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Distribution System Restoration Using Genetic Algorithm with Distributed Generation

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Abstract

Distribution system automation is carried out to improve the reliability, stability, efficiency and service quality of a system. When a fault occurs in the system quick restoration is required in the faulted area, which needs dedicated software to assist the operator. In this paper, an algorithm is developed to find the radial configuration to restore the system after a fault using Genetic Algorithm (GA). The restoration is carried out with minimum system loss, voltage drop and number of switching operations with line current and bus voltage limits as constraints. The load flow is performed by forward/backward sweeping algorithm. Additional mesh checking of the network is avoided using Prufer number encoding of strings. The effect of DG in loss reduction during restoration is analyzed which is observed to be a high level from the results. The developed algorithm is tested on IEEE 16-Bus and 33-Bus radial distribution systems.

Keywords: Distribution system, Genetic Algorithm, Restoration, Prufer number encoding, Multiobjective performance index, Distributed Generation

1. Introduction

Distribution system is planned in such a way that it supplies the consumers without any longer interruption during the outage condition. When a fault occurs in the system, relays detect the faulted areas and disconnect the network by opening the circuit breakers. During the fault, power becomes unavailable to the loads in certain areas or to the particular customer loads and the power utilities should re-energize the loads as quickly as possible. The re-energizing procedure is called as service restoration. The operators in control centers detect the out-of-service areas and decide the switches to be opened and closed in order to restore the out-of-service areas via feeder reconfiguration.

Recently Distributed Generations play an important role in the minimization of loss of the system. DG is considered as “taking power to the load” by both conventional and renewable energy resources such as wind, solar, geothermal, biomass and ocean energy. DG generates electricity with high efficiency and low pollution. Thomas Ackermann et al. (Thomas Ackermann, Goran Andersson, and Lennart Soder., 2001) stated that DG can be installed at or near the load at different ratings varying from 1 W to 300 MW. The impacts of DG on voltage regulation, losses, voltage flicker and harmonics etc. were presented by Barker et al. (Barker Philip,P., and Mello Robert W.De., 2000). In order to minimize line losses of power systems, it is important to define the size and location of DG. An analytical approach to determine exclusively the optimal location to place a DG in radial systems to minimize the total loss of the system was presented by Wang and Nehrir (Wang,C., and Nehrir,M.H., 2004). A general approach and a set of indices to assess some of the technical and environmental benefits of DG in a quantitative manner were proposed by Pathomthat et al. (Pathomthat Chiradeja, and Ramakumar,R., 2004). Reduced line losses, voltage profile improvement, reduced emissions of pollutants, increased overall energy efficiency, enhanced system reliability and security, improved power quality and relieved transmission and distribution congestion, reduced operation and maintenance costs of some DG technologies, enhanced productivity, reduced health care costs due to improved environment and reduced fuel costs due to increased overall efficiency are some of the major benefits.

In this paper, an algorithm is developed to find the optimal radial network using Genetic Algorithm to restore the system after the occurrence of a fault. The restoration is carried out for minimum system loss, voltage drop and number of switching. Distribution networks are normally radial in nature. After the occurrence of a fault, it is essential to ensure that the restored network is in radial. Generally an additional mesh checking is required after the restoration. Prufer number encoding explained by Ying and Saw (Ying-Yi Hong, and Saw-Yu Ho., 2005) is used for representing the strings to avoid this additional mesh checking. An IEEE 16-Bus applied by Ying and Saw (Ying-Yi Hong, and Saw-Yu Ho., 2005 and a 33-Bus radial distribution systems applied by Baran et al. (Baran.M.E., and Wu,F.F., 1989) are considered to validate the effectiveness of the developed algorithm. The restoration is also carried out with the inclusion of DG with a selected size and location. The effect of DG for the reduction of real power loss and total voltage drop is analyzed.

2. Problem Formulation

When a fault occurs in a system, it is essential to restore the system with minimum time. The minimization of the time is directly related with the minimization of the number of switching operations. The objective of this work is to find the optimal network for restoration with minimum system loss, voltage drop and number of switching operations. The problem is solved and analyzed into two cases.

1) Optimal network without DG

2) Optimal network with DG

The location and size of the DG are selected for minimum loss and voltage drop.

The objective function and the constraints of the service restoration problem are described below.

2.1 Objective and Constraints

The total real power loss, the voltage drop and the number of switching operations to be minimized are given in Eq. (1), (2) and (3) respectively.

$$f_1(x) = \sum_{j=1}^{nl} k_j \left| I_j \right|^2 R_j \tag{1}$$

$$f_2(x) = \sum_{i=2}^{NB} \left| V_{i+1} \right| - \left| V_i \right| \tag{2}$$

$$f_3(x) = \sum_{j=1}^{s} \left| sw_j - k_j \right| \qquad j \in 1,2,3,\ldots, s \tag{3}$$

The objective function is calculated using Eq. (4).

$$objective\ function = W_1 * f_1(x) + W_2 * f_2(x) + W_3 * f_3(x) \tag{4}$$

The weighting factors are selected such that $W_1 + W_2 + W_3 = 1$

The numbers of switching operations are calculated using the expression given by Yogendra et al. (Yogendra Kumar, Biswarup Das, and Jaydev Sharma., 2005) sw_j is the status of j^{th} switch just after the fault and k_j is the status of j^{th} switch in the restored network.

The constraints are as follows.

- Radial network should be maintained.
- Bus voltages should be within the acceptable range, which is given by Eq.(5).
- Line currents should be within the acceptable range, which is given by Eq.(6).

$$V_{min} < V_j < V_{max} \tag{5}$$

$$I_{min} < I_j < I_{max} \tag{6}$$

3. Steps for the Proposed Algorithm

The steps for solving the restoration problem are as follows:

Step 1: The bus data, line data, switch locations and concerned faults of the system for service restoration problem are read.

Step 2: The population size, crossover rate and mutation rate for GA are selected.

Step 3: Each chromosome is represented using prufer number encoding method.

Step 4: The total real power loss, voltage drop and the number of switching operations for each chromosome using forward/backward sweep method are determined.

Step 5: The fitness value and the penalty function for inequality violated constraints are calculated. This penalty function is augmented to the objective function.

Step 6: The elitist strategy and tournament selection method to select the better chromosomes with larger fitness values are used.

Step 7: Genetic operations: crossover and mutation are performed.

Step 8: If all chromosomes are identical, the iterations are convergent; otherwise, go to Step 4.

Steps for determining the optimal network by the proposed method is given in Fig.1. The same can be applied for the restoration with DG by modifying the bus and the line data.

4. Implementation of Genetic Algorithm

Genetic Algorithm (GA) is a search algorithm, based on the mechanics of natural selection and natural genetics. It combines survival of the fittest among string structures. Effective search is carried out using GA to find Pareto optimal solutions for the reconfiguration problems. The basic operators of GA applied in this work are explained as follows.

4.1 String encoding

Since the topology of a distribution network can be uniquely defined by the statuses of all available tie and sectionalizing switches, a solution to the restoration problem is encoded as a function of the controllable switch states of the network. The length of the binary string is equal to the number of switches in the network. Each switch state is represented by one bit with a value '1' or '0' corresponding to 'close' or 'open', respectively.

4.2 Initial Population of the String

The population of the strings is randomly generated such that the number of '1's is equal to the number of sectionalizing switches and the number of '0's is equal to the number of the tie switches. The length of the string is equal to the total number of available switches. All the strings are in radial since they are represented by the prufer number encoding algorithm as follows.

4.2.1 Prufer number encoding for 16-Bus system

Representation of a string [1 1 1 1 1 1 0 0 1 1 1 1 1 1 1 0] of the16-Bus system as a Prufer number

"6-4-14-5-4-1-2-9-8-2-3-13-13-15" is explained as in Fig.2.

1) The end node which is called as leaf node, with the smallest number (ie) bus 7, in the system is located. The unique adjacent bus for bus 7 is bus 6, which is assigned as the most left number of the Prufer number.

2) Bus 7 and the branch between buses 6 and 7 are deleted.

3) Now the leaf node with the smallest number is bus 6. The unique adjacent bus for bus 6 is bus 4, and therefore 4 is the next number after 6 in the Prufer number. Delete bus 6 and branch between buses 6 and 4.

4) This process is repeated until one bus is left.

A Prufer number "6-4-14-5-4-1-2-9-8-2-3-13-13-15" is obtained. For the 16-Bus distribution configuration, the length of the prufer number is 14 (16-2) for radial configuration.

4.3 Fitness Evolution

An objective function can be modified to account for the constraints by penalizing any solution that violates a constraint. In this work a penalty term, which depends on the constraint and the extent of its violation, is subtracted from the calculated fitness value. This 'penalty function method' permits new constraint formulations to be added readily to a GA-based optimization method. The multiobjective function is given in Eq.(3). The problem is a minimization problem.

Therefore, the fitness is given by Eq.(7).

$$\text{Fitness} = 1/f(x) \tag{7}$$

4.4 Penalty Functions

For dealing with inequality constraints in GA more efficiently, penalty functions are employed. This function indicates that a violated inequality constraint will be punished and then augmented to the fitness function. The penalty function dealing with the *V(i)* is represented in Eq.(8).

$$-PF^{N/NS}\{(V_i - V_{\min})\}^2 \tag{8}$$

where PF is called the penalty factor and N is the iteration number. Eq.(8) implies that the penalty weight $(PF^{N/NS})$ should be increased gradually and has less effect in the initial NS iterations. The penalty factors for the voltages should be smaller than that for the line flows because the numerical order for the line flows is larger than that for the voltages.

4.5 Tournament Selection

In tournament selection, two chromosomes are chosen randomly. Through comparing their fitness function values, the good candidate for the fitness function is survived and the chosen chromosome is copied to the next generation directly.

4.6 Single Point Cross Over and Uniform Mutation

In single-point crossover one crossover position is selected uniformly at random and the variables are exchanged between the individuals about this point, then two new offsprings are produced. The process is that certain bit or some bits of gene in the chromosome are transformed inversely, which means gene is changed from 1 to 0 or from 0 to 1**.**

4.7 Termination of GA

The conventional termination of the GA after a pre-specified number of generations is applied. After the completion of the number of generations, the quality of the best members of the population is tested against the problem definition. If no acceptable solutions are found, the GA may be restarted or a fresh search is initiated.

5. Load flow using backward sweeping method for radial distribution systems

Many of the distribution feeders do not converge while using conventional Newton-Raphson (NR) and Fast Decoupled Load Flow (FDLF) methods due to high R/X values. In backward sweeping method for load flow technique explained by Das et al. (Das,D., Nagi,H.S., and Kothari, D.P., 1994), unique lateral, node and branch numbering scheme are employed and hence the convergence is guaranteed for any radial distribution network with high R/X values. Therefore backward sweeping method is applied for obtaining the load flow results. The load flow is performed using Eq.(9) and Eq.(10).

The current through branch *j* is given as

$$I_j = \frac{|V_i|\angle\delta_i - |V_{i+1}|\angle\delta_{i+1}}{R_j + jX_j} \tag{9}$$

Voltage on the '*i+1*' th node is given as

$$|V_{i+1}| = \left\{ \left[(P_{i+1}R_j + Q_{i+1}X_j - 0.5|V_i|^2)^2 - (R_j^2 + X_j^2)(P_{i+1}^2 + Q_{i+1}^2) \right]^{\frac{1}{2}} - (P_{i+1}R_j + Q_{i+1}X_j - 0.5|V_i|^2) \right\}^{\frac{1}{2}} \tag{10}$$

Since the substation voltage magnitude V_i is known, it is possible to find out the voltage magnitudes of all other nodes. The real power loss of branch *j*, LP_j is calculated from Eq.(11).

$$LP_j = \frac{R_j * (P_{j+1}^2 + Q_{j+1}^2)}{|V_{j+1}|^2} \tag{11}$$

The real power on '*i+1*' th node is given in Eq.(12).

$$P_{i+1} = \sum_{j=i+1}^{NB} PL_j + \sum_{j=i+1}^{NB-1} LP_j \qquad \text{for } i=1,2,3,\dots,NB-2 \tag{12}$$

The total real power loss in all branches and the total voltage drop in all lines are calculated from Eq.(1) and Eq.(2) respectively.

6. Load flow with DG

The DG can be operated in three modes: lagging or leading or unity power factor. Under lagging power factor operation, DG produces reactive power for the system and Q is positive. Also Q is negative for leading power factor operation because DG absorbs reactive power from network. The real power at node *i* is decreased by adding DG at that node, which is given as PL_i-P_{Gi}. The reactive power in per unit for DG at node *i* is given in Eq.(13).

$$Q_{Gi} = \frac{(-1)^{nG} \, YPL_i \sqrt{1-(PF_G)^2}}{PF_G} \tag{13}$$

where, $nG = 1$ for leading power factor operation

= 2 for lagging power factor operation

$$Y = \frac{P_{Gi}}{PL_i}$$

The reactive power at node i is QL_i-Q_{Gi} and the load flow is done for the radial system using Eq.(9) and Eq.(10).

Fig.3. shows the flowchart for the selection of the location and size of the DG.

7. Results and Discussion

In this work, the IEEE 16-Bus and 33-Bus radial distribution systems considered for testing the developed algorithm. For the 16-Bus system, GA with prufer number encoding requires 14 (NB-2) bits for a chromosome. The population size, maximum number of generations, crossover rate and mutation rate are 10, 50, 0.8, and 0.01 respectively. The minimum and maximum values of voltage are selected as 0.95p.u and 1.05p.u. The current limits are ±3% of the line current of the original configuration.

7.1 Results for the 16-Bus system

The real power loss for the original system is 510 kW and the total voltage drop in the system is 0.6501 kV.

7.1.1 Restoration without DG

If a fault occurs on the branch 2 (between buses 4 and 5), the bus 5 is in out of service. The objective is to restore the loads connected to the bus in the out of service area. There may be a number of possible ways to restore the system by reconfiguring the network. In this case, the load can be reenergized by closing the switches 14, 15 and 16 by opening the switches 2, 4 and 7. This configuration gives the minimum loss 660 kW, minimum voltage drop of 0.6512 kV and minimum number of switching operations of 6 out of all possible configurations to restore the system. If weighting factors are 0.7, 0.2 and 0.1 then the loss, voltage drop and switching operations are 670 kW, 0.6652 kVand 2 respectively. Therefore based on the application it is essential to select the weighting factors. Similarly the faults on other branches are considered one by one and the simulation results for the restoration are obtained using GA, which are given in Table 1. The convergence characteristic is shown in Fig.4. It is observed from the graph that all the chromosomes are different at the end of the first generation. At the 33rd generation, all the chromosomes are identical. These chromosomes give optimum configuration.

7.1.2 Restoration with DG

The ratings of DG units are varied from 0 to the total real power load at all the nodes. The DG ratings are varied one by one in steps from 2000 to 30000 kW with a power factor of 0.8 lagging. For all DG ratings, the loss and voltage drops are determined for the initial configuration. The multiobjective performance index is calculated using $W_1 + W_2 = 1$. Since it is the initial configuration $W_3 = 0$. In this case, various values for the weighting factors are assumed in the initial configuration with all DG ratings at all locations and their index values are determined for loss and voltage drop. It is observed that for most of the combinations of the weighting factors, their minimum index value is obtained when the DG of 20000 kW is located at Bus-9. The variation of loss and the variation of voltage drop for different DG ratings at Bus-9 are shown in Fig.5. The variation of the multiobjective performance index values for DGs at all buses is given in Fig.6. The corresponding loss and voltage drop values are given in Table 2. It is observed from the graph that the performance index value is minimum (0.3714) at bus-9 with 20000 kW. Some points are available with index values lower than 0.3714 but their respective voltage drop is in negative, therefore they are neglected.

When the DG is present in the system the restoration is carried out by considering the faults on the lines one by one. The results are given in Table 3. The network for restoration is determined for minimum loss, voltage drop and minimum switching operations. For a fault on line 2 the restoration is done by closing the switch in branch 14 and 16 and by opening the switches 2 and 4. It is observed from the results that the loss is reduced by 43.13% and voltage drop is reduced by 98.81% for this configuration during restoration. Moreover the number of switching operations is reduced to 4. The fault is considered in all the buses one by one and the networks for restoration are determined. In all the cases there is a lot of reduction in the loss, voltage drop and the number of switching operations. The simulation is done using MATLAB 7.1 programming language on a 2.79 GHz machine. The execution time for obtaining the network for restoration is 25.594 seconds.

7.2 Results for the 33-Bus system

The faults on all the branches are considered one by one and the simulation results for the restoration without DG are obtained using GA. The restoration results after the occurrence of faults on some of the lines are given in Table 4. The DG ratings are varied one by one in steps from 400 to 4000 kW. In this case, the minimum loss and minimum voltage drops are obtained at Bus-30 with DG of 2000 kW for many of the weighting factors. The variation of the multiobjective performance index values for DGs at all buses is given in Fig.7. It is observed from the graph that the performance index value is minimum (0.1776) at bus-30 with 2800 kW. The corresponding loss and voltage drop values are given in Table 5. When the DG is present in the system the restoration is carried out by considering the faults on the lines one by one. The restoration results after the occurrence of faults on some of the lines are given in Table 6.

8. Conclusion

A Genetic Algorithm based approach to solve a multiobjective service restoration problem without and with Distributed Generation is analyzed. The multiobjective performance index used in this method with weighting factors is most suitable and valid for incorporating new objective functions and constraints arising from the introduction of DG in modern distribution systems. The introduction of DG of proper size and location reduces the system loss and voltage drop to a higher level. Due to the elimination of additional mesh check by Prufer number encoding, the execution time is reduced enormously. The convergence is guaranteed for any radial distribution network due to the application of backward sweeping method of load flow. The proposed method is capable of solving large scale systems.

Notations

nl - the number of lines

NB - the number of buses/nodes

s - number of switches

i - the node number

j - the branch number where $j=1, 2,\dots, NB-1$.

V_i, - voltage of i^{th} node

I_j - current through branch j

R_j - resistance in per unit of branch j

X_j - reactance in per unit of branch j

k_j = 1, if the branch j is closed

= 0, if the branch j is opened.

W_1, W_2 and W_3 - Weighting factors for total real power loss, total voltage drop and the number of switching operations respectively.

V_{min} and V_{max} - the minimum and maximum acceptable bus voltages

I_{min} and I_{max} - the minimum and maximum acceptable branch currents

PL_i - real power load of i^{th} node

QL_i - reactive power load of i^{th} node

δ_{i+1} - voltage angle at node $i+1$

P_{i+1} and Q_{i+1}- total real and reactive power loads fed through node $i+1$ respectively

P_{Gi} - real power of DG at node i

Q_{Gi} - reactive power of DG at node i

PF_G - the operating power factor of DG

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Table 1. Results for the restoration without DG for 16-Bus system (Case: 1)

Fault on branch	Minimum voltage		Total real power loss		Total Voltage drop		Switching Operations		Number of switching operations
	p.u.	kV	p.u.	kW	p.u.	kV	Switches to be closed	Switches to be opened	
2	0.9613	10.57	0.0066	660	0.0592	0.6512	14,15,16	2,4,7	6
3	0.9587	10.54	0.0071	710	0.0457	0.5027	14,16	3,6	4
4	0.9575	10.53	0.0069	690	0.0453	0.4983	14,15,16	4,6,7	6
6	0.9575	10.53	0.0069	690	0.0453	0.4983	14,15,16	4,6,7	6
7	0.9556	10.51	0.0069	690	0.0485	0.5335	14,15,16	6,7,16	4
8	0.9721	10.69	0.0048	480	0.0548	0.6028	14,15,16	4,7,8	6
11	0.9587	10.54	0.0057	570	0.0556	0.6116	14,15,16	3,8,11	6
12	0.9523	10.47	0.008	800	0.0512	0.5632	14,15,16	6,7,12	6
13	0.9541	10.49	0.0075	750	0.0486	0.5346	14,15,16	6,7,13	6

Table 2. Loss and voltage drop for the initial network with and without DG for 16-Bus system

Configuration Type	Switches in open	DG condition	Location of DG	Rating of DG (kW)	Total real power loss (kW)	% of Loss reduction	Total Voltage drop (p.u.)	% of voltage drop reduction
Initial Configuration	14,15,16	Without DG	-	-	510	-	0.0591	-
		With DG for min. combined loss & Voltage drop	**Bus 9**	**20000**	355.8	30.23	0.0008	98.68

Table 3. Results for the restoration with DG for 16-Bus system (Case: 2)

Fault on branch	Minimum voltage		Total real power loss		Total Voltage drop		Switching Operations		Number of switching operations
	p.u.	kV	p.u.	kW	p.u.	kV	Switches to be closed	Switches to be opened	
2	0.9802	10.78	0.0029	260	0.0007	0.0418	14,16	2,4	4
3	0.9731	10.704	0.0043	430	-0.0027	-0.0297	14,16	3,8	4
4	0.9802	10.78	0.0029	370	-0.0023	-0.0253	16	4	2
6	0.978	10.87	0.0057	520	0.0148	0.1628	14,15,16	4,6,7	6
7	0.978	10.83	0.0041	390	0.0003	0.0033	15,16	3,7	4
8	0.9802	10.82	0.0038	370	0.0025	0.0275	14,16	4,8	4
11	0.9801	10.78	0.0037	350	0.0022	0.0242	14,15,16	4,8,11	6
12	0.9735	10.703	0.0045	420	0.0026	0.0286	15,16	7,12	4
13	0.9817	10.791	0.0038	380	0.0008	0.0088	16	13	2

Table 4. Results for the restoration without DG for 33-Bus system (Case: 1)

Fault on branch	Total real power loss		Total Voltage drop		Switching Operations		Number of switching operations
	p.u.	kW	p.u.	kV	Switches to be closed	Switches to be opened	
3	0.0033	330	0.0066	0.0858	35,36,37	3,27,30	6
9	0.0018	180	0.1211	1.5743	34,35	9,13	4
10	0.0018	180	0.1123	1.4599	34,35,37	10,12	6
14	0.0029	290	0.1606	2.087	34,36	14,29	4
15	0.0019	190	0.1274	1.656	35,36,37	21,26	6
17	0.0017	170	0.1056	1.3728	35,36	17,8	4

Table 5. Loss and voltage drop for the initial network with and without DG for 33-Bus system

Configuration Type	Switches in open	DG condition	Location of DG	Rating of DG (kW)	Total real power loss (kW)	% of Loss reduction	Total Voltage drop (p.u.)	% of voltage drop reduction
Initial Configuration	33,34, 35,36, 37	Without DG	-	-	197	-	0. 1318	-
		With DG for min. combined loss & Voltage drop	**Bus 30**	**2800**	117.35	40.43	0.004	97.72

Table 6. Results for the restoration with DG for 33-Bus system (Case: 2)

Fault on branch	Total real power loss		Total Voltage drop		Switching Operations		Number of switching operations
	p.u.	kW	p.u.	kV	Switches to be closed	Switches to be opened	
3	0.0011	110	0.019	0.247	33,36	3,7	4
9	0.0014	140	0.1233	1.5899	35	9	2
10	0.0012	120	0.0015	0.0195	34	10	2
14	0.0011	110	0.0024	0.0312	34	14	2
15	0.001	100	0.0056	0.0728	33,36	15,19	4
17	0.0011	110	0.019	0.247	33,36	17,3	4

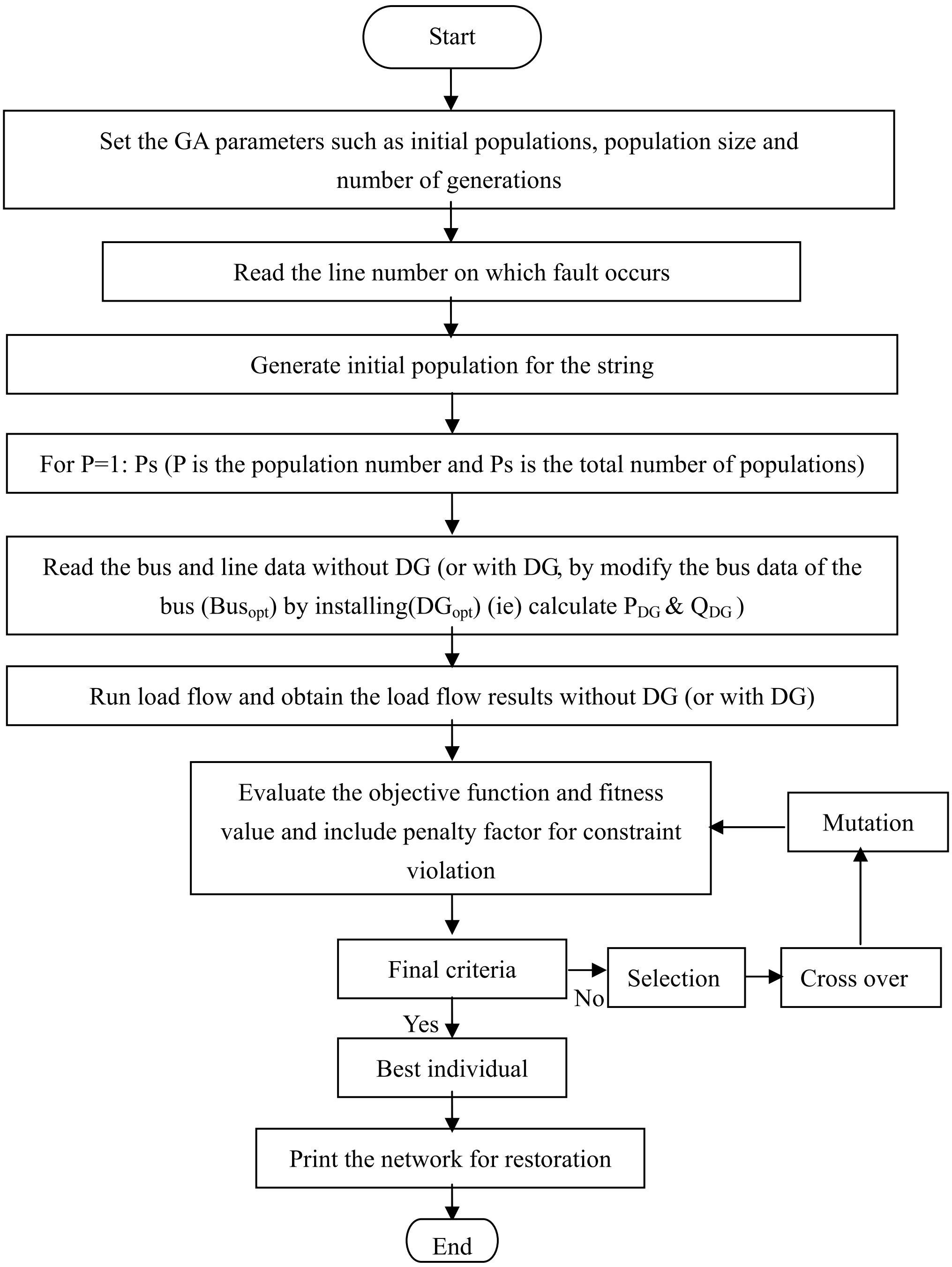

Figure 1. Flowchart to determine the network for restoration using GA

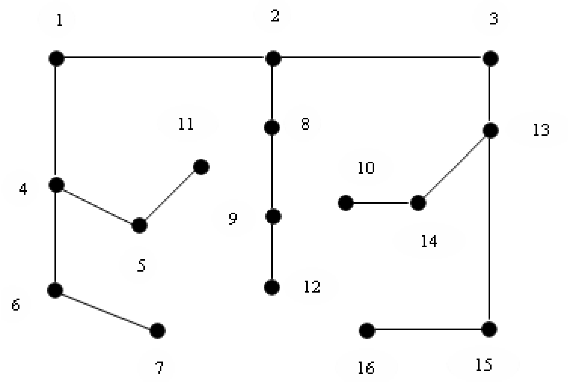

Figure 2. Representation of a string as a prufer number “6-4-14-5-4-1-2-9-8-2-3-13-13-15” for 16-Bus System

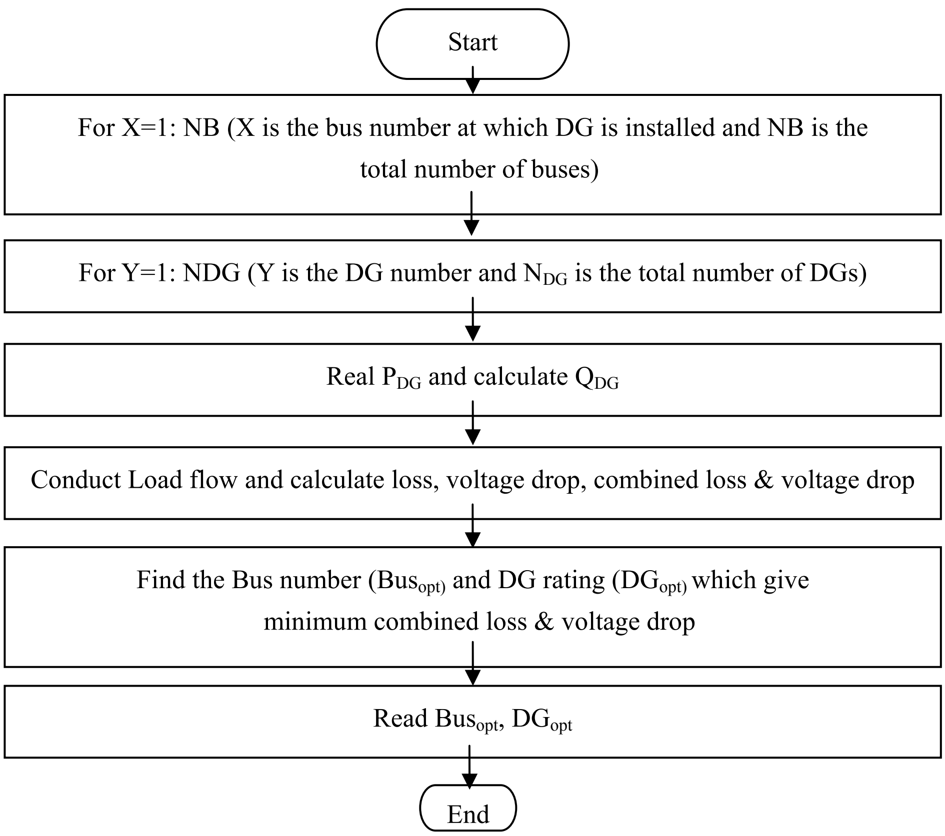

Figure 3. Flowchart to find the location and size of DG

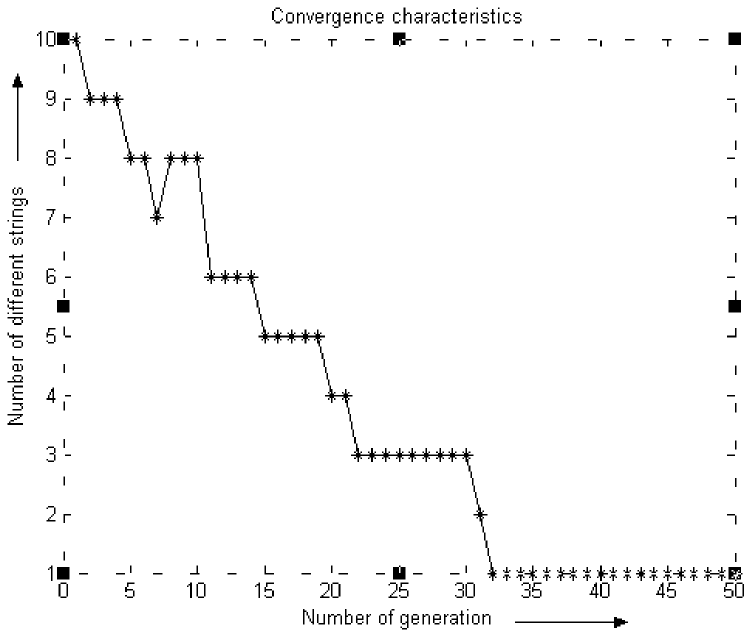

Figure 4. Convergence characteristic for restoration for 16-Bus system

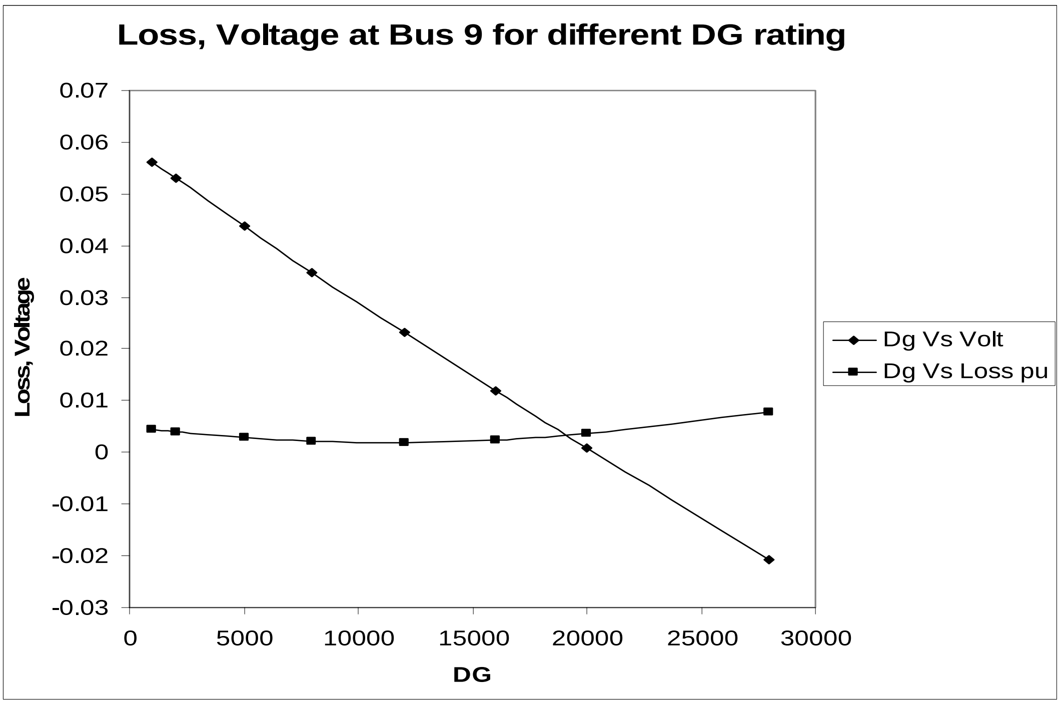

Figure 5. Variation of loss and voltage drop with different DG ratings at Bus-9 for 16-Bus system

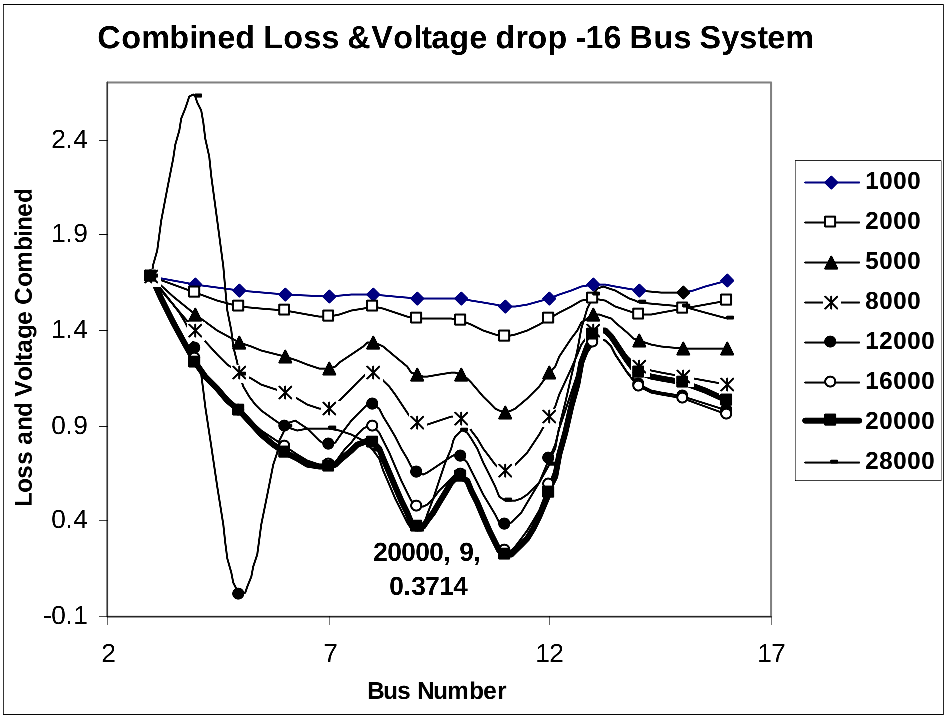

Figure 6. Loss and voltage drop (Multiobjective Index) with different DG at all buses in 16-Bus system

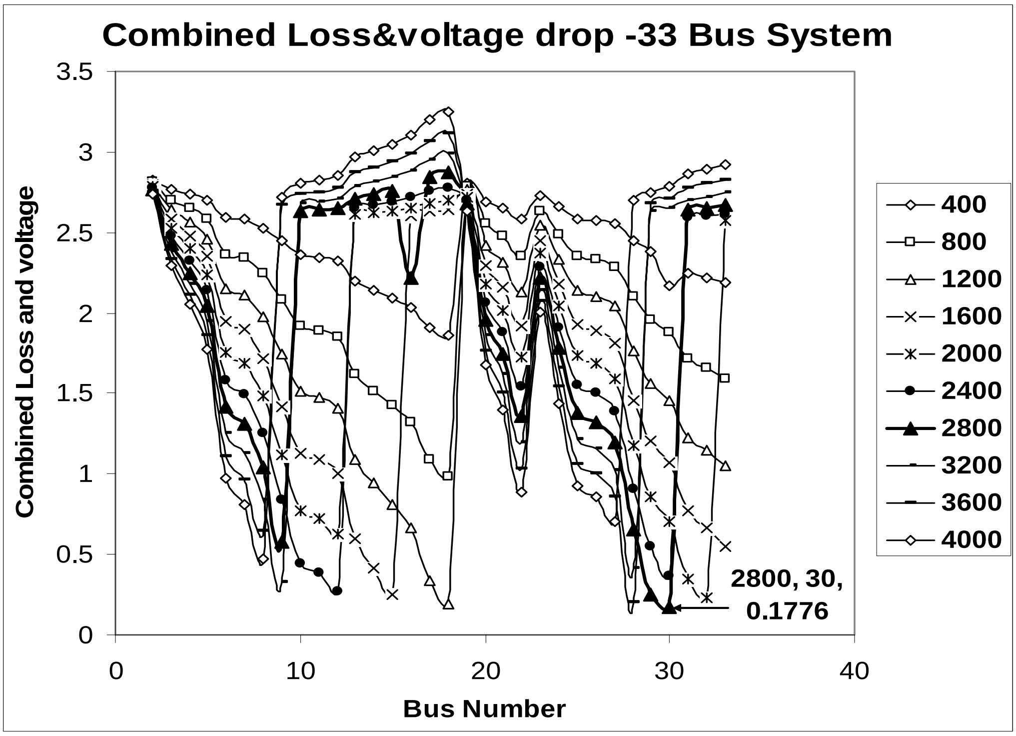

Figure 7. Loss and voltage drop (Multiobjective Index) with different DG at all buses in 33-Bus system