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A Novel Fuzzy Approach for Multi-objective Optimization of Distribution Network Configuration in Complex System

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Abstract

This paper discusses new techniques for solving network configuration problems with the presence of distributed generation (DG). The technique used is fuzzy logic based technique for multi-objective optimization of distribution network configuration in complex system. The technique transforms the multi-objectives of optimization problem into a single objective problem using theory of fuzzy set. There are three objectives which are formed in fuzzy membership function, i.e., power loss, bus voltage and load balancing the entire feeders of distribution network while a radial structure must be persisted. In this work, the fuzzy multi-objective method has been applied in optimization of an IEEE 77-bus distribution network configuration with the presence of DG. The results show quite encouraging which the network efficiency is improved significantly.

Keywords: Distribution network, DG, optimization, reconfiguration, fuzzy system, multi-objective.

INTRODUCTION

The operation of electrical power distribution systems is more complex particularly in the areas where load density is high, due to uncertainty of system loads on different feeders, which vary from time to time [1]-[3]. Electrical power loss in a distribution network will not be minimum for a fixed network configuration for all cases of varying loads. Therefore, there is a need for reconfiguration of the network from time to time [4]-5]. Reconfiguration of the network is the process of altering the topological structure of feeders by changing open/closed status of sectionalizing and tie switches [6]-[8]. In general, networks are reconfigured to reduce real power loss and to relieve overload in the network [9]. However, due to dynamic nature of loads, total system load is more than its generation capacity that makes relieving of load on the feeders not possible and hence voltage profile of the system will not be increased to the required level [10]-[16].

In order to meet required level of load demand, DG units are integrated in distribution network to improve voltage profile and also to achieve economic benefits such as minimum power loss, energy efficiency and load leveling [17]-[21]. In this case, network reconfiguration and DG placement in distribution networks are considered independently. However, in the presented technique, network reconfiguration and DG installation are dealt simultaneously for improved loss minimization and voltage profile [22]-[23].

Deregulation of markets of power electricity in many countries worldwide brings new perspectives for distributed generation (DG) of electrical energy using renewable energy sources with small capacity [24]-[26]. Typically 5-kW to 10-MW capacities of DG units are installed nearer to the costumer to provide the electrical power. Since selection of the best locations and sizes of DG units is also a complex combinatorial optimization problem, many methods are proposed in this area in the recent past [27]-[29]. In [30], it has presented a Lagrangian based approach to determine optimal locations for placing DG in distribution systems considering economic limits and stability limits. In [31], it has presented a multi-objective algorithm using GA for sitting and sizing of DG in distribution system while [32] proposed an analytical method to determine optimal location to place a DG in distribution system for power loss minimization. In [33], it has discussed placement and penetration level of the DGs under the SMD framework.

Reconfiguration of distribution network is a non-differentiable constrained optimization problem and complex combinatorial, therefore many methods are proposed in the past. Merlin and Back [34] has proposed network reconfiguration problem in first. They used a branch- and-bound-type optimization method. The drawback with this method is the solution proved to be very time consuming as the possible system configurations are, where it is line sections equipped with switches.

In our study, the problem distribution network formulation is subject to electrical and operational constraints. The formulations are converted into fuzzy circuits by using different types of fuzzy membership functions. The formulations of this study are referred to minimization of active power loss, minimization of node voltage deviation and load balancing among feeders [35].

FUZZY MULTI-OBJECTIVE METHOD

Problem Formulation

Reconfiguration of power distribution network is a very important function of distribution system. The procedure is done to reduce power loss, improve bus voltage profile, load balancing, and to improve system security. In our study, the procedure can be formulated as follows:

$$\min P_{loss} = \sum_{i=1}^{N_k} R_i \frac{P_i^2 + Q_i^2}{V_i^2} \qquad (1)$$

where P_{loss} is active power loss, P_i is the real power flowing out the bus, Q_i is the reactive power flowing out the bus, n_b is the branch number, R_i is the resistance at bus i, and V_i is the magnitude of voltage at bus i.

Membership Function of Active Power Loss

Reducing active power loss is the most important aim of reconfiguration of distribution network. The ratio of total active power loss after and before reconfiguration can be defined as follow.

$$\alpha_i = \frac{P_{loss,i}}{P_{loss,B}}, \quad for \;\; i = 1,2,3,\ldots,N_k \qquad (2)$$

where, N_k is the total of switches in the loop including sectionalyzing-switch and tie- switch when i-th tie-switch is closed, $P_{loss,i}$ is the total active power loss when i-th branch in the loop is opened, and $P_{loss,B}$ is the total active power loss before network optimization. The membership function of the fuzzy multi-objective is shown in Fig. 1.

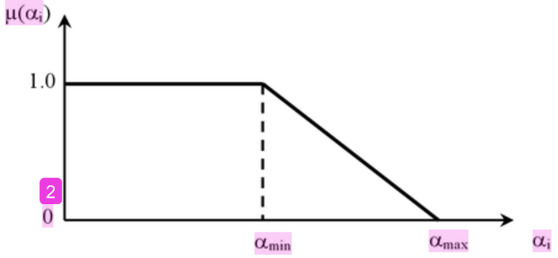

Figure 1. Fuzzy membership function for power loss

The value of $\mu(\alpha_i)$ can be expressed as

$$\mu(\alpha_i) = \begin{cases} \dfrac{(\alpha_{\max} - \alpha_i)}{(\alpha_{\max} - \alpha_{\min})}, & for \;\; \alpha_{\min} < \alpha_i < \alpha_{\max} \\ 1, & for \;\; \alpha_i \le \alpha_{\min} \\ 0, & for \;\; \alpha_i \le \alpha_{\max} \end{cases} \qquad (3)$$

Membership Function of Fuzzy Objective for Bus Voltage

Maximizing the bus voltage profile is the second important aim of reconfiguration of distribution network. The maximization factor of deviation for bus voltage can be defined as follow,

$$\beta_i = \max |V_{i,j} - V_s|, \\ for \;\; i = 1,2,3,\ldots,N_k \;\; and \;\; j = 1,2,3,\ldots,N_B. \qquad (4)$$

where, N_B is bus number of distribution system, V_s is voltage sources, in p.u, and $V_{i,j}$ is voltage of node corresponding to the opening of the i-th switch in the distribution network, in p.u. The membership function of fuzzy for bus voltage deviation is shown in Fig. 2.

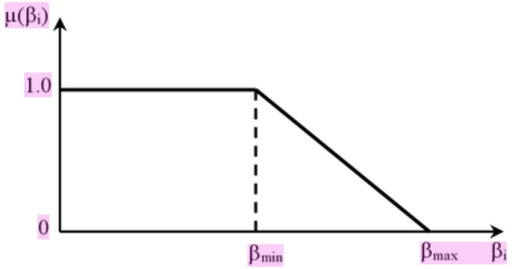

Figure 2. Fuzzy membership function for voltage deviation

Based on Fig. 2, the fuzzy membership of $\mu(\beta_i)$ can be defined as

$$\mu(\beta_i) = \begin{cases} \dfrac{(\beta_{\max} - \beta_i)}{(\beta_{\max} - \beta_{\min})}, & for \;\; \beta_{\min} < \beta_i < \beta_{\max} \\ 1, & for \;\; \beta_i \le \beta_{\min} \\ 0, & for \;\; \beta_i \le \beta_{\max} \end{cases} \qquad (5)$$

Membership Function of Fuzzy Objective for Load Balancing of Feeder

Load balancing is the third aim of reconfiguration of distribution network in this work. The load balancing index could be expressed as follow,

$$LBI_{i,j} = \frac{(IFF_{i,\max} - IF_{i,j})}{IFF_{i,\max}}, \\ for \;\; i = 1,2,3,\ldots,N_k, \;\; and \;\; j = 1,2,3,\ldots,N_F. \qquad (6)$$

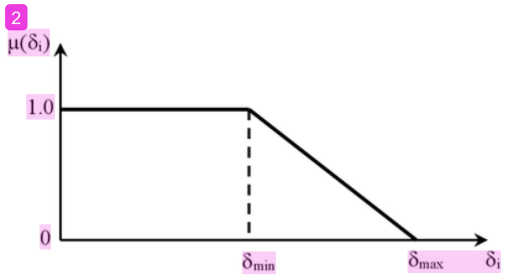

Figure 3. Fuzzy membership function for the load balancing index

where, $IF_{i,j}$ is the electric current of a feeder corresponding to the opening of the i-th switch in distribution network, $IFF_{i,max}$ is the maximum of all currents corresponding to the opening of the i-th switch in distribution network while $IFF_{i,max} = \max(IF_{i,j})$, for $j = 1, 2, 3, \ldots, N_F$.

Fuzzy membership function for index of load balancing is shown Fig. 4. Based on Fig. 4, the fuzzy membership of $\mu(\delta_i)$ could be writen by

$$\mu(\delta_i) = \begin{cases} \frac{(\delta_{max} - \delta_i)}{(\delta_{max} - \delta_{min})}, & for\ \delta_{min} < \delta_i < \delta_{max} \\ 1, & for\ \delta_i \le \delta_{min} \\ 0, & for\ \delta_i \le \delta_{max} \end{cases} \qquad (7)$$

RESEARCH METHODOLOGY

In this study, fuzzy rules are considered which minimize the number of tie-switch operations. An algorithm for the reconfiguration of distribution network is given below:

Step 1) Read the bus data, load data, and branch data of distribution system;

Step 2) Run the load-flow program for distribution networks;

Step 3) Determine the fuzzy membership values of each objective functions;

Step 4) Compute the voltage difference across the open tie switches;

Step 5) Identify the open tie-switch across which the voltage difference is maximum;

Step 6) Select a tie switch and identify the total number of network loop branches including the tie branch when the switch is closed;

Step 7) Open one branch at a time in the loop and evaluate the fuzzy membership value for each objective and also evaluate the overall degree of satisfaction;

Step 8) Obtain the optimal solution for the operation of tie-switch of distribution network.

RESULTS AND DISCUSSION

In this research, optimization of power distribution network configuration has examined using multi-objective fuzzy technique. A 33-bus radial distribution network was considered for the study. The load data, transmission line details, and data of tie lines are presented in Fig. 4 along with a single line diagram and Table 1.

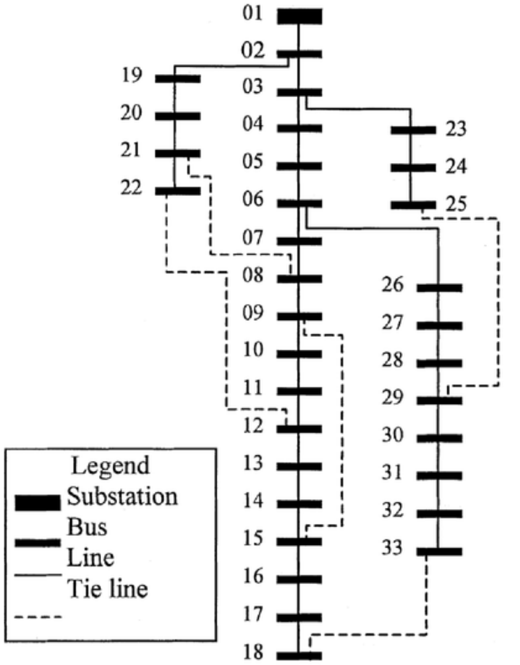

Figure 4. The 33-bus radial distribution network

In order to quantify the maximum loadability of the distribution network under study, the total additional load that may be drawn from the network before it suffers a collapse is determined. The 33-bus radial distribution network has been tested as can be seen in Fig. 4. This additional load is referred to as the kVA margin to maximum loadability. The load is increased while retaining the existing power factor of the loads and load distribution in the radial distribution network. For the base case, the total load is equal to 4369.35 kVA and the kVA margin to maximum loadability value is equal to 11 468.10 kVA. When an additional load equal to kVA margin to maximum loadability, it was added to the base case, supply lines to buses 3 and 6 were carrying maximum allowable power. In that case, the voltage magnitudes at these buses at the point of collapse were 0.578 92 p.u. and 0.384 54 p.u., respectively.

Table 1. The load data of a 33-bus distribution network under study

Line number	Sending Bus	Receiving Bus	Resistance (Ω)	Reactance (Ω)	Load at Receiving End Bus	
					Real Power (kW)	Reactive Power (kVAr)
1	1 Main SS	2	0.0922	0.0477	100.0	60.0
2	2	3	0.4930	0.2511	90.0	40.0
3	3	4	0.3660	0.1864	120.0	80.0
4	4	5	0.3811	0.1941	60.0	30.0
5	5	6	0.8190	0.7070	60.0	20.0
6	6	7	0.1872	0.6188	200.0	100.0
7	7	8	1.7114	1.2351	200.0	100.0
8	8	9	1.0300	0.7400	60.0	20.0
9	9	10	1.0400	0.7400	60.0	20.0
10	10	11	0.1966	0.0650	45.0	30.0
11	11	12	0.3744	0.1238	60.0	35.0
12	12	13	1.4680	1.1550	60.0	35.0
13	13	14	0.5416	0.7129	120.0	80.0
14	14	15	0.5910	0.5260	60.0	10.0
15	15	16	0.7463	0.5450	60.0	20.0
16	16	17	1.2890	1.7210	60.0	20.0
17	17	18	0.7320	0.5740	90.0	40.0
18	2	19	0.1640	0.1565	90.0	40.0
19	19	20	1.5042	1.3554	90.0	40.0
20	20	21	0.4095	0.4784	90.0	40.0
21	21	22	0.7089	0.9373	90.0	40.0
22	3	23	0.4512	0.3083	90.0	50.0
23	23	24	0.8980	0.7091	420.0	200.0
24	24	25	0.8960	0.7011	420.0	200.0
25	6	26	0.2030	0.1034	60.0	25.0
26	26	27	0.2842	0.1447	60.0	25.0
27	27	28	1.0590	0.9337	60.0	20.0
28	28	29	0.8042	0.7006	120.0	70.0
29	29	30	0.5075	0.2585	200.0	600.0
30	30	31	0.9744	0.9630	150.0	70.0
31	31	32	0.3105	0.3619	210.0	100.0
32	32	33	0.3410	0.5302	60.0	40.0
33*	21	8	0.0000	2.0000		
34*	9	15	0.0000	2.0000		
35*	12	22	0.0000	2.0000		
36*	18	33	0.0000	0.5000		
37*	25	29	0.0000	0.5000		

* Tie Lines, Substation Voltage =12.66 kV

The original configuration of 33-bus distribution network without DG has been shown in Fig.4. In initial study, the impact of DG integration to distribution network is analyzed. Therefore, there are as many as five DG have been installed on buses of 12, 17, 22, 25, and 27, respectively, as shown in Table 1. The DGs consist of both solar photovoltaic and wind farm models. Power factor of all DG solar photovoltaics are unity while wind farms are ranging from 0.8 to 0.9 (lagging).

Table 2. DG Location and Capacity of 33-Bus Test System

Bus Numbe	DG Active Power (kW)	DG Power Factor	DER Reactive Power (kVAr)
12	250	0.8	187.50
17	250	0.9	121.08
22	300	1	0
25	400	0.9	193.73
27	300	0.8	225

The results of simulation are shown in Fig. 5, Fig. 6, Fig. 7, and Table 3. Network reconfiguration using fuzzy multi-objective technique is resulted that there are four tie switches that must be closed, i.e., switches of 33, 35, 36, and 37, while the sectionalizing switches to be opened are switches of 7, 10, 28, and 31. Power loss dispersion under several scenario for 33-bus radial network test system has been shown in Fig. 5.

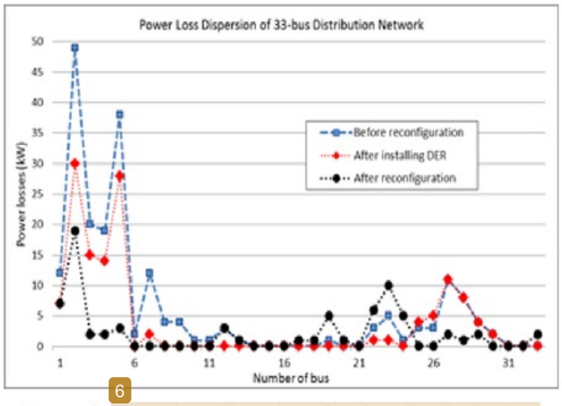

Figure 5. Power loss dispersion of 33-bus distribution test system

It can be seen in Fig. 5 that power loss of each bus depends on line length of network and loading size. The longer distribution line, the greater power loss. From Fig. 5, it is also shown that the greater the load the greater the power loss. The presence of five DGs on buses of 12, 17, 22, 25, and 27 has the effects on the power loss reduction over the system, especially on buses closest to the DG.

Before reconfiguration the network, total active power loss under study is 208.46 kW. Total active power loss after installing as many as five DGs is 133.45 kW, while total active power loss after reconfiguration of distribution network with DG integration is 75.12 kW, as shown in Table 3.

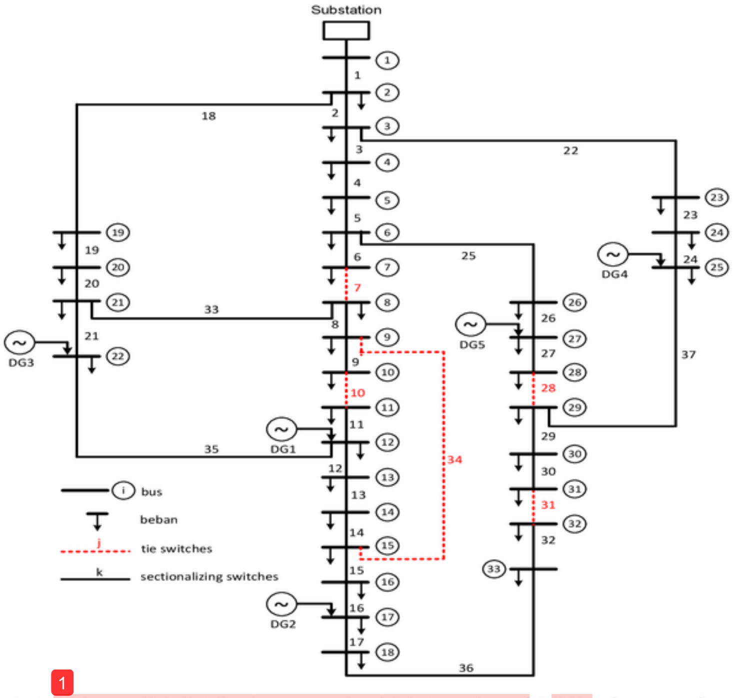

Figure 6. A 33-bus radial distribution network with integration of 5 DGs after reconfiguration.

These results have proved that the reconfiguration of the network have a considerable influence on the reduction of active power loss in distribution system. Reduction of power loss is certainly improving the efficiency of the distribution network. Table 3 also shows that the efficiency of distribution network in original condition is 94.39%. The efficiency has increased to 96.11% after integration of five DGs. After DG integration, optimization is carried out on the network configuration. The result has been shown that an increasing in efficiency be a 97.92% after network reconfiguration is achieved. The 33-bus radial distribution network with integration of five DGs after reconfiguration has been shown in Fig. 6.

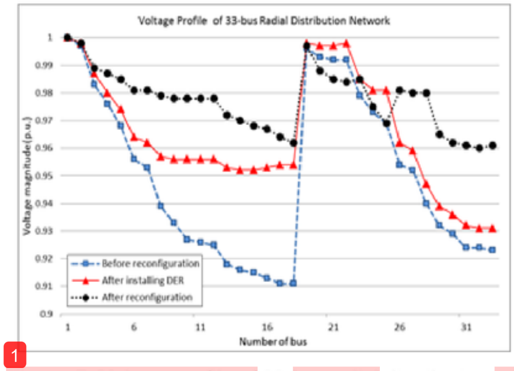

Figure 7. Voltage profile of 33-bus radial distribution test system.

Fig. 7 shows voltage profile of 33-bus distribution network under study. Bus voltage profile is to be improved further by reconfiguring the distribution network than ever before. From Fig. 7, it can be seen that only a voltage magnitude along the main feeder of bus is viewed. In original configuration of network, the highest voltage magnitude is 1.00 p.u. on bus 1 while the lowest is 0.911 p.u. on bus 18 as shown in Fig. 7 and Table 3. The farther away from the substation location, the lower the amplitude of the bus's voltage. Integration of five DGs has resulted in increasing of voltage profile. After installation of five DGs in 33-bus distribution network, the highest voltage magnitude is 1.00 p.u. on bus 1 while the lowest voltage magnitude is 0.927 p.u. on bus 33, as shown in Fig. 7. Integration of five DGs on buses of 12, 17, 22, 25, and 27 has the great effects on the voltage profile improvement, especially on buses closest to the DGs. The voltage improvement is occurred almost the entire bus, except for bus 1, because the voltage magnitude has maximum.

Table 3. Results of 33-bus distribution network test

Test Case of Distribution Network	Parameters of Analysis					
	Active Power Loss (kW)	Efficiency of Distribution Network (%)	Minimum Voltage (p.u.)	Maximum Voltage (p.u.)	Tie Switches to be Closed	Sectionalizing Switches to be Open
Without DG integration before reconfiguration	208.46	94.39	0.911 (V_{18})	1.00 (V_1)	NA	NA
With DG integration before reconfiguration	133.45	96.11	0.927 (V_{33})	1.00 (V_1)	NA	NA
With DG integration after reconfiguration	75.12	97.92	0.959 (V_{32})	1.00 (V_1)	33 35 36 37	7 10 28 31

Furthermore, the use of fuzzy multi-objective technique for optimization of network configuration on 33-bus network with five DGs DER has been examined. The optimization results have also been seen in Fig. 7 and Table 3. The 33-bus distribution network reconfiguration using fuzzy multi-objective method has the great impact of bus's voltage profile. The highest voltage magnitude post optimization is kept 1.00 p.u. on bus 1 while the lowest voltage is 0.959 p.u. on bus 32. This voltage magnitude is better than the voltage before optimization. These results prove that the distribution network optimization with DG integration using fuzzy multi-objective method has been successful in improving the performance of 33-bus radial distribution network which is the complex system.

CONCLUSION

The paperpresented a methodology for optimization of radial distribution network with integration of DGR using fuzzy multi-objective method. The methodology was based on minimizing power losses and improving voltage profile in order to improve distribution network performance in complex system. The methodology was tested on a 33-bus radial distribution network test system. Based on simulation results, it was shown that the method is very attractive in improving distribution network performance in complex systems. The efficiency of the radial distribution system under study in pre reconfiguration, after integration of five DGs, and post reconfiguration are 94.39%, 96.11%, and 97.92%, respectively. Integration of five DGs in the networks has resulted in improved voltage profile. The profile is to be improved further by optimization of the networks using fuzzy multi-objective method.

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