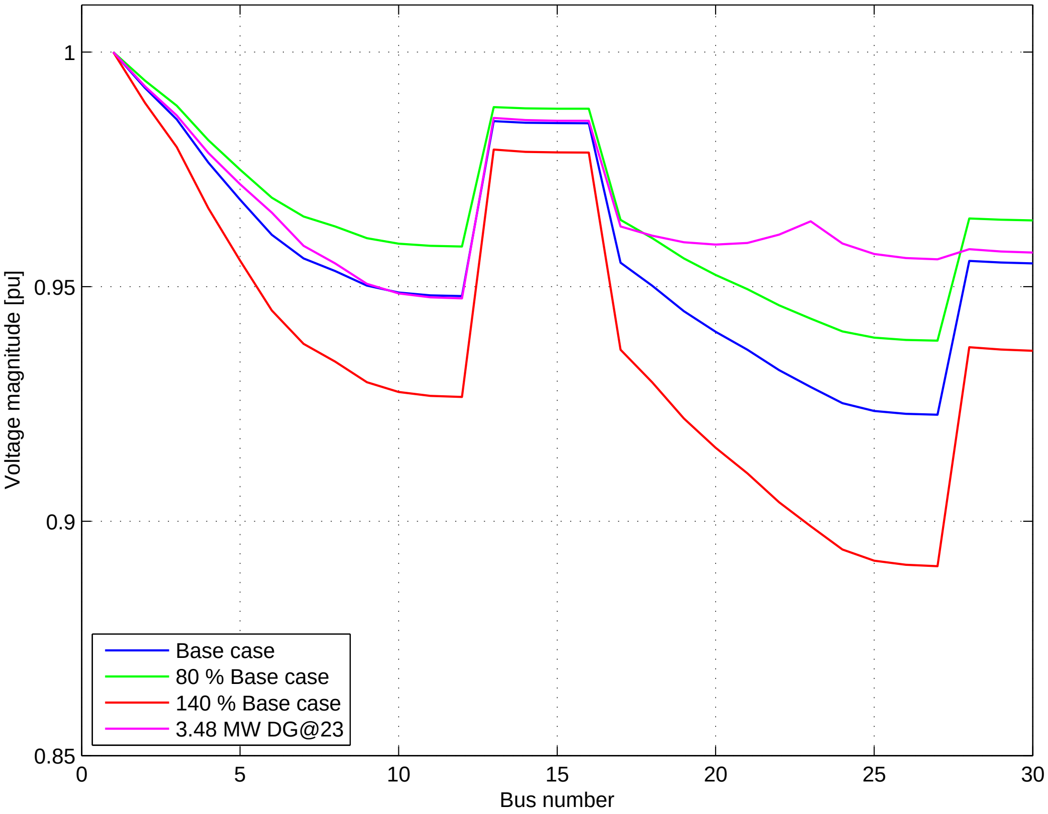


Fig. 5: Voltage profile of the 30-bus system.

The system obtained from [14] is an 11 kV distribution system having 29 load buses and 1 source bus. It has a main feeder and three laterals as shown in Fig. 4. Although the load composition of the distribution system is not stated, the loads have been modelled in this work as composite loads consisting of 46 % constant power, 31 % constant current and 23 % constant impedance. This is done to reflect the real life scenario of distribution systems load models.

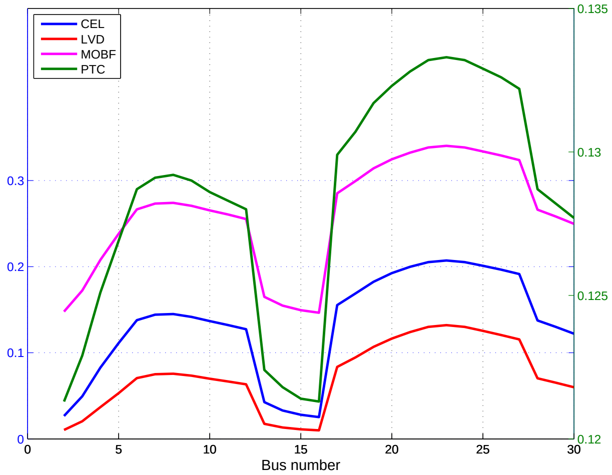


Fig. 6: Objective functions values for the 30-bus system with $W_1 = 0.4$, $W_2 = W_3 = 0.3$.

This test system is slightly modified to have a base case active and reactive powers capacity of 6.22 MW and 3.83 MVar respectively. However, increasing the loading of the system under study linearly at a constant power factor across the buses by 40 % would force some buses to violate the specified voltage limits. For example, buses 23–27 fall below the lower bound of 0.9 V as shown in Fig. 5.

Applying the proposed algorithm to the over loaded system (i.e. 8.7163 MW, 5.4034 MVars); an optimum DG size of 3.48 MW is obtained. The optimum bus is determined from Fig. 6 as the load bus that maximises the multi-objective function, MOBF. This is bus 23; hence declared the best location to site the DG unit. The three objective functions are also plotted in the figure, where the secondary axis is exclusively for the power transfer capability (PTC) objective function.

The effect on the voltage profile of locating the optimal DG size in bus 23 could be seen in Fig. 5. The voltage plots of other scenarios are also shown in the figure. Similarly with a DG unit of 3.48 MW, the power loss is plotted against load buses as shown in Fig. 7. This graph further confirms the results of the proposed model that bus 23 is the best location for the DG since it has the least total system power loss.

Tab. 1: Annual energy loss calculation based on three loading levels.

Load Level	**80 % (light)**		**100 % (normal)**		**140 % (heavy)**	
Duration/yr [hrs]	1 700		4 200		1 300	
30-Bus System						
	With DG	Without DG	With DG	Without DG	With DG	Without DG
Power Loss [MW]	0.1198	0.2445	0.1880	0.3851	0.3711	0.7697
Energy Loss /yr [MWhr]	203.66	415.65	789.60	1 617.42	482.43	1 000.61
Energy Loss Cost/yr [$]	22 198.94	49 878.00	86 066.40	194 090.40	52 584.87	120 073.20
Total Energy Loss Cost per yr [$]	With DG 160 850.21 Without DG 364 041.60					
Savings per year [$]	203 191.39					
69-Bus System						
	With DG	Without DG	With DG	Without DG	With DG	Without DG
Power Loss [MW]	0.0538	0.1329	0.0846	0.2247	0.1677	0.4387
Energy Loss /yr [MWhr]	91.46	225.93	355.32	943.74	218.01	570.31
Energy Loss Cost/ yr [$]	9 969.14	27 111.60	38 729.88	113 248.80	23 763.09	68 437.20
Total Energy Loss Cost per yr [$]	With DG 72 462.11 Without DG 208 797.60					
Savings per year [$]	136 335.49					
With 2.13 MW DG sited at Bus 60 in the 69-Bus System						
	With DG	Without DG	With DG	Without DG	With DG	Without DG
Power Loss [MW]	0.05914	0.1329	0.09318	0.2247	0.18533	0.4387
Energy Loss /yr [MWhr]	100.54	225.93	391.36	943.74	240.93	570.31
Energy Loss Cost/yr [$]	10 958.64	27 111.60	42 657.80	113 248.80	26 361.26	68 437.20
Total Energy Loss Cost per yr [$]	With DG 79 877.71 Without DG 208 797.60					
Savings per year [$]	128 919.89					

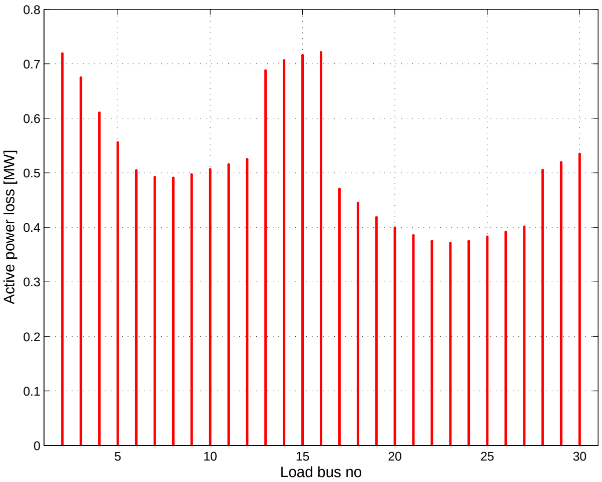


Fig. 7: Power loss with DG at various locations.

Locating a DG unit of 3.48 MW at bus 23 in the test system reduces the total power loss from 0.7697 MW (without DG) to 0.3711 MW. This translates to a savings of $203 191.39 for the DISCO for a period of one year if the DG unit is assumed to run for 300 days in a year. The annual power loss using three loading levels is calculated as shown in Tab. 1. The unit costs of electric energy used in this study are $109 and $120 for DG and grid respectively.

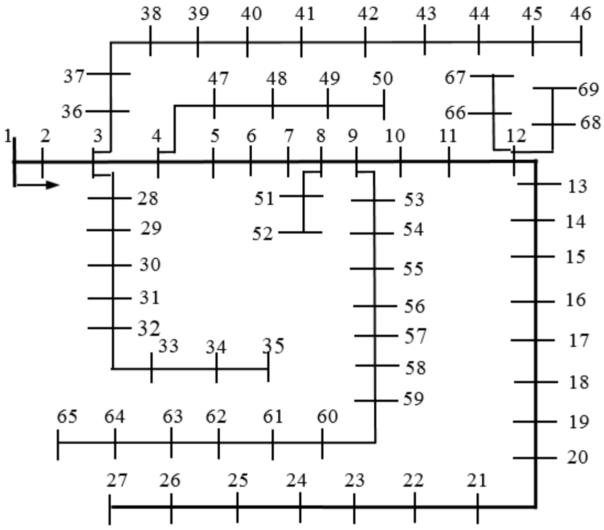


Fig. 8: 69-bus radial distribution system.

6.2. Case 2 - 69-Bus Radial Distribution System

The 69-bus distribution network is as shown in the single line diagram in Fig. 8. The system obtained from [29], has a base case capacity of 3.8021 MW and 2.6945 MVar active and reactive power respectively at 12.66 kV. The load data could be found in the cited reference.

The optimum DG size as determined by the proposed model is 2.13 MW for 140 % base case (5.32 MW, 3.77 MVar) capacity. Looking at Fig. 9, it is found that bus 61 has the maximum value of MOBF at 0.5118; hence, declared the optimal location for the DG. The effect of the weighting factors on each objective function is illustrated in Fig. 10, where MOBF now has a maximum value of 0.4720, though at the same bus.

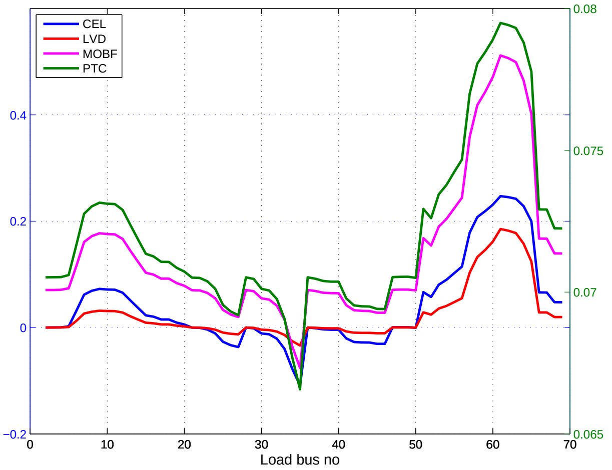


Fig. 9: Objective functions values for the 69-bus system with $W_1 = 0.4$, $W_2 = W_3 = 0.3$.

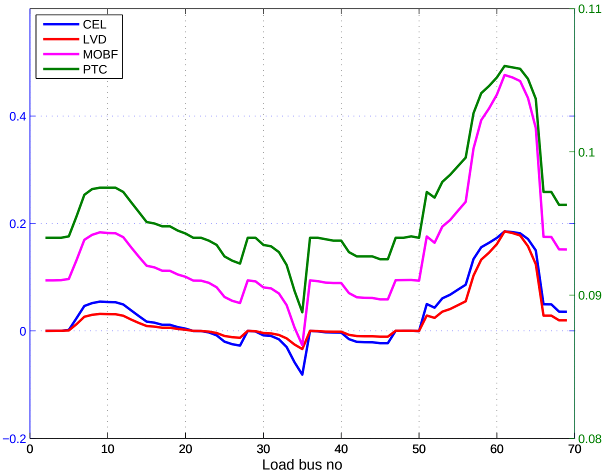


Fig. 10: Objective functions values for the 69-bus system with $W_1 = W_2 = 0.3$, $W_3 = 0.4$.

Interestingly, this is corroborated by the plot in Fig. 11, since the minimum power loss is when the DG is located in bus 61. The power loss without DG is 0.4387 MW; while 0.1677 MW is the recorded loss when 2.13 MW DG is installed on the system. This is equivalent to a savings of $136 335.49 for the DISCO for the period of one year. If for any reason, the IPP decides to install the DG unit at bus 60 instead; his savings reduces to $128 919.89 for the same period as shown in Tab. 1.

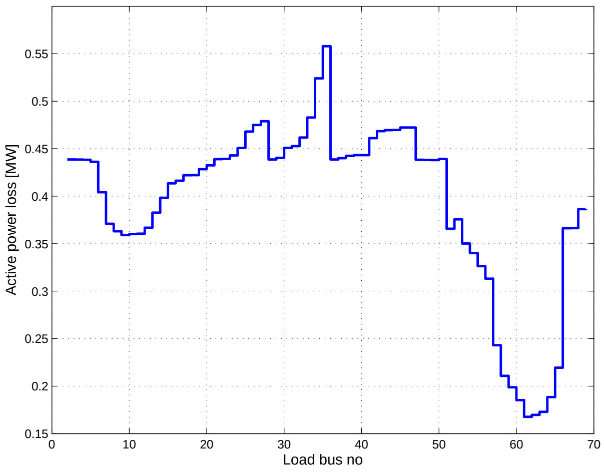


Fig. 11: Power loss with DG at various locations.

Figure 12 shows the voltage profiles of the system at base case, 80 % base case, 140 % base case before DG, and when 2.13 MW DG is installed on bus 61. It is evident from the figure that there is a significant improvement in the voltage profile due to DG connection.

Nevertheless, it is worthy of note that siting the DG size in buses 21–27, 29–35, 37–46, and 50 would amount to a great disservice to the distribution network, as the power loss when DG is placed in any of these buses is greater than when no DG is sited in the system at all. This is shown in Fig. 9 with objective function values less than 0. It is therefore recommended to the IPP not to attempt to site DG in any of these buses.

7. Results Comparison with Others

The results obtained with the proposed approach were evaluated against the existing methods on the base case of a number of test systems, and were found to be highly impressive, as presented in Tab. 2. For example, while the proposed method obtained the optimal size to be 1.5208 MW which results in 0.0877 MW total system power loss on the 69-bus system, Gozel [13] and Vinothkumar [30], whose optimal sizes are 1.8078 MW and 2.0 MW are only able to reduce the total power loss to 0.0920 MW and 0.091 MW respectively. It is obvious and 2.0 MW are only able to reduce the total power loss from this that the proposed method produces a much better result. Even though the Acharya's methods [4] recorded the least power loss of 0.0814 MW and 0.08133 MW, a further critical analysis would however reveal that the results have gone beyond the most optimal level. For instance, the extra loss reduction of 0.0063 MW (0.0877–0.0814 MW) vis-a-vis the proposed method is attained with a 0.2892 MW DG size extra (1.81–1.5208 MW) in the table. This would certainly not motivate the DISCO to invest more on the

DG capacity since there is no commensurate economic justification from the output.

This simply underscores the fact that focusing attention on power loss alone, without a fair consideration for other factors, would not yield the most optimal result.

Similar analysis is applicable to the 33-bus test system when compared with the proposed method. These results obviously show that the proposed method produces more optimal results (DG size and location) than other approaches as demonstrated in the table. While refs [4], [13], [31], [32]] obtained bus 6 as the optimal location for 33-bus, the proposed method obtained bus 8, instead. On the other hand, [30] and [4] obtained buses 7 and 10 as the optimal locations respectively for the same system. The optimality of the results obtained in this study is demonstrated in the DG size and consequently power loss shown in Tab. 2. Where the energy savings are higher than that of the proposed method, the investment cost on the extra DG capacity may not encourage the DISCO to implement it.

8. Conclusion

A multi-objective model for optimal allocation of a single DG unit in a radial distribution network has been proposed in this paper. The Fuzzy Genetic Algorithm based approach was premised on maximising loss cost savings, minimisation of lines voltage drops, and maximisation of the power transfer capability of the system. In the study, fuzzy controller was implemented to dynamically control the GA control parameters. The essence of this is to overcome the premature convergence of the simple GA. The proposed model takes into cognisance, the peculiarities of radial distribution systems, such as high R/X ratio, voltage dependency and composite nature of the loads, which most of the early works did not consider. In this study, an appropriate weighting factor is allocated to each of the objective functions by the network planner, based on his preference for each objective at any time instant.

The accuracy and reliability of the proposed approach was evaluated using three radial distribution networks. The results obtained appeared to be more optimal than those of the earlier existing methods cited in the literature, and would help the DISCO save energy cost. One other advantage of the model proposed in this paper is the exceptionally high processing speed. For example, while it took more than 40 seconds on a Pentium Dual-Core CPU E6500 at 2.93 GHz and 2 GB RAM personal computer to produce results for the 69-bus system using the approach of [31], it only took the proposed method just less than 3 seconds for the same test system.

Appendix

Table 3 presents the fuzzy control rules as used in this work.

Tab. 3: Fuzzy control rules.

Rule no.	**Input**			**Output**
	A	**B**	**C**	ΔN_p
1	Low	Low	High	High
2	Low	Medium	Low	High
3	Low	Medium	Medium	Low
4	Low	Medium	High	High
5	Low	High	Low	Low
6	Low	High	High	Medium
7	Medium	Low	Low	Low
8	Medium	Low	Medium	Medium
9	Medium	Low	High	Low
10	Medium	Medium	Low	Low
11	Medium	Medium	Medium	Medium
12	Medium	Medium	High	High
13	High	Low	Low	Medium
14	High	Low	High	Low
15	High	Medium	Low	High
16	High	Medium	Medium	High
17	High	Medium	High	High
	A	**B**	**C**	ΔP_c
18	Low	Low	Low	Low
19	Low	Low	Medium	Medium
20	Low	Low	High	Low
21	Low	Medium	Medium	High
22	Low	High	Low	Medium
23	Low	High	Medium	Low
24	Low	High	High	Low
25	Medium	Low	Low	Medium
26	Medium	Low	Medium	Medium
27	Medium	Medium	Medium	High
28	Medium	Medium	High	Low
29	Medium	High	Low	Low
30	High	Low	Medium	Low
31	High	Low	High	High
32	High	Medium	Medium	Low
33	High	Medium	High	Low
34	High	High	Low	Medium
35	High	High	High	Medium
	A	**B**	**C**	ΔP_m
36	Low	Low	Low	Low
37	Low	Low	High	Medium
38	Low	Medium	Medium	Medium
39	Low	Medium	High	High
40	Low	High	Low	Medium
41	Medium	Low	Low	Medium
42	Medium	Low	Medium	High
43	Medium	Low	High	Medium
44	Medium	Medium	Low	Medium
45	Medium	High	Low	High
46	Medium	High	Medium	Medium
47	Medium	High	High	Medium
48	High	Low	Low	Low
49	High	Low	High	High
50	High	Medium	High	High
51	High	High	High	Low

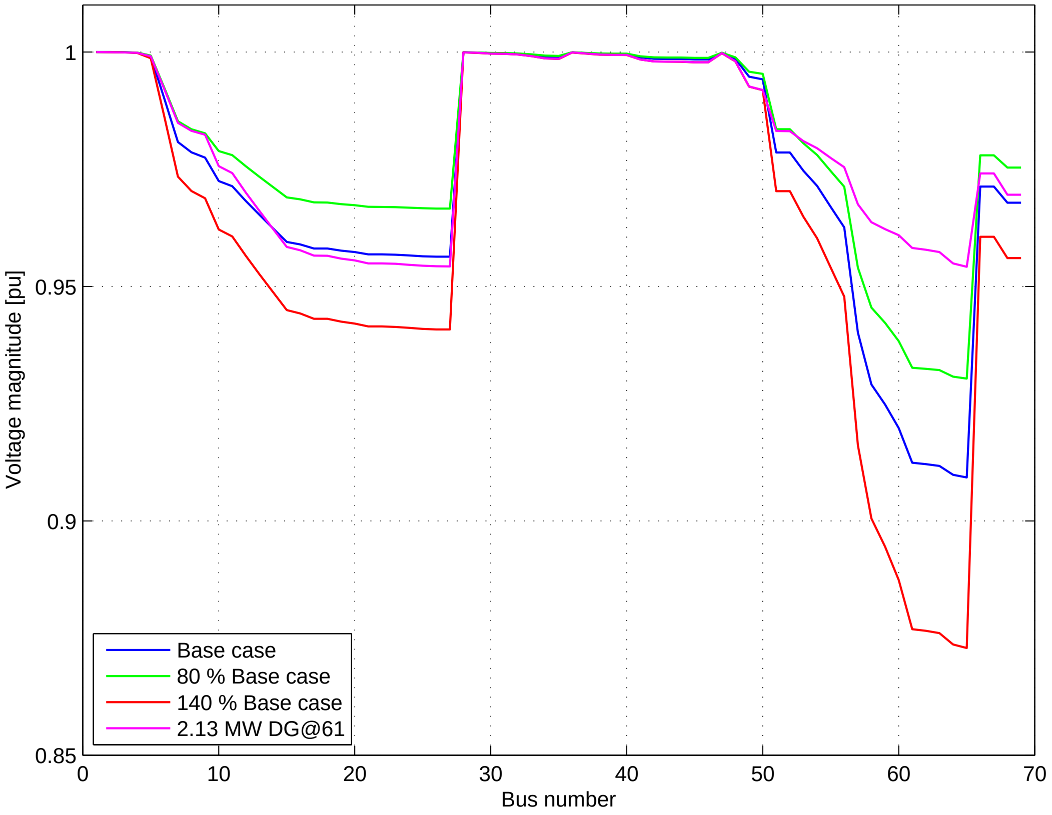


Fig. 12: Voltage profile on 69-bus system.

Tab. 2: Results comparison.

Author	**Method**	**Test system**	**PL without DG [MW]**	**Opt loc**	**Opt size [MW]**	**PL with DG [MW]**	**Energy savings [\$/hr]**	**DG Invest Cost [\$ million]**
Acharya [4]	Analytical	69-bus	0.2193	61	1.81	0.0814	16.55	2.61
Acharya [4]	Loss Sensitivity	69-bus	0.2193	61	1.9	0.08133	16.56	2.74
Gozel [13]	Analytical	69-bus	0.2249	61	1.8078	0.092	15.95	2.60
Gozel [31]	Analytical	69-bus	0.225	61	1.8727	0.0832	17.02	2.70
Shukla [32]	GA	69-bus	0.225	61	1.872	0.0832	17.02	2.70
Vinothkumar [30]	FGA	69-bus	0.22	61	2.00	0.091	15.48	2.88
Akorede	Proposed	69-bus	0.225	61	1.5208	0.0877	16.48	2.19
Acharya [4]	Analytical	33-bus	0.2112	6	2.49	0.1112	12.00	3.59
Acharya [4]	Loss Sensitivity	33-bus	0.2112	10	1.4	0.12382	10.49	2.02
Gozel [13]	Analytical	33-bus	-	-	-	-	-	-
Gozel [31]	Analytical	33-bus	0.211	6	2.5902	0.111	12.00	3.73
Shukla [32]	GA	33-bus	0.216	6	2.49	0.1328	9.98	3.59
Vinothkumar [30]	FGA	33-bus	0.2	7	2.00	0.11	10.80	2.88
Akorede	Proposed	33-bus	0.211	8	1.486	0.1206	10.85	2.14

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