Utilizing Fuzzy Optimization for Distributed Generation Allocation

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Abstract— **Distributed generation (DG) allocation problem is addressed utilizing fuzzy multi-objective optimization in this paper. It is shown that the methodology provides needed consideration for DG allocation and accounts for uncertainty using fuzzy set theory. Voltage drop reduction, short circuit capacity (SCC) augmentation, decrease operation cost and system losses reduction were considered as objectives for formulating fuzzy optimization. The paper discusses in detail the approach adopted and several numerical examples are presented to test the developed methodology.**

***Index Terms*—distributed generation, distribution systems, fuzzy set theory, optimization.**

I. INTRODUCTION

DISTRIBUTED energy resource (DG) interconnection in electric distribution systems brings new dimension in planning and operations of these systems. The nature of distribution systems before distributed generation interconnection are passive and will be much active in the presence if such energy resource. Regulatory code [1] for distribution systems specify data for studying DG integration into distribution systems are detailed for the anticipation of such interconnection. The interconnection of DG, sometimes called as embedded or dispersed generation, accounts for detailed planning studies [2]. DG interconnection can impact profile of voltage, equipment loading, system reliability, stability, fault currents [3] and power quality in distribution systems [2], [4]. But these effects can vary depending on the placement and sizing of DG. Allocation of distributed DG in distribution systems has been a subject of research given this assumption.

Using non-linear optimization [5], optimal placement of DG has been identified in an IEEE 30 bus system which is a transmission test system. In [6]-[7], DG investment planning was optimized using technical and economic methods and consideration of electricity market parameters. Analytical approaches minimizing line losses were also utilized for DG allocation as provided in [8]. In [9], the authors have integrated DG in distribution systems using power systems studies coupled with linear programming method. Analyzing these studies, the consideration of uncertainty in the DG allocation in distribution systems is neglected. Papers [10]-[11] utilized evolutionary programming for identifying placement of DG in distribution systems. In [10], a multi-objective index was formulated to quantify the impact of DG integration. Authors in [11] introduced a cost based evolutionary programming method for placement of DG. In this reports, rigorous mathematical computational effort is required to arrive to the solution. A more simple and straightforward solution can be formulated.

In this paper, fuzzy multi-objective optimization as applied to DG allocation in distribution systems is discussed. Fuzzy sets theory can handle uncertainties and imprecision [12] and are much less in computational exertion.

This paper is organized as follows: Section I introduces the research subject area; Section II discusses the fuzzy optimization methodology applied to DG allocation; Section III presents several numerical examples; lastly, Section IV presents the conclusions and further recommendations of the paper.

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II. FUZZY OPTIMIZATION METHODOLOGY

A. DG Allocation Considerations

DG integration in distribution systems are expected to impact voltage drop, short circuit capacity (SCC), system losses and operational cost.

The DG will provide voltage support upon interconnection that the percent voltage drop is likely to decrease depending on the placement. Voltage drop analysis from load flow computations was employed here.

Voltage sags and fluctuations are mitigated by higher SCC within the distribution system which will be augmented by the DG integration. In this paper, we utilized grid positive sequence impedance as *0.144 + j1.4022 ohms* and DG positive sequence impedance as *6.2972 ohms* [10]. Short circuit analysis was utilized for *SCC* computation.

In the case of losses, the application of DG within load centers will decrease line losses for power delivery. Upon the operation of DG, operational cost for distribution system will be impacted for DG cost is expected to be lower than the grid price [6].

So, in this study the following multi-objective functions are considered:

1. Minimization of *PVD*

$$PVD = \frac{V_{Si} - V_{Ri}}{V_{Si}} \text{ x } 100 \tag{1}$$

Where, *PVD* is percent voltage drop, V_{Si} is sending end line voltage and V_{Ri} is receiving end line voltage.

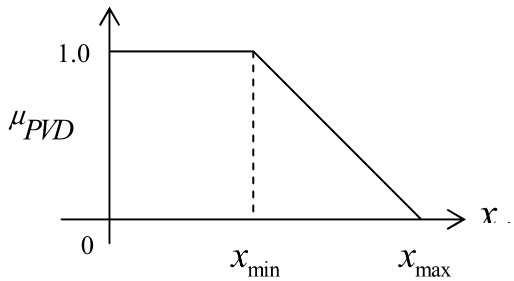

Figure 1. Membership function for percent voltage drop metric.

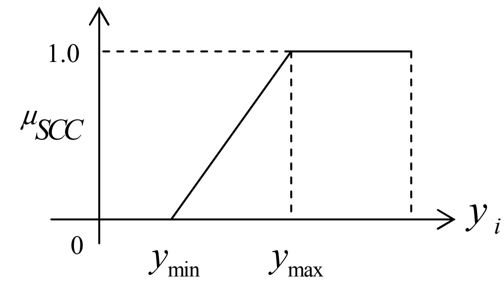

Figure 2. Membership function for short circuit capacity metric.

2. Maximization of *SCC*

$$SCC = \sqrt{3} \cdot I_{3F} \cdot kV_{base} \quad (2)$$

Where, *SCC* is short circuit capacity (MVA), I_{3F} is three-phase fault at the nth bus and kV_{base} is line voltage base.

3. Minimization of system losses

$$P_l = \mathrm{Re}(Z_{ij}) \cdot I_{ij}^2 \quad (3)$$

Where, P_l is the total system loss in kW, $Re(Z_{ij})$ is the resistance of line from node *i* to node *j*, (Ohms) and I_{ij} is current flow from node *i* to node *j* , (Amps.).

4. Minimization of operation cost

$$C(P_i) = P_g \cdot \lambda_g + P_{dg} \cdot \lambda_{dg} \quad (4)$$

Where, $C(P_i)$ is the cost function of power generated in the distribution system ($/MW), P_g is the power generated from the grid, (MW), P_{dg} is the power generated by the DG, (MW), λ_g is the nodal price of power generated by the grid, electricity market price, we used 70$/MWh [6], and λ_{dg} is the marginal cost of power generated by the DG, we used 42 $/MWh [6].

The investment cost of putting up DG within the franchise of the distribution system is assumed equal at all possible system connection points, thus it is neglected in this study.

B. DG Metrics Membership Functions Development

1) PVD Metric Membership Function

For each case, we classify the *PVD* metric as:

$$x_i = \frac{PVD_i}{PVD_0} \quad for \ i = 1, 2, \ldots n \quad (5)$$

Where x_i is the normalized percent voltage drop from the ratio of PVD_i, which is the *PVD* for case *i*, and PVD_o, which is the *PVD* for base case before DG interconnection. From equation (5), when x_i is high, the reduction of *PVD* is low after DG interconnection, then it is assigned with lower membership value. On the other hand, when x_i is low, the reduction of *PVD* is high then it is assigned with higher membership value. Then the *PVD* membership function, given in figure 1, is defined:

$$\mu_{PVD} = \begin{cases} 1 & for \quad x_i \le x_{\min} \\ \dfrac{x_{\max} - x_i}{x_{\max} - x_{\min}} & for \quad x_{\min} < x_i < x_{\max} \\ 0 & for \quad x_i \ge x_{\max} \end{cases} \quad (6)$$

It is assigned that x_{min}= 0.25 while x_{max} = 1.0 in this paper. This indicates that if the PVD_i is 25% or less of PVD_o, the unity membership value is assigned and if the PVD_i is 100% or more of PVD_o, the zero membership value is assigned. In this paper, *PVD* is computed at the node with highest voltage drop with reference to the grid or substation node in the simulation of the base case.

2) SCC Metric Membership Function

For each case, we classify the SCC metric as:

$$y_i = \frac{SCC_i}{SCC_0} \quad for \ i = 1, 2, \ldots n \quad (7)$$

Where y_i is the normalized short circuit capacity from the ratio of SCC_i, which is the *SCC* for case *i*, and SCC_o, which is the *SCC* for base case before DG interconnection. From equation (7), when y_i is high, the increase in *SCC* is high after DG interconnection, then it is assigned with higher membership value. On the other hand, when y_i is low, the increase in *SCC* is low then it is assigned with lower membership value. Then the *SCC* membership function, given in figure 2, is defined:

$$\mu_{SCC} = \begin{cases} 0 & for \quad y_i \le y_{\min} \\ \dfrac{y_{\max} - y_i}{y_{\max} - y_{\min}} & for \quad y_{\min} < y_i < y_{\max} \\ 1 & for \quad y_i \ge y_{\max} \end{cases} \quad (8)$$

It is assigned that y_{min}= 1.0 while y_{max}= 1.80 in this paper. This signifies that if the SCC_i is 100% or less of SCC_o, the zero unity membership value is assigned and if the SCC_i is 180% or more of SCC_o, the unity membership value is assigned. In this paper, *SCC* is computed at the node with highest voltage drop in the simulation of the base case.

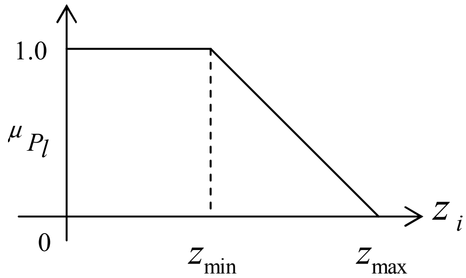

Figure 3. Membership function for system loss metric.

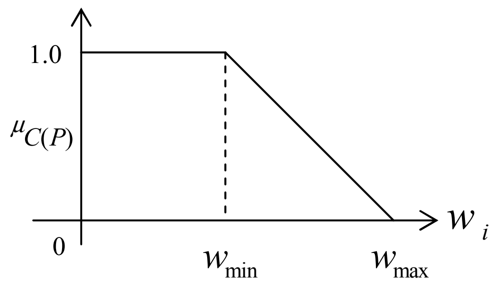

Figure 4. Membership function for operation cost metric.

Where z_i is the normalized system loss index from the ratio of P_{li}, which is the P_l for case i, and P_{lo}, which is the P_l for base case before DG interconnection. From equation (9), when z_i is high, the reduction of P_l is low after DG interconnection, then it is assigned with lower membership value. On the other hand, when z_i is low, the reduction of P_l is high then it is assigned with higher membership value. Then the P_l membership function, given in figure 3, is defined:

$$\mu_{P_l} = \begin{cases} 1 & for \quad z_i \le z_{min} \\ \dfrac{z_{max} - z_i}{z_{max} - z_{min}} & for \quad z_{min} < z_i < z_{max} \\ 0 & for \quad z_i \ge z_{max} \end{cases} \quad (10)$$

It is assigned that $z_{min} = 0.25$ while $z_{max} = 1.0$ in this paper. This indicates that if the P_{li} is 25% or less of P_{lo}, the unity membership value is assigned and if the P_{li} is 100% or more of P_{lo}, the zero membership value is assigned.

3) *Operation Costs Metric Membership Function*

For each case, we classify:

$$w_i = \frac{C(P_i)}{C(P_0)} \quad for \; i = 1, 2, \ldots n \quad (11)$$

Where w_i is the normalized operation cost from the ratio of $C(P_i)$, which is the $C(P)$ for case i, and $C(P_o)$, which is the $C(P)$ for base case before DG interconnection. From equation (11), when w_i is high, the reduction of $C(P)$ is low after DG interconnection, then it is assigned with lower membership value. On the other hand, when w_i is low, the reduction of $C(P)$ is high then it is assigned with higher membership value. Then the $C(P)$ membership function, given in figure 4, is defined:

$$\mu_{C(P)} = \begin{cases} 1 & for \quad w_i \le w_{min} \\ \dfrac{w_{max} - w_i}{w_{max} - w_{min}} & for \quad w_{min} < w_i < w_{max} \\ 0 & for \quad w_i \ge w_{max} \end{cases} \quad (12)$$

It is assigned that $w_{min} = 0.50$ while $w_{max} = 1.0$ in this paper. This indicates that if the $C(P_i)$ is 50% or less of $C(P_o)$, the unity membership value is assigned and if the $C(P_i)$ is 100% or more of $C(P_o)$, the zero membership value is assigned.

C. Max-min Fuzzy Optimization

The fuzzy multi-objective optimization methodology is one algorithm that can be proposed.

The following are the specific steps for this solution methodology.

Step 1 - For each node of possible DG interconnection, all the membership functions discussed above are evaluated.

Step 2 - The scale of overall satisfaction for a specific node of DG possible interconnection is the minimum of all the above membership functions.

$$N_{i,n} = \min(\mu_{PVD}, \mu_{SCC}, \mu_{P_l}, \mu_{C(P)}) \; for \; i = 1, 2, \ldots n \quad (13)$$

Step 3 - The optimal solution of the DG allocation is the maximum of the scales of overall satisfaction.

$$OPS_i = \max(N_{i.n}) \quad (14)$$

III. Numerical Examples

We consider radial and meshed distribution systems from paper [8] to test the methodology presented herein and compare its results with [8]. Distribution data can be acquired from [8].

A. Radial Distribution System

For testing the method in radial distribution systems, we consider figure 5, with three cases of loading; uniformly distributed, centrally distributed and increasingly distributed. In this case, *PVD* and *SCC* are evaluated at node 11.

The methodology described above is followed and in Table 1, the results and comparison are presented.

The fuzzy optimization results shown in table 1 considers not only line losses as in the case of [8] but integrates fault currents, cost of operation and voltage drop reduction in the integration of DG in distribution systems. In this system, fuzzy optimization agrees only when the load is centrally distributed with the results in [8].

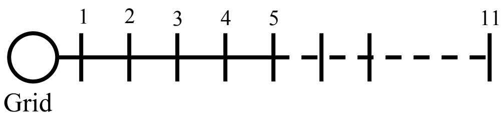

Figure 5. Radial distribution system for DG allocation [8].

TABLE 1
DG ALLOCATION RESULTS FOR RADIAL DISTRIBUTION SYSTEM.

Loading	Analytical Optimal DG Allocation [8]	Fuzzy Optimization DG Allocation
Uniform	6	7
Central	6	6
Increasing	8	9

B. *Meshed Distribution System*

The figure below is a meshed distribution system from [8]. In this case, *PVD* and *SCC* are evaluated at node 3. We consider 5 MW DG allocation in this system and compare the results of [8] with the fuzzy optimization described herein. Table 2 presents the results for DG allocation.

It is shown in table 2 that the fuzzy optimization considering increased fault currents, reduced operation cost, reduction of voltage drop and system losses results in DG allocation in bus number 3 for the system given in figure below. The results of [8] agree with the results given here though line losses are only considered in [8].

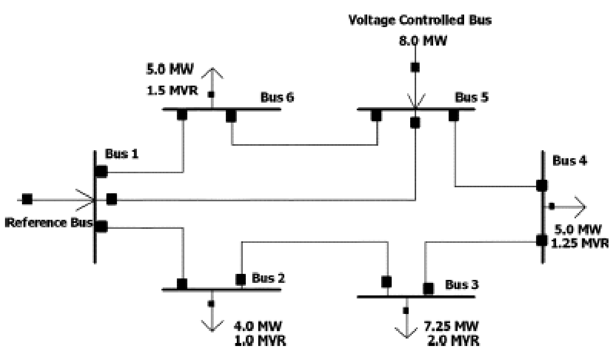

Figure 6. Meshed distribution system for DG allocation [8].

TABLE 2
DG ALLOCATION RESULTS FOR MESHED DISTRIBUTION SYSTEM.

Meshed System	Analytical Optimal DG Allocation [8]	Fuzzy Optimization DG Allocation
Bus Number	3	3

IV. CONCLUSIONS

In this paper, a fuzzy multi-objective optimization is developed for DG allocation for distribution systems. Detailed discussion of the methodology is provided and numerical examples are given where the said methodology is tested and compared with analytical algorithm. It was shown that the fuzzy optimization has technical and economic considerations neglected in other studies.

For further refinement of the study, DG dispatch and demand variations should be integrated in the formulation. The sizing of DG can be included in the formulation for further research. Nevertheless, the formulation presented in this work is a useful tool for distribution system planning and operations engineers studying DG allocation in distribution systems.

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